A Study of Laterite
Used in Khmer Architecture in Thailand

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ABSTRACT

This thesis is to study whether laterite is suitable to be used as a building material and whether ancient laterite in such architecture needs to be conserved. To evaluate the suitability of laterite for being used in building construction, the mechanical strength of laterite is mainly focussed. The strength, as well as other properties, of the laterite samples are measured and characterised.

The study begins with the evaluation of the efficacy of standard tests for stone characterization and the results prove that they are effective for characterising mature laterite. Environmental decay agents and their effects are also discussed accompanied by a simulation programme of their effects. The tests show that laterite is not susceptible to wet-dry cycles, but harmed by the crystal growth of sodium decahydrate. However, sodium chloride is the only salt actually present in the laterite samples and its amount is nearly nil hence may prove that salt is not harmful to laterite. Then, to investigate the effects of environmental decay agents on laterite buildings in reality, the deterioration problems on the façades of a case study are assessed. The samples collected from different positions on each façade are also characterised to study how the environment altered their properties. The results show that laterite is affected by such agents in different degree when it is placed in different aspects and in different positions. The correlations amongst the properties of laterite, between its properties and locations, and between its deterioration problems and locations are also analysed, particularly to find out what affects the alteration of its mechanical strength. It proves that the alteration of compressive strength is related to the percentage of micro porosity and the structure of its large pores.

The research proves that laterite offers acceptable compressive strength and is resistant to weathering and deterioration; therefore, it can undoubtedly continue to be used as a building material or in restoration. It is also so durable that conservation treatments to such ancient laterite are not urgently needed.

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INTRODUCTION

THE PURPOSE OF THE THESIS

What is Khmer? The term *'Khmer'* has sometimes been misused by Thai or other Southeast Asian people, and applied only to Cambodia and its culture and people, and in the general perception of the West, Khmer refers to a communist guerrilla organization that opposed the Cambodian government in the 1960s and waged a cruel civil war in 1970-1975. In fact, the Khmer Empire (3rd century-1430 AD) is one of the greatest empires to have conquered the Indochina Peninsula since the first century AD. Its art and culture including massive architecture existed throughout the empire, and has since influenced all those present-day countries in this region which once were parts of the empire or its dependencies.

Angkor Wat is justly one of the most famous World Heritage sites due to its age, enormous size, structural complexity, and remarkable craftsmanship. It was estimated that tens of thousands of workers spent almost forty years building this temple complex with approximately thirty-five million cubic feet of stone blocks. It occupies nearly 500 acres of land (Narasimhaiah 1994, 6). Built in the twelfth century, it is but one example of great Khmer architecture that was constructed during the Khmer Empire era. The charm and beauty of Khmer architecture is the result of its well-designed and clear silhouettes, elaborate iconography, and artistic decoration, making Khmer architecture among the most impressive of man-made structures to be found anywhere in the world. Nevertheless, throughout the long era of the Khmer Empire, and since, all Khmer monuments have deteriorated, weathered or collapsed, and their current condition is critical.

Urgent conservation is required not only for Khmer architecture in present-day Cambodia, but also for Khmer monuments in Thailand. International experts from France, Germany, Japan, India, China, the United States of America and so on have entered Indochina, especially *Siem Reap* in Cambodia, and have proposed systematic conservation plans to restore the monuments to a stable state. In contrast, in Thailand, although some Khmer stone architecture has been restored, there has never been a systematic plan or strategies for the treatment of the fabric. Hence, stone conservation in Thailand is still in a preliminary phase and needs development. My intention is that this thesis will provide a source of information that will aid this development. In particular, it will broaden knowledge of laterite, one of the main building materials used in Khmer construction which awaits an appropriate conservation approach.

This chapter will introduce the dissertation aims and methodologies of the thesis. Its purpose including its questions and objectives will be identified.

I.1 Objectives of the thesis

Khmer monuments in Thailand are mostly located in the Northeast and were built during the Khmer Empire era in the ninth to the fifteenth centuries, the most prosperous periods in Southeast Asia. At that time, Northeastern Thailand was a part of the Khmer Empire, which was named '*Upper Chenla* or *Chenla of the land*' in the eighth century and is located in the middle of the Mekong Valley north of the Dangrek Mountain Range (Coedes 1966, 2; Macdonald 1987, 40; SarDesai 1997, 27 and see Map 1.1.3 in Chapter I on page 80). Sandstone, laterite and brick were used as building materials in the construction of monuments. The design concepts were based on Hindi beliefs (in combination with Buddhist beliefs in some reigns) and on a cult called *Devaraja*—or the belief in kings as gods—which originated in Java and became established in Khmer during the reign of Jayavarman II (802-850 AD). (For a chronology of Khmer rulers, see Table 1.1 on page 22.)

There are several major Khmer complexes mainly built of sandstone in Thailand, such as the *Phnom Rung, Phnom Wan,* and *Phimai* complexes. A main road, called the *Imperial Road* (see Map 1.2 on page 81), which originated from Angkor and led directly to Phimai (a city in the present-day Nakhon Ratchasima Province (Korat) in Thailand), linked these monuments. Along the road were a number of minor Khmer monuments called *Ku* and *Arokayasala* used as rest houses and hospitals for pilgrims. Such monuments were mostly built of laterite during the reign of Jayavarman VII (1181-1220 AD).

I.1.1 Current problems of Khmer architecture in Thailand

These days, Khmer stone monuments in Thailand are in a critical condition. As in Angkor and other parts of Indochina, monuments in Thailand were abandoned and became hidden by jungles for centuries. As a result, their condition was critical when they were rediscovered. Most of them had decayed, weathered and collapsed, and they required urgent conservation.

In the nineteenth century, French scholars were the first to enter the ancient sites in Cambodia which were at that time buried by jungle and mounds, and to reveal the archaeological architecture to the world (Poshyanandana 1997, 66). Subsequently, international conservation teams—such as experts from UNESCO, Indonesia, China, India, Japan, Germany, the United States, and further French teams—have begun working on Khmer sites mainly in Cambodia, and to some extent in Thailand and Laos. They have been and are attempting to excavate systematically, to assess the current condition of the architecture, to study the properties of the building materials, to investigate the causes of its decay and damage, and to propose conservation plans to save it. This is to say that most of the successful conservation projects have so far been carried out in Cambodia, where international teams have produced documentation, drawings, reports, and photographs of Khmer architecture—either published or unpublished— that form a good resource of information for interested researchers.

Survey and conservation projects in Thailand did not begin until the early twentieth century. At this stage, only about 60% of the Khmer structures were still standing while the other 40% had collapsed (Watsantachad 2001, 2). With the cooperation between UNESCO and the French government, the first restoration project was carried out at the main tower of the Phimai complex in 1964 (Poshyanandana 1997, 68 and see Figure 1.1 in Chapter I on page 48) Nevertheless, the methodology introduced to restore monuments was only *anastylosis*[1], fostering a tradition of disassembly and reconstruction. Since then, the Division of Fine Arts of the Department of the Interior in Thailand has been in charge of supervising all these historic stone restoration projects. Hence, the main conservation activity for Khmer monuments in Thailand focuses only on

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[1] Anastylosis is a stone restoration method that re-erects collapsed stone monuments using original stone blocks and as little new material as possible. It was first proposed by Nikolaos Bakanos in the First International Congress of Architects and Technicians of Historic Monuments in Athens in 1931. According to Chapter 15 of the Venice Charter, anastylosis is recommended for restoring the historic monument: '...All reconstruction work should however be ruled out '*a priori.*' Only anastylosis, that is to say, the reassembling of existing but dismembered parts can be permitted. The material used for integration should always be recognisable and its use should be the least that will ensure the conservation of a monument and the reinstatement of its form...'

architectural and structural restoration or reconstruction with a little consideration of material conservation and of ancient construction techniques. That has resulted in the application of incompatible new materials and inappropriate conservation methods. Without a clear understanding of the original construction technology—materials and methods, existing conditions and decay mechanisms, and the environmental context—any consideration of intervention strategies is difficult.

A little concern about original building materials appears to be one sided; Thai and international conservators have shown interest only in ancient sandstone and brick with little interest in laterite. As yet, little research has been directed at the characterization, decay mechanisms and especially conservation techniques of laterite blocks used in architecture despite laterite being a major Khmer building material, especially in bases and foundations, where it forms the main structural elements. Replacing broken laterite with fresh laterite blocks or Portland cement slabs, as in current Thai conservation strategies for laterite, may cause more structural and chemical problems to monuments. Besides, most of the major sandstone monuments in Thailand have already been restored but many laterite monuments remain in a state of decay. Such lack of action in the area of laterite study and conservation, especially in Thailand, becomes the main focus of this thesis.

I.1.2 Questions, objectives and methodologies

In order to conserve architecture, one of the initial and vital tasks is to investigate the causes and effects of architectural decay and damage. If these are successfully identified, investigation of appropriate conservation approaches can follow. Material deterioration is likely to be one of these causes and it seems logical that a suitable way to learn about the effects of deterioration should begin with knowledge of the material properties and decay mechanisms. Since conservation of laterite monuments in Thailand is the focus of this study, I will present research on laterite in Thailand according to its physical, chemical and mechanical properties, and discuss whether it is a suitable material for architectural construction. Since laterite was extensively used in ancient Khmer structures, other issues for consideration will be whether or not these structures require urgent conservation and the potential methods for understanding remedial works.

Therefore, the questions that need to be answered are:

1) Is laterite suitable to be used as a building material?
2) Does laterite used in Khmer monuments especially in Thailand need to be conserved? Why?

The objective of this thesis is to investigate the properties of laterite and the correlations amongst them, as well as their correlations with the environment. As laterite was used as a building material, particularly in Khmer architecture constructed using a drystone masonry technique, the investigation will mainly focus on the mechanical strength of laterite and on any other properties and environmental decay agents that affect the alteration of its strength.

I.1.3 Methodologies and contents of the thesis

The research is arranged as follows:

- **Chapter I: An introduction to Khmer architecture**

  This chapter provides such information about Khmer architecture as needs to be understood before considering the nature of laterite used in this kind of construction. The information on Khmer architecture is based on literature reviews and the author's own fieldwork.

- **Chapter II: Laterite: literature review of laterite**

  This chapter provides the information about laterite in terms of its origins, formations and characteristics based on literature reviews.

- **Chapter III: The efficacy of standard tests for the characterization of laterite**

  A pilot testing programme to characterise the properties of laterite is offered followed by the results and conclusions of the tests.

- **Chapter IV: Environmental decay mechanisms**

  Because of the lack of research on the decay of laterite used as stone in building construction, this chapter introduces various environmental agents that cause stone, particularly sandstone, to decay and discusses their effects on such material. It also provides information about the environment in Thailand involved in the decay of Khmer architecture. The discussion in this chapter is based on literature reviews.

- **Chapter V: Effects of some environmental decay agents on laterite**

  To study the decay mechanisms of laterite, this chapter offers a testing programme for simulating the effects of some environmental decay agents on selected laterite followed by the results and conclusions of the tests.

- **Chapter VI: Deterioration assessments of laterite façades**

  A field test on a selected laterite Khmer building is discussed. The deterioration of its façades was assessed through the effective characterization tests developed through the pilot tests in Chapter III. The purpose of this chapter is to assess the deterioration and property differences of laterite placed in different locations, and, finally, to calculate the correlations as to whether and how for the environmental difference in different locations caused the properties of laterite to deteriorate in different ways.

- **Chapter VII: Discussions**

  The aim of this chapter is to answer the questions identified in the introduction chapter as to whether or not laterite is suitable to be used as a building material and as to whether or not it needs to be conserved. In this chapter, the characteristics of laterite used in Khmer architecture through the applied tests in Chapter VI are concluded. The deterioration occurring on the laterite façades assessed in Chapter VI will be again discussed, but in more detail concerning the causes of such deterioration. Thereafter, the correlations amongst the properties of laterite and other environmental agents are calculated and discussed in order to identify which properties and/or agents affect the strength of laterite.

- **Chapter VIII: Conclusion and recommendations**

  This chapter provides the summary of all research carried out in this study. It again clarifies the aims of the thesis and discusses whether they have been achieved, and whether the knowledge gained from the research can contribute to the field of laterite conservation and to the development of material conservation in Thailand in particular. The pros and cons of the research and recommendations for further study of laterite are included.

In brief, this thesis will provide general information about laterite used in Thailand, which could be of use not only for Thai but also for international researchers who are interested in laterite as an architectural building material. The detailed understanding of the characteristics, decay mechanisms and use of laterite presented in this thesis may encourage Thai and international conservators to realise its significance and to find successful ways in which to conserve Khmer laterite architecture and laterite as a building material in Thailand.

CHAPTER I

AN INTRODUCTION TO KHMER ARCHITECTURE

At its greatest extent, the Gulf of Siam to Vientien and from Saigon to the Valley of Menam including present-day Cambodia, the greater part of the Indochina Peninsula, the southern part of Laos and the east and northeastern parts of Thailand was the land of the 'Khmer Empire' (Coedes 1966, 1 and see Map 1.1 on page 80). Evidence of ancient Khmer culture and civilization, especially Khmer arts and architecture, remains in several parts of these countries today, but only Khmer religious architecture, mainly in stone or brick and laterite with a unique construction technique called 'drystone masonry', remains while Khmer houses built of wood vanished. Therefore, in this thesis, religious architecture has been the only focus of study.

In order to propose appropriate conservation approaches to Khmer architecture and its building materials, thorough understanding of the origin, typology, construction technique and causes of the failures of the architecture as well as the culture, concepts and beliefs of the builders is necessary. Therefore, in this chapter, a brief history of the Khmers and their architecture in terms of beliefs, chronology and typology is discussed. Thereafter, Khmer construction techniques and the use of laterite in the construction are discussed. Finally, the causes of Khmer structural failure are identified.

It is to be noted that the Khmer construction techniques discussed in this research are mainly based on my own observations and study of Khmer monuments and the field trips with the Japanese Government Team for Safeguarding Angkor (JSA) in Siem Reap in Cambodia in 2002.

1.1 General history of Khmer

'*Khmer*' or '*Kambuja*' is a word used to describe the people, culture and civilization developed in the northeastern region of Southeast Asia during the first to the fifteenth century AD. As discussed at the beginning, from the Gulf of Siam to Vientien and from Saigon to the Valley of Menam, this area was called the 'Khmer Empire', 'Kambujas' or 'Khmers'. The empire included the land of present-day Cambodia, the greater part of the Indochina Peninsula, the southern part of Laos and the east and northeastern parts of Thailand (Coedes 1966, 1 and see Map 1.1 on page 80). Although the beginning of the Kambuja period and the name of the empire and its people are still debatable, several scholars state that the continuity of this nation and its people started in the first century AD (Coedes 1966, 1; Chandler 1983, 9-13; Macdonald 1987, 34; SarDesai 1997, 23; Steinberg 1959, 2-9 and see Appendix I: Chronology of Khmer empires and conquerors). Khmer people originally called themselves 'Kambuj,' which was the root of the nation's name 'Kambujas,' while the name 'Chenla' was generally recorded in Chinese inscriptions. However, it is unclear when the word 'Khmer' was introduced to the nation. Coedes stated that the word 'Khmer' was first found in an inscription during the reign of Jayavarman VII (1181-1220 AD), but it is possible that the word was used before it was recorded in writing (Coedes 1966, 1; Suksawasdi 1995, 31). Evidence of ancient Khmer culture and civilization, especially Khmer arts and architecture, remains in several parts of these countries today. However, since the fall of the Khmer Empire in the fifteenth century, the word 'Khmer' has referred to a group of Cambodian people and their culture, as well as the remaining civilization of the ancient Khmer Empire throughout the rest of Southeast Asia.

Hinduism and Buddhism derived from India were the predominant religions of the Khmers. According to Hindu mythology, there are three major gods who play the most powerful roles—*Brahma* the creator, *Vishnu* the preserver, and *Shiva* the creator and destroyer. They live on top of *Meru Mountain*, which is believed to be the centre of the universe. Meru Mountain is surrounded by seven oceans that separate the lands of gods, men and devils. The belief that Meru Mountain is the centre of the universe forms the fundamental design concept of Indian Hindu architecture and Khmer religious architectural complexes.

Despite being based on the same religious beliefs as in India and some parts of Southeast Asia, Khmer people developed their own culture called *Devaraja*, which held their kings to be gods. (*Deva* means gods while *Raja* means king.) Within this belief, religious architecture and artefacts used to worship or symbolise gods also represented the power of kings. Each king established himself as the incarnation of a god and used aspects of gods such as *linga,* a phallic symbol used to represent Shiva indicating fertilization and richness. Moreover, unlike Indian religious places, Khmer temples became sacred places where only the king and his Brahmins were allowed to worship. The *Devaraja* cult dominated the Khmers throughout the Empire era and thereafter expanded into Siam (Ancient Thailand), while it became an absolute monarchy.

1.2 Chronology of Khmer architecture

(See Appendix I: Chronology of Khmer empires and conquerors for details)

1.2.1 **Pre-historic style** (4200BC- approximately 1st century AD)

Although there is no architecture from the pre-historic period that remains today, it is likely that the houses of early people living in this region were raised above the ground and made accessible by ladders (Macdonald 1987, 10). About 1000 BC, they may have lived in fortified villages—often in circular forms. However, building materials are not mentioned in any written records. They might have been nondurable materials.

1.2.2 **Pre-Angkorian Style** (1st – late 8th centuries AD)

During the Funan period (1st-mid 6th centuries AD), the styles of art and architecture were borrowed from India (Macdonald 1987, 36). However, fewer than a hundred early Funan temples dating from the mid-sixth to mid-eighth centuries survive, and most of them are in a critical condition. Dwellings built of wood vanished, while a few religious shrines built of brick and partially of stone remain. In the Chenla period (mid 6th- late 8th centuries AD), most of the architecture was also built of brick with certain stone elements (Macdonald 1987, 40). Notably, all of the remaining structures are religious buildings. This may be due to a Hindu belief that only gods could live in houses constructed with durable stone and brick. Therefore, even the palaces of kings were built of wood (Coedes 1966, 7).

Coedes believed that the architecture in Kampong Thom such as *Sambor Prei-Kuk* might be characterized as Pre-Angkorian (Coedes 1966, 5). The main characteristics of the Pre-Angkorian style include a square-planned brick tower, false doors and a stepped pyramid of shallow rising storeys of decreasing size—each of which replicated the one below. This form subsequently disappeared, later leaving no traces in Khmer architecture (ibid.). In Figure 1.2 on page 48, *Prasat Ak Yum* is an example of the Pre-Angkorian architecture built in the second half of the eighth century AD. From an inscription remaining on a carved stone, the temple may have been built during the reign of Jayavarman I. Since no excavation and restoration work has been carried out at this site, it is difficult to see the original shape and form of the temple.

However, there were a few differences between Pre-Angkorian monuments constructed in the Funan and Chenla periods. For example, Funan towers did not have false doors while those of Chenla did. The absence of the false door became the hallmark of the Funan towers. During the Chenla period, a new architectural form was created. Rather than a single tower called '*Prasat*' standing in isolation, three additional prasats were built to comprise a group. The central prasat probably housed the principal god while the others would house attendant divinities. (Macdonald 1987, 87)

Throughout the Funan and Chenla periods, the Khmer people showed their creative skills by blending Indian influences with their own art styles and beliefs. The brick temples were decorated with stucco of delicately designed carved flora, and figures of monsters and deities. However, if compared with the artistic and aesthetic values of later Classical Khmer art and architecture, they were particularly simple and austere. (Macdonald 1987, 40)

1.2.3 **Angkorian style** (approximately 790-1113 AD)

Angkorian architecture includes all monuments dating from the ninth century to the twelfth century. The centres of the group were located in Angkor Region—Roluos and Angkor, *Koh Ker, Preah Khan, Beng Mealea, Banteay Chmar, Prah Vihear* and *Phnom Chisor*. The main characteristic of the Angkorian style is a group of towers—usually five—built on a huge raised platform. The five towers—one at the centre surrounded by the rest at each corner—represented the five peaks of Meru Mountain where the gods lived. However, only three elevations of the towers could be seen if one stood on one side. These three elevations represented *Trimurati*, the three Hindu gods—Shiva, Vishnu, and Brahma.

The worship of the royal linga became the official state religion after Jayavarman II introduced the Devaraja cult to Khmers. Each king had to build a holy temple to house this sacred symbol. Shrines or central sanctuaries were constructed at the centre of the complex to serve this purpose (Macdonald 1987, 46). The idea of a central shrine housing the most sacred image became omnipresent in all Khmer architecture from this time. However, not only did the Khmer kings introduce the custom of constructing new sanctuaries for religious belief and ideas of kingship, they also built temples dedicated to their ancestors.

Built by Yasovarman I (889-910 AD), *Phnom Bakeng* is one example of Angkorian architecture. (See Figure 1.3 on page 49) Its innovation of form to contain five towers over one large stepped platform became one of the famous architectural patterns as seen in the Ta Keo complex. (Figure 1.4 on page 50) Its popularity continued into the ensuing centuries, and its artistic decoration became a pattern of art styles called *Bakeng*. (Figure 1.5a on page 51)

Thereafter, there were several artistic styles named after the main or significant monuments or locations, such as Koh Ker style at Koh Ker City; Pre Rup style derived from the monument named Pre Rup; Banteay Srei style named after the Banteay Srei complex; Kleng style at Kleng; and so on. (See Figure 1.5b, 1.5c, and 1.5d on page 51 and see details in Table 1.1: Chronology of Khmer architecture on page 22) The categorising and dating of all Khmer monuments was based on these artistic styles rather than on their builders or architectural styles. (The study of Khmer architecture is generally based on the categories stated in the book titled 'Le Cambodge' written by Jean Boisselier in 1966 (Charernsupkul 1998, 7)). This criterion, however, has been applied successfully and is widely acceptable for classifying the monuments and especially for dating them when only some pieces of architectural elements were found. Nevertheless, it was not only the aesthetic of arts and decoration, but also its perfect proportion and the purity of its silhouette that made Khmer architecture universally admired (Diskul 1983, 26)

1.2.4 Classical Angkorian Style (1113-1181 AD)

The Khmer architectural and artistic evolution reached its zenith and perfection at Angkor Wat, built by Suryavarman II in the twelfth century. (Figure 1.6 on pages 52-53) Its perfect form, proportion and art style can be traced back to those of Angkorian monuments such as Phnom Bakeng, East Mebon, Pre Rup, Banteay Srei. Not only the combined form of a prasat group over a huge platform constructed on an artificial hill, Angkor Wat also featured *gopuras* or galleries and flanking libraries as main components. This became the pattern of the classical style. Its decorations on doorways, walls, balustrades and turrets also expressed the advanced skills of Khmer artisans. The decorations appeared in every part of the monument—from the foundation to the roof. An example of the most elaborate works of art can be found at Angkor Wat as the bas-reliefs on the lowest terrace walls of the gallery that surround the main sanctuary.

Several monuments are grouped under the Classical Angkorian style, for example *Chau Say Tevoda* and *Banteay Samre* (Figure 1.7 and 1.8 on pages 54-55). They were built of sandstone and laterite. Most of them were constructed outside the city walls during the reign of Suryavarman II.

1.2.5 Post-Classical Angkorian Style (1181-1430 AD)

After the perfection of the Classical Angkorian style of Suryavarman II, Khmer architectural achievement has been seen by architectural historians to decline. Although post-classical architecture was more intensively designed (which resulted in monuments that were more complex), its extravagant architectural elements and lavish decorations overcomplicated it. Nevertheless, the post-classical Angkorian architecture still had its own charm and beauty.

The mighty Bayon, built by Jayavarman VII in the thirteenth century, is the major example of post-classical architecture. (Figure 1.9 on page 56) The main characteristics of this style include an over-complicated design, wall-decorations with Lokesvara's faces representing Jayavarman VII (see Figure 1.10 on page 56), and an overhasty massive construction without regard for structural safety.

1.2.6 Summary

In conclusion, the chronology of Khmer architecture started with the Proto-Khmer architecture that was first derived from India and later mixed with Khmer and neighbouring trends and traditions to turn into a unique Khmer architectural style. Thereafter, starting from fifth-century wood and brick constructions, the architectural evolution to stone-built monuments reached its apogee in the Angkor period, the so-called classical Angkor Wat style, under the reign of Suryavarman II (1113-1150 AD). Architecture then became more complex and extravagant during the reign of Jayavarman VII (1181-1220 A.D.), especially at the main sanctuary of Bayon built in 1190-1210. Thereafter, the architectural evolution of styles, forms and construction techniques began to decline until the end of the Empire in the fifteenth century.

1.3 Typology of Khmer architecture

According to Khmer beliefs, only religious architecture could be built of durable materials, which is why only that group of monuments remains today. Khmer religious monuments can generally be divided into three groups according to characteristics of building plans —buildings with a long axis of causeway and terraces, pyramid type buildings, and horizontally distributed buildings (JSA 2000, 10). The first type is the oldest construction that remains today. It has a long access way with several storeys of terraces. (Figure 1.11 on page 57) Secondly, the pyramid-like building consists of a high tower-like shrine built on a hill or, if in the centre of a city, on a series of platforms. (Figure 1.12 on page 58) This type of architecture was usually used as either religious complexes or tombs. Lastly, the horizontally distributed building is a minor form of architecture around a main temple, often with the function of a library or *Bannalaya,* or schools, or markets. (See libraries(C) in Figure 1.13 on page 59) However, after the tenth century, a new type of architecture was introduced, combining the three existing types. An example of this type can be seen at Baphuon, built in the middle of the eleventh century, in Angkor Thom. (Figure 1.13)

If, however, structural systems and locations are taken into account, World Monuments Fund divides Khmer architecture into nine types as follows (1994, 17-18). Firstly, the Tower, or *Prasat* or *Garbhagrha*, that is a single structure with a central space or shrine surrounded by other towers of different sizes having the same basic structural systems (a on Figure 1.14 and see Figure 1.15a on page 60). Secondly, the Entrance Towers which are similar to the first type, i.e. having the same structural system as a tower, but placed in different locations (see b on Figure 1.14). An entrance tower is a part of the entrance complex (*gopura*) and has a great centre that often contains supporting columns. The third type consists of the Halls, or *Mandapa*, that connect the central towers, but are separated by construction joints that may have been consciously planned as expansion joints (c on Figure 1.14 and see Figure 1.15a). Next, the Entrance

Halls comprise a corbelled vaulted structure with longitudinal load-bearing walls which form the entrances (gopuras) on each of the four sides of the temple complex (d on Figure 1.14 and see Figure 1.15b). The Vestibule, or *Mukha*, forms an entity of the central shrines and has relatively small attached porches (e on Figure 1.14 and see Figure 1.15a). Corner Towers are located at the corner of the enclosure wall (see f on Figure 1.14 and see Figure 1.15b). The Cloisters or corridors associated with the enclosure walls form the seventh type (g on Figure 1.14 and see Figure 1.15b). This type is sometimes called 'Galleries'. Single Shrines, or *prangs*, are the eighth type of architecture (h on Figure 1.14). They are single temples representing isolated structures of a relatively small size located within the enclosure wall. Lastly, the Special Buildings type includes other unique or particularly interesting structures such as *sala(s)* or pavilions; *dharmasala(s)* or pilgrims' rest houses; and *bannalaya(s)* or libraries (i on Figure 1.14).

There are three types of Khmer architecture regarding its roles or functional purposes (Charernsupkul 1998, 4-6). Mountain Temples are the first type, which was built to express the power of kings. The temples were also used as the kings' mausolea after their deaths. (Since the reign of Jayavarman II (802-850), there had been a royal tradition to provide facilities for a city and to build a major monument and then to be crowned. However, only thirteen kings of all dynasties could build these mountain temples and establish themselves as 'King the Great' (Charernsupkul 1998, 5).) Ancestral Temples are the second type, dedicated to their ancestors (generally former rulers) by the kings. The last type consists of the Community Temples placed in villages or provinces to be centres of settlements. This type of temple may have been built as victory memorials or kings' pilgrimage sites.

1.4 Khmer architecture in Thailand

There is evidence of Khmer architecture dating to the sixth and seventh centuries AD in '*Isan*' or Northeastern Thailand. When the Khmer Empire conquered the Indochina Peninsular (about 540-1230 AD), Thailand— called Siam at that period — formed the border of the empire. The country was connected to the Empire's centre by the Imperial Road that ran northwest from Angkor, crossed the Dangrek Mountain, passed through the Burirum Province, where the *Phanom Rung* and *Muang Tum* complexes were located, and ended at the Nakhon Ratchasima Province, where the *Phimai* complex was located. (See Map 1.2 on page 81) There were many Khmer monuments which served as temples, hospitals or rest houses, built of sandstone, laterite, and fired brick, constructed along this road and in the surrounding territory. Like those in Khmer, the monuments in Thailand also represented the sanctuary of Hindu gods and, sometimes, Buddhist temples. In respect of the size, location, and function of the existing monuments, the Phimai, Phanom Rung, Phanom Wan, and Muang Tam Khmer complexes are the most predominant and important Khmer complexes in Thailand (Watsantachad 2001, 1-2 and see Figure 1.16 on page 61).

Arogayasala (hospitals) and *dharmmasala* (pilgrims' rest houses) are the major Khmer monuments remaining in Thailand. They were built of laterite in the reign of Jayavarman VII all with virtually the same plan, composition and size (Sri-arun and Leksukhum 1992, 2). They contain five architectural elements: a main sanctuary as the centre of a complex surrounded by a boundary wall; a *bannasala* (library) within this area; a pond to the northeast, outside the boundary wall; and a gopura which was used as the site entrance and was always located to the east. There may also have been a nearby community built of nondurable materials. Interestingly, the exterior of such monuments was never completed, but the interior spaces were finished, at least for serving as a place of worship. This may have been because functionality and speed of construction, rather than aesthetics, were the main architectural criteria since monuments in the reign of Jayavarman VII were usually built with low-quality materials and non-standardised, local construction techniques. The lack of professional masons and building materials was probably another cause of incomplete work. Instead of using sandstone, laterite (abundant in the east and northeast of Thailand) was roughly cut and disorderly placed to be the foundation, wall and roof of monuments. Sandstone, used as window- and doorframes, was brought from nearby monuments and reused.

The styles and forms of Khmer art and architecture in Thailand were derived from those of Kambuja and were generally called 'the Khmer School in Thailand' (Charernsupkul 1998, 4). When Isan (Northeastern Thailand) was ruled by Khmer kings, their royal prerogatives spread over the land, and monuments were built under their royal commands. However, built by Thai artisans and blended with Siamese styles, the Khmer school in Thailand had its own traditions of craftsmanship and artistic expression. The remaining evidence of architecture, art and iconography revealed that it was independent from, or perhaps surpassed, the traditional Khmer styles from the Kambuja metropolis (Boisselier 1975, 107). Nevertheless, such unique style and beauty was obvious only in major monuments built in or before the reign of Suryavarman II (1113-1150), while the later monuments, particularly in the reign of Jayavarman VII (1181-1220), were constructed with less masonry skill and artistry.

Table 1.1: Chronology of Khmer monuments and rulers

YEAR	MONUMENT	REIGN	ART STYLE	ARCHITECTURAL STYLE
Md.6thC	-	Bhavavarman	-	-
7thC	Sombor Preikuk	Isanvarman	Sambor	Pre-Angkorian
	Phnom Thom	Isanvarman	Sambor	Pre-Angkorian
	Dumbong Dek	Isanvarman	Sambor	Pre-Angkorian
8thC	Prei Mek	Jayavarman I	Prei Mek	Pre-Angkorian
	Swai Preim	Jayavarman I	Prei Mek	Pre-Angkorian
	E.Ent Phnom Buksek	Jayavarman I	Prei Mek	Pre-Angkorian
	S. Prei Prasat	Jayavarman I	Prei Mek	Pre-Angkorian
	Andet	Jayavarman I	Prei Mek	Pre-Angkorian
2nd half of 8thC	Prasat Ak Yum	Jayavarman I	Kumpong Preah	Pre-Angkorian
707-807	Kumpong Preah	Unknown	Kumpong Preah	Pre-Angkorian
	Trapeang Pong	Unknown	Kumpong Preah	Pre-Angkorian
	W.Ent Phnom Buksek	Unknown	Kumpong Preah	Pre-Angkorian
	Bhumi Prasat	Unknown	Kumpong Preah	Pre-Angkorian
805	Prasat O Paong	Jayavarman II (802-850)	Kulen	Angkorian
832-857	Sombor C1	Jayavarman II (802-850)	Kulen	Angkorian
	N.Prei Prasat	Jayavarman II (802-850)	Kulen	Angkorian
	Dumrai Krab	Jayavarman II (802-850)	Kulen	Angkorian
	Krating Slab	Jayavarman II (802-850)	Kulen	Angkorian
	Rup Arak	Jayavarman II (802-850)	Kulen	Angkorian
	Tmor Dob	Jayavarman II (802-850)	Kulen	Angkorian
	Koki	Jayavarman II (802-850)	Kulen	Angkorian
	Krahom	Jayavarman II (802-850)	Kulen	Angkorian
	Neak Ta	Jayavarman II (802-850)	Kulen	Angkorian
857-882	C.Trapeang Pong	Jayavarman II (802-850)	Transition	Angkorian
	Kokpo (A,B)	Jayavarman II (802-850)	Transition	Angkorian
	-	Jayavarman III (854-877)	-	-
879	Preah Ko	Indravarman I (877-889)	Preah Ko	Angkorian
881	Bakong	Jayavarman III-Indravarman I	Preah Ko	Angkorian
893	Lolei	Yasovarman I (889-910)	Tst Preah Ko/ Preah Rup	Angkorian
893	Phnom Bakheng	Yasovarman I (889-910)	Bakheng	Angkorian
End of 9th-10thC	Phnom Krom	Yasovarman I (889-910)	Bakheng	Angkorian
End of 9th-13thC	Tep Pranam	Yasovarman I (889-910)	Mixed 12th, 13th&Bayon	Angkorian
	Phnom Bok	Yasovarman I (889-910)	Bakheng	Angkorian
921	Prasat Kravan	Hashavarman I (910-923)	Tst Preah Ko/ Preah Rup	Angkorian

Table 1.1: Chronology of Khmer monuments and rulers (continued)

YEAR	MONUMENT	REIGN	ART STYLE	ARCHITECTURAL STYLE
	-	Isanavarman II (923-928)	-	-
	Koh Ker	Jayavarman IV (928-941)	Koh Ker	Angkorian
908-956	Sang Sinjaya	Jayavarman IV (928-941)	Koh Ker	Angkorian
	-	Harshavarman II (941-944)	-	-
947	Baksri Chamkrong	Rajendravarman (944-968)	Tst Bakheng/ Koh Ker	Angkorian
952	East Mebon	Rajendravarman (944-968)	Preah Rup	Angkorian
957-978	Phimeanakas	Rajendravarman (944-968)	Kleang	Angkorian
961	Pre Rup	Rajendravarman (944-968)	Praeh Rup	Angkorian
	Prang Kek	Rajendravarman (944-968)	Praeh Rup	Angkorian
967	Banteay Srei	Rajendravarman-Jayavarman V	Banteay Srei	Angkorian
Mid 10th-11thC	Srah Loa	Rajendravarman (944-968)	Banteay Srei	Angkorian
	N. Kleang	Rajendravarman (944-968)	Banteay Srei	Angkorian
	Ban Mai	Rajendravarman (944-968)	Banteay Srei	Angkorian
End of 10th-End of 11thC	Klengs (N&S)	Jayavarman V (968-1001)	Kleang	Angkorian
970-1010	Ta Keo	Jayavarman V (968-1001)	Kleang	Angkorian
	-	Udayadityavarman I (1001-1002?)	-	-
	-	Jayaviravarman (1002-1011?)	-	-
11thC	Royal Palace	Suryavarman I (1001-1050)	Transition	Angkorian
11thC	Phnom Jisor	Suryavarman I (1001-1050)	Transition	Angkorian
	Preah Vihear	Suryavarman I (1001-1050)	Transition	Angkorian
	Choa Srei Vibol	Suryavarman I (1001-1050)	Transition	Angkorian
11th C?	West Baray& Temple	Suryavarman I (1001-1050)	Transition	Angkorian
11thC	**Meung Tum**	Suryavarman I (1001-1050)	Baphuon	Angkorian
1050-1066	Baphuon	Suryavarman I-Udayadityavarman II	Baphuon	Angkorian
	West Mebon	Udayadityavarman II (1050-1066)	Baphuon	Angkorian
	Wat Khnar	Udayadityavarman II (1050-1066)	Baphuon	Angkorian
	-	Harshavarman III (1066-1089?)	-	-
	Wat Phu	Jayavarman VI (1080-1113?)	Angkor Wat	Angkorian
12thC	Ta Meun Thom	Jayavarman VI (1080-1113?)	Angkor Wat	Angkorian
1107-1156	Beng Mealea	Dharanindravarman I (1080-1113?)	Angkor Wat	Angkorian
	Preah Palilay	Dharanindravarman I (1080-1113?)	Angkor Wat	Angkorian
	Upper Prasat	Dharanindravarman I (1080-1113?)	Angkor Wat	Angkorian
1108	**Phimai**	Dharanindravarman I (1080-1113?)	Angkor Wat	Angkorian
1113-1150	Angkor Wat	Suryavarman II (1113-1150)	Angkor Wat	Classical Angkorian
1150-	Chau Say Tevoda	Suryavarman II (1113-1150)	Angkor Wat	Classical Angkorian
1150-	**Thommanon**	Suryavarman II (1113-1150)	Angkor Wat	Classical Angkorian
1150-1175	Banteay Samre	Suryavarman II (1113-1150)	Angkor Wat	Classical Angkorian
1st Half of 12th C	Preah Pithu	Suryavarman II (1113-1150)	Angkor Wat	Classical Angkorian

Table 1.1: Chronology of Khmer monuments and rulers (continued)

YEAR	MONUMENT	REIGN	ART STYLE	ARCHITECTURAL STYLE
	Wat Attawa	Suryavarman II (1113-1150)	Angkor Wat	Classical Angkorian
	Preah Khan	Suryavarman II (1113-1150)	Angkor Wat	Classical Angkorian
	Phnom Rung	Suryavarman II (1113-1150)	Angkor Wat	Classical Angkorian
	Preah Palilay	Suryavarman II (1113-1150)	Angkor Wat	Classical Angkorian
	-	Narendratitaya (1150?)	-	-
	-	Haranya (1150?)	-	-
	-	Dharanindravarman II (1150-1160?)	-	-
	-	Yasovarman II (1160-1165/6)	-	-
	-	Tribhuvanandityavarman (1165-1181)	-	-
1186-?	Ta Prohm	Jayavarman VII (1181-1220)	Bayon	Post-classical Angkorian
1190-1210?	Banteay Kdei	Jayavarman VII (1181-1220)	Angkor Wat & Bayon	Post-classical Angkorian
1190-1210	Neak Pean	Jayavarman VII (1181-1220)	Bayon	Post-classical Angkorian
1190-1210	Ta Som	Jayavarman VII (1181-1220)	Bayon	Post-classical Angkorian
1190-1210	**Srah Srang**	Jayavarman VII (1181-1220)	Bayon	Post-classical Angkorian
1190-1210	Angkor Thom	Jayavarman VII (1181-1220)	Bayon	Post-classical Angkorian
1190-1210	Bayon	Jayavarman VII (1181-1220)	Bayon	Post-classical Angkorian
1190-1210	Terrace of the Elephants	Jayavarman VII (1181-1220)	Bayon	Post-classical Angkorian
1190-1210	Terrace of the Lepe King	Jayavarman VII (1181-1220)	Bayon	Post-classical Angkorian
1191-?	Preah Khan	Jayavarman VII (1181-1220)	Bayon	Post-classical Angkorian
L12th-E13th C	Krol Ko	Jayavarman VII (1181-1220)	Bayon	Post-classical Angkorian
End of 12th C	Prasat Suor Prats	Jayavarman VII (1181-1220)	Bayon	Post-classical Angkorian
End of 12th C	Chapel of the Hospital	Jayavarman VII (1181-1220)	Bayon	Post-classical Angkorian
	Banteay Chmar	Jayavarman VII (1181-1220)	Bayon	Post-classical Angkorian
	Library @Phnom Rung	Jayavarman VII (1181-1220)	Bayon	Post-classical Angkorian
	Kut @Meung Tum	Jayavarman VII (1181-1220)	Bayon	Post-classical Angkorian
	Prasat Ban Prasat	Jayavarman VII (1181-1220)	Bayon	Post-classical Angkorian
	Ban Bu	Jayavarman VII (1181-1220)	Bayon	Post-classical Angkorian
	Meung Singha	Jayavarman VII (1181-1220)	Bayon (Socalled)	Post-classical Angkorian
	Ku Kantanam	Jayavarman VII (1181-1220)	Bayon	Post-classical Angkorian
	Ku Pone Rakang	Jayavarman VII (1181-1220)	Bayon	Post-classical Angkorian
	Prang Ban Prang	Jayavarman VII (1181-1220)	Bayon	Post-classical Angkorian
	-	Indravarman II (1120-1243)	-	-
	-	Jayavarman VIII (1243-1295) (abd)	-	-
	-	Indravarman III (1295-1308)	-	-
	-	Srindravarman (1300-1307?) (abd)	-	-
	-	Indrajayavarman (1308-1327)	-	-

Table 1.1: Chronology of Khmer monuments and rulers (continued)

YEAR	MONUMENT	REIGN	ART STYLE	ARCHITECTURAL STYLE
	-	Paramathkemaraja (1330-1353)	-	-
	-	Hou-eul-na (1371-?)	-	-
	-	Samtac Pra Phaya (1404)	-	-
	-	Samtac Pra Phaya Phing-ya (1405)	-	-
	-	Nippean-bat (1405-1409)	-	-
	-	Lampong/ Lampang Paramaja	-	-
	-	(1409-1416)	-	-
	-	Sorijovong/Sorijong/Lambang	-	-
	-	(1416-1425)	-	-
	-	Barom Racha/ Gamkhat Ramadhapati	-	-
	-	(1425-1429)	-	-
	-	Thommo-Soccorach/Dharmasoka	-	-
	-	(1429-1431)	-	-
	-	Ponha Yat/ Gam Yat (1432-?)	-	-

Note: The bold names indicate the monuments that are located in Thailand

1.5 Khmer construction techniques and the use of Laterite

The combination of strong religious beliefs, Khmer building ingenuity and incalculable amounts of labour and building materials resulted in exceptional Khmer constructions. However, how ancient Khmer architects and masons built such constructions and ensured their stability has puzzled generations of scholars. Khmer architecture was constructed using a drystone masonry technique, that is, stone blocks laid over one another without any mortar. The structure depends upon the weight and strength of the stone to stabilise it against all active forces.

This section considers Khmer construction techniques as gathered from drawings, photographs and secondary bibliographical sources. Some information is gained from the author's interviews with experts and site visits and surveys in Siem Reap in Cambodia and selected sites in Thailand. The use of laterite in Khmer structure will be discussed simultaneously within each structural element.

1.5.1 Building Materials

From surviving evidence, it seems that only a limited range of building materials was used in Khmer architecture. In the pre-Angkor period (prior to the late eighth century), fired bricks were a chief building material while sandstone was used only for window and doorframes, or for decoration of, for instance, pediments and lintels. In all cases, the bricks were originally covered with a high quality decorative stucco finish made of lime and coarse sand (WMF 1992, 25). Early shrines were rarely built of stone. However, there was rare evidence of the use of lime mortar in either Khmer brick or stone construction. Brick masons used a special mixed organic adhesive as the mortar rather than cement, lime, or clay. Khmer masons had applied lime only as stucco to brick walls and laterite bases. The dominant building material changed to sandstone after the early Angkor period, although brick construction techniques continued to be used.

Thus, it is sometimes observed that a site is composed of one main stone tower surrounded by minor brick constructions. The bricks of the Pre-Angkor and of the Angkor periods may be differentiated according to size, the former being approximately 12x12x30 centimetres while the latter are somewhat smaller. The dimensions of the stone blocks used in Khmer construction, although various, may have ranged between approximately 38-50 cm x 65-105 cm x 25-40 cm, according to records, drawings and field survey.

Timber was used for roofs, ceilings, door and window panels, and, in some cases, to supplement stone beams and lintels. Whether or not timber could supplement beams/lintels depends on its position, direction and appropriate thickness. Sometimes, rather than supplementing, timber may weaken the strength of a stone beams/lintel if a part of it has been cut away and replaced with an inserted wooden beam (see Figure 1.44 on page 74). Timber was also a main building material for constructing temporary or common pavilions, dwellings and sanctuaries. Nevertheless, there is little evidence of timber as a construction element remaining today, except for door lintels and posts in a few gopuras. The reason for their survival may have more to do with location than function. Extant examples tend to be in relatively sheltered position where such timber has not been exposed directly to the environment.

Use of metal, such as bronze and iron, was limited to anchors or clamps to tie stone blocks and, possibly, as sheets for lining some sanctuary walls. From the record of Chou Ta-Kuan, a Chinese envoy, during his stay in Angkor from 1296 to 1297 AD, we may see that metal goods had been imported from China since the Funan Period (Macdonald 1987, 74). (However, there is also archaeological evidence of bronze casting in Cambodia in the prehistoric period (ibid, 9).)

Laterite is one of the materials that became prevalent in the Angkorian period and it was often used in the surrounding walls, hidden structures or foundations. In addition, it was used as a main building material for minor monuments, particularly the hospitals and rest houses built during the reign of Jayavarman

VII (1181-1220), because of its abundance and the ease of quarrying. These minor monuments generally contained less detail than the major ones because it was not possible to carve laterite. Structurally, Khmer masons often used the construction techniques applied to sandstone masonry to build their laterite architecture.

In summary, Khmer construction is mainly composed of sandstone, laterite or brick masonry, with wooden and metal elements used as supplementary structural elements. Although the scale of architecture of the later periods changed, there was no significant change of building materials used in Khmer construction throughout the empire era.

1.5.2 Performances and construction techniques of Khmer structure

Like all buildings, Khmer edifices have their own structure to support and make them stable to withstand environmental impacts. Their structural elements might be broadly divided into three categories according to their functional purposes, i.e. roofs, vertical elements (walls and colonnades) and foundations. According to the typology of Khmer architecture described in the previous section, all types were composed of these elements. In this section, the structural performance of Khmer architecture will thus be reviewed according to these elements; the construction techniques of each element will also be considered.

Roof construction

There are various types of roof construction technique which result in different structural performances. One example is the corbelled roof which was widely used in drystone construction, such as in Khmer architecture. This roof is constructed of cantilevered stone: each stone is placed so as to overhang the course immediately underneath it. The reason why some ancient builders preferred constructing corbelled vaults may be the ease and simplicity of construction. For instance, it is easy to cut stones in a roughly parallel shape and place them without, or with only a small, centring (Croci 2000, 20).

Corbelled roofs act vertically in compression rather than in diagonal thrusts as in true arch constructions. Each stone performs as a compressive support and transforms loads through the stones beneath. Therefore, it acts as a cantilevered beam with limitations on the length of overhang, and when cantilevered effects occur in a stone block, tension created at its upper part and compression developed at its lower part (Gordon 1991 and see Figure 1.17 on page 61). However, stone is weak in tension and strong in compression, it is therefore not subjected to support tension or shearing stress and tends to be broken or split easily when used as a beam—either cantilever or normal. Regarding cantilever effects in corbelled arches, the deformation will occur when the strength of the stone has reached its limit due to overloaded stresses, especially tensile stresses. Because of this limitation, corbelled vaults can cover only narrow-spanned spaces—up to three to five metres (ibid).

Khmer roofs are generally composed of stones placed with a header-bonded dry masonry technique as corbelled vaults. Each stone roof element is placed horizontally, partially projecting over those below, and the loads are then transmitted directly to the lower stones in compression. Interestingly, a characteristic of the working of stone roof blocks is the joggle joints on stretchers (JSA 2000, 128) imitating halved joints in timberwork (see element B in Figure 1.18 on page 62). In terms of carpentry, a halving joint joins two pieces of wood by cutting away an end of each to half its thickness and fitting the cut ends together (Agnes and Laird (eds.) 2002). The form and direction of these joggle joints on each roof element can also demonstrate the construction process of Khmer roofing as well as allowing the reassembly of fallen stones to their former positions (see Figure 1.19 on page 62). It was the skill of the ancient Khmer people to construct the roof with this special joint both to interlock the stones safely and to prevent rain leakage. The joggle joints vastly increased the friction between the blocks and hence made the roof stable and, with the slope outwards from the joints, drained water away from the building (see element B in Figure 1.20 on page 62). In addition, in some cases, wooden beams were inserted into the gables, either to support wooden rafters or to supplement a corbelled vaulted stone roof (see Figure 1.21 and 1.22 on page 63).

Corbelled roofs usually covered only rectangular-planned spaces, such as galleries, libraries or vestibules *(mukha)*, while square-planned towers were constructed with load-bearing walls, which were inclined inward at the top (see Figure 1.23 on page 64). With the construction of every horizontal course, a ring was formed, which provided a horizontal stabilization (Croci 2000, 20 and see Figure 1.24 on page 64).

A roof structure, consisting of a wooden tie beam, rafters and purlin, and tile roofing, can sometimes be seen in the internal face of stone gables, for example at Banteay Srei in Angkor; the stones placed on the top are carved beams with an L-shaped section to support wooden rafters (see Figure 1.25 on page 65). The curved stone or brick tiles were normally laid convex side downward. Fired clay and stones were both used as tiles. With wooden roof structures, instead of placing purlins over rafters as same as traditional temples in Thailand, Khmer roofing technique is inverted. That means that the purlins were inserted into the stone pediments, and then the rafters were placed over them (and on the stone wall at the lower ends) to support concave-shaped tiles sitting on wooden cleats (See Figure 1.26 on page 65). As previously described, the farthest end rafters were sometimes also placed on the L-shaped section stone blocks at the gables as seen at Banteay Srei. Unlike the corbelled vaulted roof, the Khmer wooden roof was concave, and a sprocket was inserted at the base of the roof to achieve such a shape. Such a roofing system has been reconstructed from the evidence of gable ends and fallen tiles, for no such roofs survive.

As previously discussed, like other corbelled roofs, the Khmer roof structure uses only compressive thrusts down to its support—load-bearing walls and stone colonnades—but creates tensile stresses from a cantilever effect in each stone block. However, the problem of the cantilever effect on stone is solved in wooden roof structures by using wooden purlins and rafters to support compressive and tensile stresses caused by the weight of tiles. Then, all the loads are transferred to stone pediments and walls through their supporting joints. Nevertheless, the wooden structure eventually rotted and decomposed, and consequently caused the roof to collapse.

Vertical elements

Vertical elements (walls and columns) provide a weatherproofing skin around the interior and support upper floors and roofs. In drystone buildings, the main structural components of enclosures are load-bearing walls and columns. To create openings, post and lintel or corbelled arch systems were used. The unique character of drystone walls or columns lies in the fact that they are built of stone blocks, or sometimes of rubble, without any cement or mortar. Friction leading to the stabilization of buildings is obtained by the neat cutting of each stone block face, called 'ashlar', to ensure a tight joint. To assure and increase the strength and stabilization of stone walls, stone wedges or iron cramps were sometimes used.

A post-and-beam system was also widely used in stone masonry although stone has a limitation of tensile strength. Columns perform the same structural support as load-bearing walls: they support roof loads and transfer them to the ground. Since stone is weak in tensile stress support, ancient masons often solved the problems by reducing the weight loading over beams, increasing the width of beams, narrowing the span between two column supports, or inserting iron or wooden beams to strengthen the stone beams.

In Khmer architecture, walls of towers or rooms were usually built of mass wall construction—either sandstone, laterite or bricks. However, in this thesis, only stone and laterite masonry, which have the same construction techniques, will be considered. (Generally, in Khmer construction, the walls and roofs are in the same plane and material—in other words, the roofs are corbelled. In this thesis, the 'wall' is everything from the ground up to the spring of the corbelled roofs.) Since the walls bore many loads of self-weight and superstructure, they were generally solid and thick, as thick as the length of the stretcher of one stone block. Regarding the ratio of slenderness (that is the ratio of effective height to effective thickness of the wall), and because the greater the slenderness ratio, the weaker the wall, Khmer walls were sufficiently thick to prevent wall buckling under heavy compression loads. With a drystone masonry technique, the remains of the walls display the patterns of their masonry bond. Generally, the stones were laid without any consistent jointing patterns. However, Khmer masons tried to place the stone with overlapping vertical joints and even horizontal courses. In terms of stone orientation, the basic pattern of masonry laying for the walls is header bond, in which the stretcher of a block is used for the thickness of the walls. However, there are some places where a mixture of headers and stretchers is used.

The stone blocks were often not cut in a regular rectangular shape. As in the corbelled roofing system, there are some blocks with joggled angles to yield interlocking joints to the masonry. Hence, the order and direction of the laying of the stone wall can also be investigated (see Figure 1.27 on page 66). A keystone—a small reverse trapezoid-shaped stone—sometimes appears to have been the last stone piece to be inserted to complete each course of the wall (see Figure 1.28 on page 66). It seems to have been placed downward from the top or horizontally from the front. Noticeably, most of the keystones were laid in edge-bedded orientation, possibly because of the availability of the blocks (see Figure 1.29 on page 66). These pre-cut blocks might have been fitted in the gaps only when laid in edge-bedded direction. Practically, edge-bedded stone should not be constructed for both walls and architectural details due to its weathering susceptibility (Maude 1997, 95). Again, despite their skilfulness, this seems to be further evidence showing the lack of structural knowledge of Khmer masons, as discussed in the introduction chapter. It is possible that the trapezoid-shaped stone, which at first was thicker than the thickness of the wall, was shaped specially to fit into the hole—the space left in the wall for a last block—perfectly. Then, when the wedge stone was inserted into the wall, two edges of the stone that exceeded the thickness of the wall were finally cut, possibly to achieve a perfectly smooth wall. Moreover, in order to stabilise the structure further, horizontal I-shaped steel and bow-shaped stone clamps were also used. The evidence of this technique can be seen in some fallen stone blocks on the wall when careful dismantling was carried out.

Wall corners appear not to be bonded, possibly because of the lack of structural knowledge of ancient Khmer masons, or because of the addition of a secondary wall in later periods. It appears that the Khmer masons usually first built a main wall; after that, the secondary wall was constructed and joined to the main one with a straight joint. That is the reason why the corner of the wall was usually the first part to be torn apart when uneven soil subsidence occurred. However, occasionally, the masons built the corners of walls with a masonry-interlocking joint or sometimes even used metal or stone clamps to tie the stones from different directions together. Moreover, in a few cases, the stones at the corners were cut in a special shape to fit the joints and then tied with clamps.

In order to make a perfectly fitting joint, the faces of blocks in contact with each other were generally treated carefully to form a smooth surface, called a 'rubbed face' (JSA 2000, 123). Traces of rough chiselling on the other faces can sometimes be found. In many cases, however, there are small traces of chiselling on the upper face. According to a field trip to some Khmer complexes in Siem Reap with Professor Shinichi Nishimoto in 2002, he suggested me that these seemed to be the result of the following procedure: a lower block was laid and an upper one placed above it. The mason would then observe the closeness of the fit, remove the upper block, and chisel the upper face of the lower block to improve the fit. The upper was then replaced. It seems clear from the presence of holes in the blocks that they were manoeuvred horizontally using timber levers, and not turned over (Figure 1.30 on page 67).

The dimension of the walls was usually predetermined by the number of masonry courses. The first two courses of masonry normally formed the base of the wall up to the sill of the window frame. Window frames were four or five courses in height with three courses above to the springing of the corbelled roof. However, the height of the wall may have varied from monument to monument. At Bateay Srei in Cambodia, the monument is not human-scaled but smaller, so that the entire wall is only three or four courses high. (Interestingly, at Banteay Srei, the walls were composed of vertical stones at each corner to frame the wall; the spaces within the frames were filled with stone blocks. The wall construction, therefore, was built as if it were a post-and-beam system rather than a wall bearing system (see Figure 1.31 on page 67).)

There are two types of opening—real and false. The false ones were blocked with stone. False and real windows sometimes have mullions, or the stone blocks were sometimes carved as a trompe l'oeil wooden door or window panel. In the case of doors, both types of openings are supported by stone frames. Charernsupkul considers all the elements composing a doorframe as a 'Door Set' (Charernsupkul 1998, 69). It usually comprises a set of lintel and colonnettes at the front, a set of stone doorframes placed behind the former set, and, sometimes, a huge stone slab beneath them (see Figure 1.32 on page 68). The set of the doorframe supports the load of the superstructure and the self-weight of the door head, and then transfers them to the threshold through the doorjambs while the colonnettes transfer the lintel weight to the ground or slab (see Figure 1.33 on page 68). (Tensile stresses were created at the lower half of the lintel and door head and they consequently cracked the stone.) However, it can sometimes be found that there is a supplemental stone beam placed above the frame to support the upper loads while the threshold is sometimes composed of a shorter horizontal element, which means that it is not as long as the actual opening (see the door construction elements and their names in Figure 1.34 on page 69). At the entrance or main doors vertical sandstone pieces with vertical bedding planes are used for the jambs of the door, whereas the jambs of some minor doors are not made of a single piece of stone (see Figure 1.35 on page 70).

For windows, the head was often composed of double lintels while the sill was composed of the upper face of stone blocks that also formed parts of the course beneath the window. Moreover, in many cases, long vertical elements with vertical bedding planes (edge-bedded stone blocks rather than face-bedded), that were normally used for jambs, did not stretch the full height of the window, possibly because of the reduction in strength in edge-bedded stone. Thus, one or two stone blocks—sometimes they were parts of the wall masonry—were added to supplement the jambs (see Figure 1.36 on page 70). Hence, it may be concluded that the constitution of the window frames varied from one window to another, although they were parts of the same monument, and that there was no uniformity. Noticeably, in some early periods of construction like those in the Angkor period, the frames were more precisely constructed than those of the monuments constructed in the Post-classical Angkor period. In the latter, the window frames were usually made only to fit into the wall, but not as a part of the wall structure.

Noticeably these stone window- and doorframes were skeuomorphs of their timber precursors; some were cut to look like mitre joints. However, these joints are special because, for example, although they appear as 45°-degree angles, the inner hidden part of the joint is a normal right angle as shown in Figures 1.37a and 1.37b on page 71. With regard to the doorframes, there are traces that a wooden header may have been inserted into the upper portion of the inner pilasters while there may have been pivot holes on the sill used as door hinges. The complex structure of a multi-order door arrangement is shown in Figure 1.38 on page 71. In addition, a pair of opposing square holes could sometimes be found in the walls at the level of the door head or of the threshold. These may be assumed to have taken wooden beams as a frame to hang door panels from (see Figure 1.39 on page 72). From this evidence, it could be assumed that there used to be a wooden double swinging door opening inward or outward depending on the locations of the holes. As far as window openings are concerned, their frames are similar to those of the doors, except that there is no trace of mortises for window panel tenons. There are, however, mullion holes—either circular or square—remaining on the head and sill of window frames. Additionally, some stone mullions still exist in their original positions. These mullions were not only used as a decorative element, but they may also have reduced the load that the beam supported. False doors and windows that were filled with stone blocks were possibly built for these purposes as well.

Since stone is weak in tension, Khmer masons tried to decrease the loads over the doorframe or lintel with various techniques. Most commonly, the upper wall above the head of the doorframe is composed of two blocks with a 45°-angle cut only at the base to form a triangular-shaped hole (Figure 1.40c on page 72). Consequently, fixed loads over the head could be dispersed to the sides with this technique. This technique can be seen in several monuments built in the Post-classical Angkor period, for instance the Northern Library of Bayon and Banteay Chmar in Cambodia. The other technique that was applied to the frame structure is the separation of two door heads—one laid on top of the other—with a gap in the middle of the upper head (Figure 1.40b on page 72). Again, this technique helped divide the loads from the upper part onto two sides of the lower head which decreased the risk of shear cracking of the door head. However, this technique may lead to the weakening of the upper head due to its loss of thickness (see Figure 1.41b on page 72). Another technique that can be found on doorframe structures is the combination of the post-and-beam and the corbelled-arch system. Since a lintel in drystone masonry generally supports only triangle-shaped loads over it because of the corbelled structural effect (see Figure 1.42 on page 73) and most of the upper loads are transferred to the ends of the upper head and to the jambs, leaving the middle or most of the head free of loads, the blocks in the triangle may be removed. Figure 1.40d shows how the stone blocks were placed in the corbelled-arch system over the head of the frame to eliminate the load in the triangle (see Figures 1.40d and 1.41d on page 72). Khmer masons sometimes used forcing wedges to reinforce vaults above lintels (see Figure 1.43 on page 73). This solution gave a fairly successful result in decreasing loads over lintels by yielding an arch-like load effect.

Strengthening lintels was also one of the structural solutions for weakness in the tensile strength of stone. Since stresses usually occurred mostly in the middle of lintels, wooden beams were inserted to strengthen them. However, the Khmer masons applied their solutions without theoretical structural knowledge resulting in unsuccessful strengthening. As seen in Baphon complex, the technique of wooden beams inserted inside the lintels was applied by hollowing out more than three-quarters of the lintels' thickness (see Figure 1.44 on page 74). The result was not satisfactory and led to a weakening of the stone lintels due to their lack of sufficient proportion to withstand the thrusts. In addition, wood degradation over time resulted in the loss of its strengthening capacity. Thus these mistakes may be considered as evidence for the lack of knowledge of statistics and mathematics of ancient architects and masons. Their structural successes seem to have been the result of intuition and experience, rather than theoretical understanding.

In using these various techniques, it can be observed how Khmer architects and masons tried to solve structural problems without damaging the aesthetic design. The special techniques of frame construction described above can only be observed from the interior or after dismantling because they are hidden behind a stone lintel placed in the front. When viewed from the exterior, only the double doorframe structures—an actual doorframe and a set of lintel and colonnettes—are exposed (see Figures 1.32 and 1.34 on pages 68-69).

While the mass walls were constructed with dry masonry technique, a mixed structural construction technique was applied in the galleries: one side was a solid wall while the other side consisted of nave and aisle columns. Moreover, like the opening frame, the stone structure connecting nave and aisle columns with a beam was also derived from wooden structures (JSA 2000, 11). There are two types of column used in Khmer architecture. One is the column constructed from a sandstone monolith, the other is composed of sandstone or laterite blocks in dry bond. The latter might be the result of the masons' concern about the orientation of the bedding plane of sandstone. Since the monolith is placed in edge-bedded orientation, it consequently has a lower capacity of loading support than a series of natural-bedded blocks. (Dry sandstones can bear about 11% more loads perpendicularly to the natural bed planes than parallel to the bed lines or rifts (Watsantachad 2001, 58).) Laterite, by contrast, may have strength problems particularly when used together with sandstone columns or walls. This assumption will be one of the subjects to be studied in this thesis.

Khmer columns are composed of three parts—a base, shaft, and capital. If the column was a monolith, its capital and shaft were made of one stone piece and its base of another. A mortise and tenon joint technique was applied in order to connect the two parts. The stone tenon, carved from the same monolith, was about 6x6x4 centimetres located on the upper or lower face of each part. However, it is not consistent which element contains a tenon or which one has a mortise. The position of the tenon and mortise is also variable—in some columns, it is in the centre while, in other cases, it is on one side of the face. At the head of the capital, either a tenon or mortise can be found. It might have been used to tie a beam placed over the capital (Figure 1.45 on page 75).

Beams comprise of two courses of stone placed horizontally in a lengthwise direction (from east to west since buildings are planned rectangularly with the shorter sides facing east and west). The beams were possibly placed to support the corbelled roof structure. The lower beam was composed of two stone elements placed next to each other horizontally with the stretcher sides facing each other; beams were tied together with metal clamps and processed so as to form one continuous beam (see Figure 1.46a and 1.47 on page 76). The long sides of the elements were placed next to each other with a halving joint (JSA 2000, 127). Then, another beam was placed on top of them. This upper beam has a halving joint on the header as well. In addition, there are traces of clamps having been used in a lengthwise direction to tie the upper blocks of the beams (Figure 1.46b on page 76). However, the structure of the beams could vary, depending on the loads they had to support.

Base and foundation

Foundations could be in the form of either single or spread footings, or piles. Various types of foundations show different structural performances. However, they are all based on the principle that stabilization and bearing capacity of the structure will be achieved by friction between soil and surfaces of the foundations, or by the reaction force of the attached bedrock (see Figure 1.48). Generally, such foundations should have a sufficient contact area in order to support the structural loads effectively. A wider contact area results in more friction between the foundations and soil which, in turn, results in a better stabilization. For instance, in the case of a load-bearing wall over a spread footing foundation, the friction between the base of the wall and its foundation must be much greater than the lateral force of the soil in order to maintain the stability (see Figure 1.48b on page 77).

Khmer structures were usually built on a platform over either a natural or an artificial hill due to the Hindu belief that monuments represented Meru Mountain, the centre of the universe, and that they had to be built on 'pure soil' (Dumarçay and Royere 2001, 34). This conceptual construction has been called 'Temple Mountains' (WMF 1992, 21). To create an artificial hill, Khmer masons had to deposit large amounts of earth dug from surrounding areas, and, sometimes, additional layers of laterite (Pichard 1972, 10). This kind of hill could be as high as twenty-seven metres at Angkor Wat (Narasimhaiah 1994, 3). Generally, Khmer temples were surrounded by moats resulting from the earth excavation necessary for creating a hill. Not only did these moats serve religious beliefs, but they also show the skill in construction management of the Khmer people, in terms of a cut and fill strategy.

The platforms were generally constructed on layers of several materials over the natural soil: sandstone, laterite, stone fragments and soils, for instance. Ashlar sandstone and/or laterite masonry is often used as pavement material on the surface, while laterite is used inside the platform. The number of masonry courses of the platform varies from site to site. For example, there are three courses of masonry for the platform construction of the Northern Library of Bayon in Angkor (JSA 2000, 11) while there are only two –one in sandstone and the other in laterite—outside of the Northeast Gate of the Royal Palace (IGT 1996, 12). Generally, the total number of stone masonry courses for platform constructions of each level would have been the same within each building. However, the latter site proves an exception in that the numbers of masonry courses are not equal in the interior and exterior of the building. The exterior platform consists of two layers while the interior consists of five (IGT 1996, 13 and see Figure 1.49 on page 77). This might have been because of consideration of the greater loads that the interior platform had to bear.

In addition, Khmer buildings were usually placed on a high and steep platform to give an illusion of greater size and to achieve a sense of monumentality through a false sense of scale (WMF 1992, 22). The stairways leading to the temples are not human-scaled. Khmer stairways are composed of risers of up to 45 centimetres and treads of only 15 centimetres while the size of a comfortable human step should consist of a set of a 15-19-centimeter riser and, at least, a 22-centimetre tread. To exaggerate the false scale even further, the doorways are often smaller than expected as well. Additionally, the majority of the ‘temple mountain’ structures are set between 50 to 60 degrees while the normal angle of a shape for an unconsolidated earthen structure or mound should be only about 45 degrees. Due to the steepness and height of the platform, retaining walls had to be inserted underneath it. For example, in the case of pyramid-like sanctuaries that are composed of several levels of platforms, stone retaining walls were constructed as boxes that contained earth and sand fill inside. Laterite was normally used for internal retaining walls, but in many cases, sandstone was used as the outer material for both durability and aesthetic effect.

In terms of sectional platform construction from the surface to the base, based on the results of excavations carried out at the North Library of Bayon (JSA 2000), exposed sections of the floor of the platform were generally paved with sandstone blocks while laterite was used where the floor was protected by the wall construction on top of the platform. Wedge-shaped sandstone blocks were often inserted into the small spaces between the floor elements to fill the gaps and complete the floor work, but there are cases in which soil mixed with sandstone fragments was used instead. Beneath the sandstone layer that formed the floor were laterite blocks as the second (and, sometimes, also the third) course. Beneath this, there is normally a layer of compacted soil; however, in some places there is a tier of laterite blocks. Trench excavation at Bayon shows that within the compacted soil layer sand is also found. The depth of this layer is approximately 50 centimetres. Sometimes, it can be found that this layer is as deep as 160 centimetres from the surface of the platform. At this point another layer of hard material, which seems to be laterite, can be found. However, in some cases, such as the south side of the Northern Library of Bayon, evidence from the excavation confirms that laterite blocks had a depth of 140 centimetres from the terrace surface, below which a layer of compacted soil up to a thickness of 170 centimetres was found. Beneath this, a hard material layer, possibly laterite, was found (JSA 2000, 107). The section drawing of the foundation is shown in Figure 1.50 on page 78.

At the Northern Library of Bayon, within the compacted soil layers, broken stones were sometimes added to form the artificial fill under the laterite layer. These stone fragments were laid randomly at low density. Some small fragments of earthenware, porcelain pieces and roof tiles are sometimes found in each layer. The ratio of the fragments and the compacted soil was usually the greatest in the layer underneath the laterite layer, i.e. the third layer from the surface. Soil in this layer was more cohesive than that used elsewhere in the foundation. This clay-like soil was also used for filling joints between stone blocks in the platform construction.

Regarding the joints between the blocks, their width and the amount of soil fill varied according to the size of the blocks and the way in which they had been shaped or formed (JSA 2000, 113). The soil varied in thickness from 5mm to several centimetres and filled in the bed joints and vertical joints between sandstone and laterite blocks and in the bed and vertical joints between two laterite blocks. However, there is no evidence that the bed and vertical joints between the sandstone blocks below the column bases were intentionally filled with the soil. Noticeably, unlike Western masonry techniques, Khmer masons filled the joints with soil rather than mortar and this soil fill was found only in the foundation masonry construction. Sometimes, small fragments of sandstone or laterite were mixed into the soil to fill in wide vertical joints—a width of 20 centimetres or greater— between sandstone and laterite blocks. The amount and size of the gravel mixed in the soil also varied according to the width of the joints.

The purpose of joint filling might be for adjustability or cohesion. The JSA report suggests that soil was used to adjust the level in masonry technique for which no standardized blocks were used, and that it was used for connecting and stabilising as well (JSA 2000, 37). However, since the ratio of clay to silt in this kind of soil is rather high, the soil could lose the cohesion of its particles easily when water is present, resulting in significant subsidence of the platform, and, in the worst case, collapse of monuments. Such an occurrence could happen particularly in cases where the soil in the bed joints was up to 10 centimetres thick (ibid).

Additionally, in order to construct and support the upper structure, it was necessary to adjust the level of the upper face of the artificially laid soil and to provide a certain amount of strength. Because the weight of the upper structures might cause the soil to subside unevenly, inclusions were added to strengthen the mix. Noticeably, more stone fragments are found near the laterite blocks in all layers. Furthermore, a clay-rich mixture was sometimes added to the sandy soil matrix to provide better support. This also helped to prevent differential settlement thus ensuring reliable horizontal levelling—although it is later proved that the foundation still unevenly subsided possibly because of the poorly-compacted layers of soil, or because the loss of the cohesion in the soil.

In conclusion, Khmer architecture was usually constructed on a spread footing acting as a platform over a hill—either natural or artificial. The foundation of the artificial platform was generally composed of at least four layers of material, i.e. sandstone, laterite, compacted soil and hard materials such as stone, to support the load of the buildings. It is also possible that the compacted soil and hard materials were alternately placed, and ended with the hard material layer. However, the depth of each foundation layer varies with each construction site. The variation in depth and materials might be the result of the conditions of the natural soil where monuments were constructed, the size or importance of monuments, or the availability of materials at the period of construction.

Like other spread footing constructions, the loads of Khmer superstructures were transferred down to the ground through their platforms to the soil hills. These platforms were their footing and supported all compressive stresses above them. The stabilization of the structure could therefore be achieved with the equilibrium of the compression of the superstructure and the reactive forces of the soil. However, since Khmer masons built the foundation with one or more layers of laterite and clay under a course of sandstone, it might have been the cause of defects in the foundation. Due to the heavy superstructure loads and the infiltration of rainwater, the laterite foundation became crushed and disaggregated while the clay layers did not uniformly subside resulting in uneven load-bearing foundations (see Figure 1.51 on page 79). Such failure in the foundations consequently led to the overall structural deformation of Khmer monuments. The deformations of superstructure and foundation are probably a chain-cycle—once the foundation unevenly compacted, the superstructure lost its equilibrium and inclined outward or inward resulting in the change of load distribution. Because of the latter phenomenon, the ground and foundation then subsided irregularly because of uneven pressure of loads further destabilising the superstructure. Outward movement is generally much more severe than an inward one because, due to the movement of their supports, lintels or beams can slip out from their supports or corbelled roofs can lose their stability (Figure 1.52 on page 79). In contrast, inward movement may cause only minor damage to the structure because the structural elements can adjust themselves to be stable in new equilibrium conditions and support a deformed but surviving structure (Figure 1.53 on page 79). In this case, only some patterns of deformation occur in the structure until further forces appear and exceed the limit of structural equilibrium, and then the structure may collapse.

The use of laterite as structural members in Khmer architecture

As discussed above, laterite was used in every part of Khmer architecture. It was mainly used as the foundation of every monument; in some parts of the walls of sandstone or brick monuments; and as walls and roofs in minor monuments, especially the ones built in the reign of Jayavarman VII. However, laterite had never been used as structural members that supported tensile forces such as lintels and beams.

1.6 Failures of Khmer Structural Performance

It is still debatable whether or not Khmer monuments would have collapsed if no other extrinsic architectural decay agents, such as wind, water, or root penetration, had been present, and whether or not the Khmer structural system could sustain its self-weight and remain stable through time. In this section, the causes of Khmer construction failure will be listed and concluded.

Firstly, as previously described, the main failure of the Khmer structural system was the failure of its foundation (Pichard 1972, 15). Being built of such a weak and partly soluble and erodible material as soil, it would inevitably subside. The use of laterite in construction was possibly the other principal cause of the failure. Uneven load-bearing capacity of the foundation resulted in non-uniform movement of the structure leading to overall structural deformation. For instance, the outward movement of columns and walls consequently caused unbalanced and collapsed corbelled roofs. However, this failure was caused not only by the misuse of material and ineffective design, but also by the presence of water—either the infiltration of rainwater or groundwater—when the soil becomes saturated the soil begins to behave like a fluid.

The misuse of material includes the incompatibility of adjacent materials. Each material has its characteristics and durability, which are different from one to another. Iron clamps inserted in the stone have different thermal expansion from the stone and consequently break the stone when expanded. Iron clamps, when rusted, also break the stone by their increasing volume. Wood has much less durability than stone and degrades over time, and thus should not have been used as any main structural element in stone masonry structures. Consequently, wooden roofing structure or wooden beams inserted in stone beams rot and decompose resulting in collapse of the roofs or weakening of the beams. Again, this problem is aggravated by the material decay mechanisms, mainly the result of the presence of water and salts. The difference in load-bearing capacities of sandstone and laterite is a further example of material incompatibility. Problems occurred when they were used together to support structural elements resulting in uneven structural support and thence the deformation.

Stone is weak in tension and therefore should not be used as any tensile structural element. In Khmer structure, stone was used as lintels and beams resulting in tensile stresses created in the bottom half of the stone. Cracks were usually found in the area where tensile stresses were greatest. Although Khmer masons tried to solve the problem by decreasing or dispersing the loads over the beams or lintels, the results were relatively successful. This problem was caused by the inappropriate structural design of Khmer architects. The roofs and upper walls depended on door sets as well as columns for their supports; consequently, serious movements and even collapse occurred when these elements, which were unsuitable for the purpose, began to fail under the loads. (Since stone lintels were broken at the bottom creating an arch-like effect, the structure, however, may have been stabilised and survived.)

Regarding drystone masonry construction, sandstone blocks in Khmer walls were sometimes laid in different orientation—or mixed with laterite blocks as previously discussed— resulting in uneven strength of the walls. Since the compressive strengths between natural-bedded, edge-bedded and face-bedded sandstones are dramatically different, when some blocks were vertically laid, they created weak spots within the walls resulting in uneven load-bearing walls. This failure was caused by the error of the construction process which is an intrinsic cause. In addition to the presence of water and salts, such vertical blocks tended to deteriorate more easily than the natural-bedded ones with a resultant weakening of the mechanical strength of the blocks. Regardless of the orientation of the stone, the decay mechanism of stone over time has caused the stone blocks to lose their perfectly sharp edges; the wall has lost its perfectly fitted joints resulting in the reduction of surface friction between the blocks. This might have caused the wall to have less stability. (Where mixed with laterite this problem is compounded by the properties of laterite which I will discuss in Chapter III, V, VI and VII.)

The other errors of construction work can be found in other parts of the structure, such as the lack of bond at the wall corners. Such corners were easily torn apart, especially when the foundation was unstable. However, this lack of corner bond may make the structure flexible and able to move partially without any critical structural damage when the soil subsides. Where the walls supported a superstructure, the displacement of such walls resulted in the deformation or collapse of the superstructure. The other inappropriate design is the skeuomorphs of carpentry joints in window- and doorframes. When cut back to make such joints, the strength of the stones was weakened, and, when heavy loads were applied, the heads of the frames tended to displace downward more easily than the ones which were simply laid over the jambs.

When extrinsic decay agents, such as tree root penetration and land sliding, were present, drystone Khmer walls supporting only compressive stresses, failed to withstand lateral, shearing or flexural stresses. Pressures caused by tree root penetration were much greater than the friction between blocks of a wall resulting in displacement, deformation or, at the worst, collapse of the wall. The failure of withstanding combined forces tended to be the most important cause of the collapse of Khmer structure.

In summary, Khmer structure failed not only because of its ineffective structural design or misuse of building materials, but also because of the combined effects of several agents that caused different patterns of decay and damage. As mentioned above, the use of laterite is possibly one of the main factors causing Khmer architecture to suffer damage or to deform but has never been studied thoroughly. In this research, the study of the properties of laterite used in Khmer architecture should also be able to confirm whether laterite is the main cause of Khmer architecture failure. However, before narrowing the scope of study to laterite used in Khmer buildings in Thailand alone, a review of available research on laterite is required, and this will be undertaken in the next Chapter.

Figure 1.1: The Principal Tower of the Phimai Complex after anastylosis restoration, 1964-1969. (in June 2000)

Figure 1.2: Prasat Ak Yum
(Freeman and Jacques 1999)

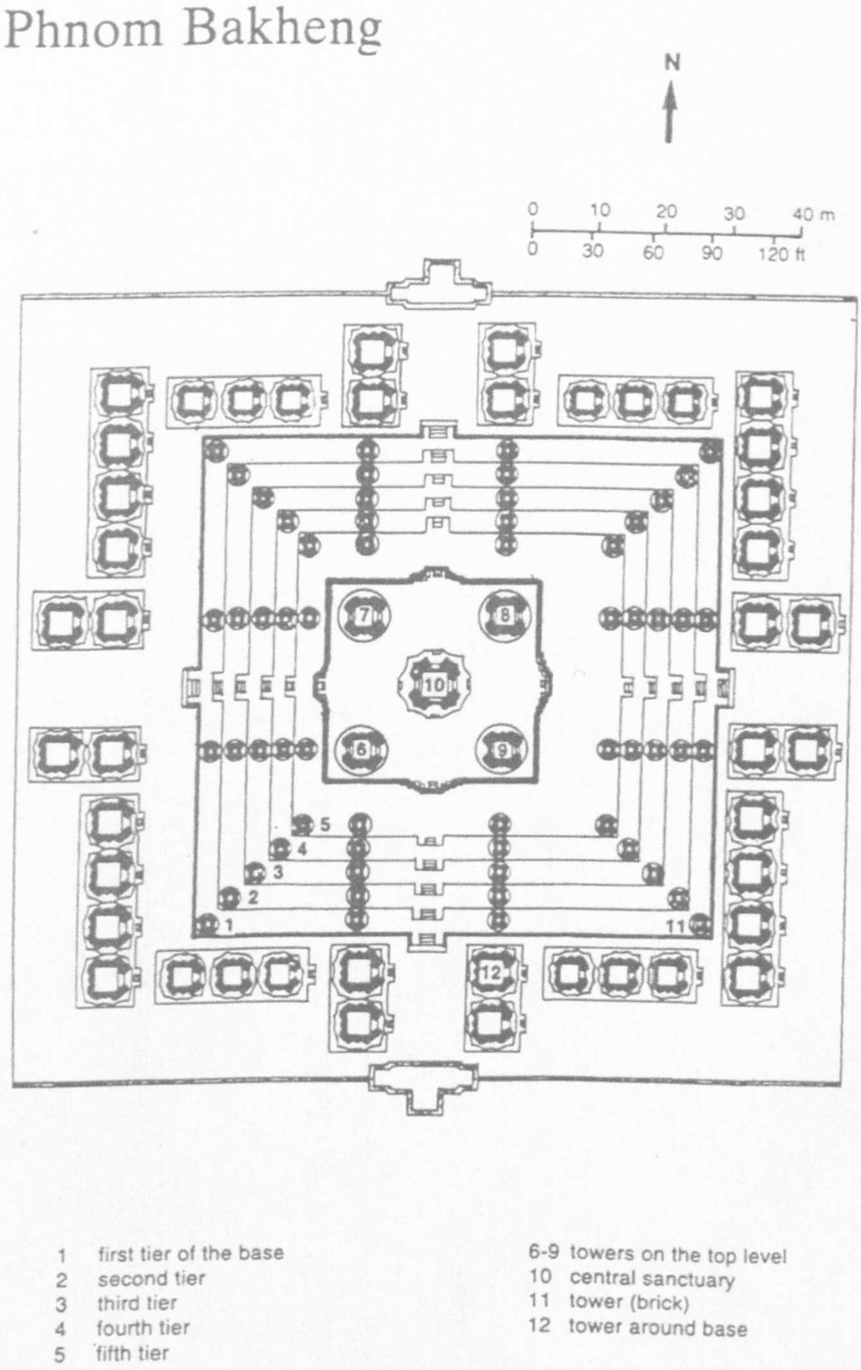
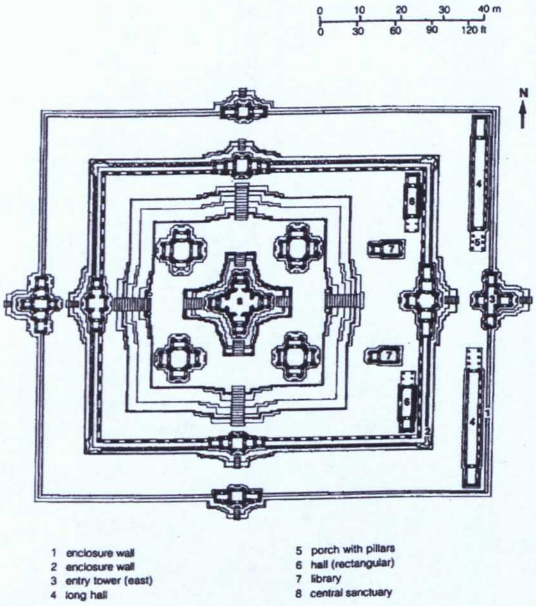


Figure 1.3: Plan of the temple of Phnom Bakeng
(Rooney 2000)

Ta Keo

Figure 1.4: Ta Keo



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Plan of Ta Keo (Rooney 2000)

Ta Keo
(Freeman and Jacques 1999)

Figure 1.5a: Apsara in Bakeng style

Figure 1.5b: Apsara in Banteay Srei style

Figure 1.5c: Apsara in Pre Rup style

Figure 1.5d: Apsara (s) in Angkor Wat style (a later Classical artistic style)

Figure 1.5: Apsara(s) in different styles (Freeman and Jacques 1999)

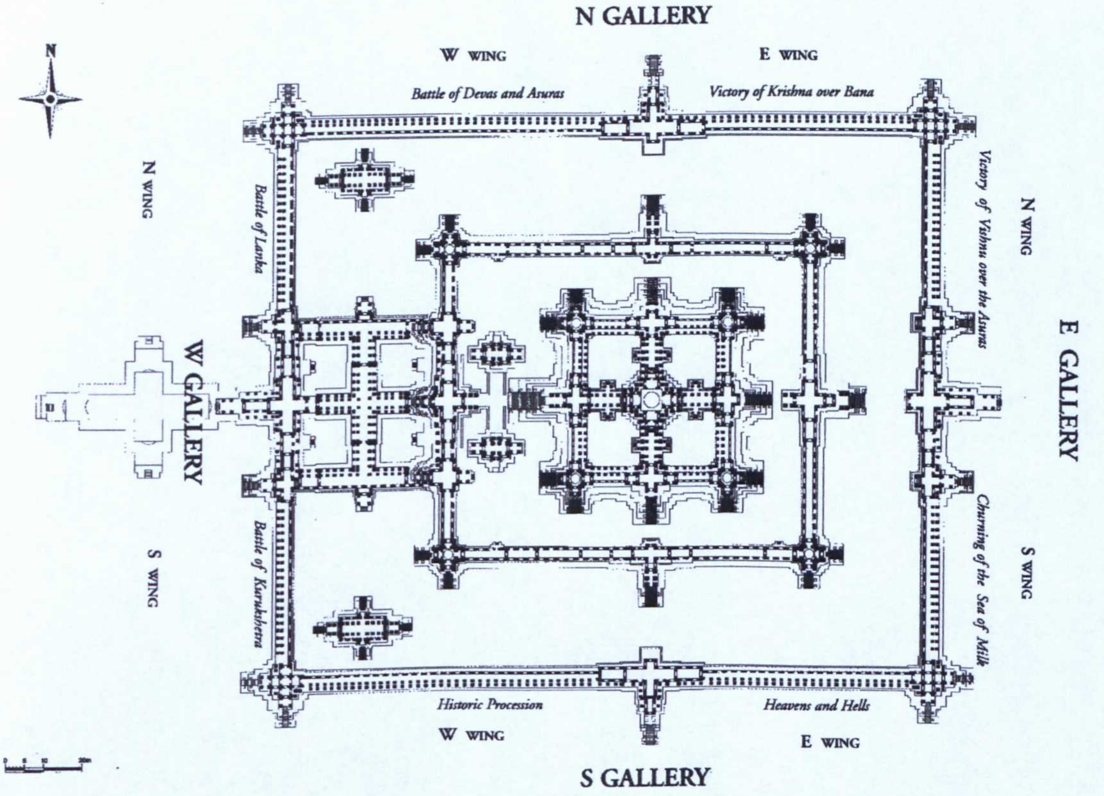


Figure 1.6a: Plan of Angkor (Freeman and Jacques 1999)

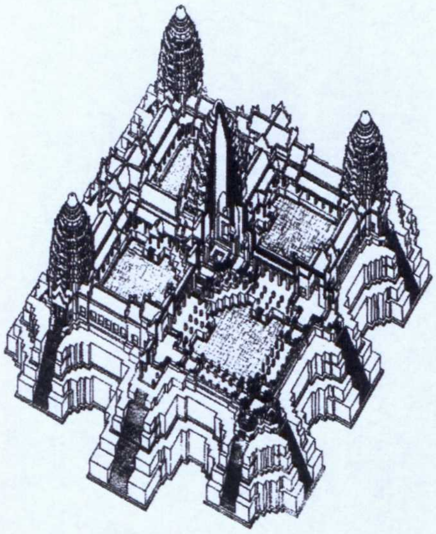


Figure 1.6b: Isometric section of Angkor Wat (Freeman and Jacques 1999)

Figure 1.6c: Causeway of Angkor Wat (in 2002)

Figure 1.6d: Angkor Wat from the entrance (in 2002)

Figure 1.6e: Upper level and towers from the courtyard of the second level (Freeman and Jacques 1999)

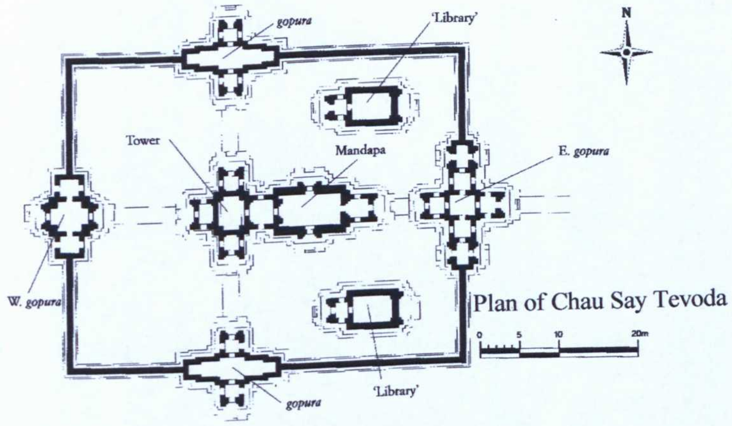
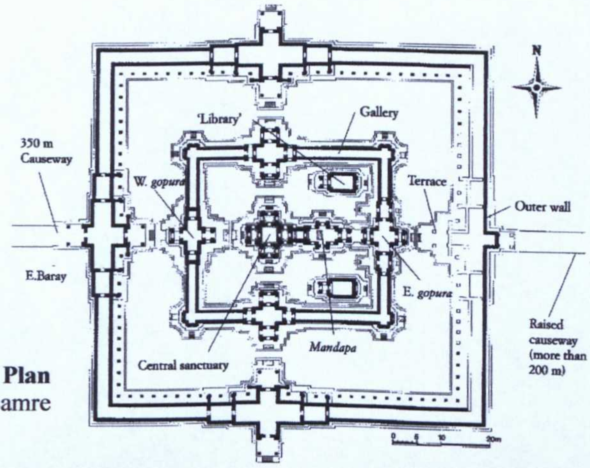


Figure 1.7: Chau Say Tevoda
(Freeman and Jacques 1999)

Chau Say Tevoda:
Mandapa and the south side of the sanctuary
(Freeman and Jacques 1999)

Figure 1.8: Banteay Samre
(Freeman and Jacques 1999)



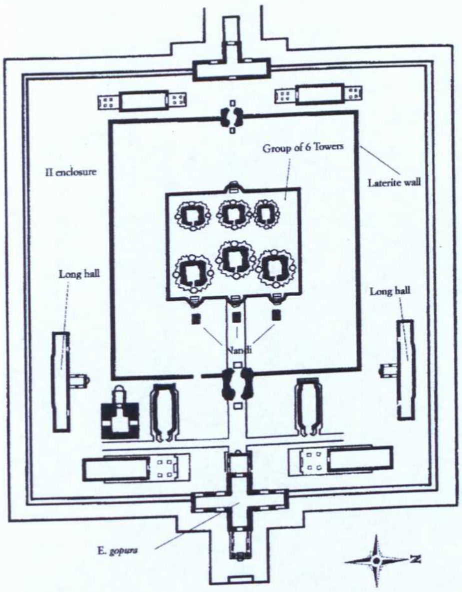
Plan
of Banteav Samre

The tower of Banteay Samre
(Freeman and Jacques 1999)

Figure 1.9: Bayon Tower and the east gopara (in 2002)

Figure 1.10:
Lokesvara's faces on the towers of Bayon
(Freeman and Jacques 1999)

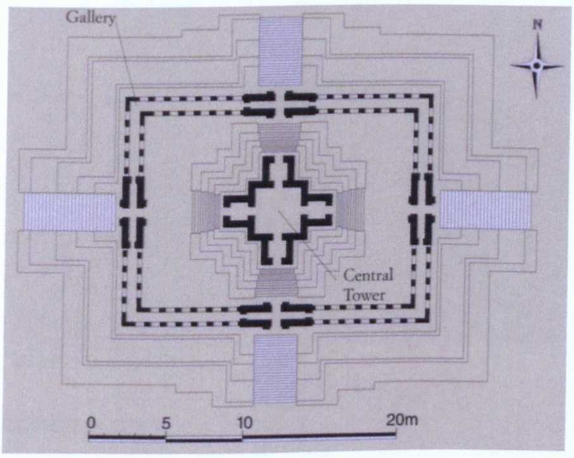
Figure 1.11:
Long axis of causeway and terraces



Plan of Preah Ko (Freeman and Jacques 1999)

Three towers of Preah Ko
(Freeman and Jacques 1999)

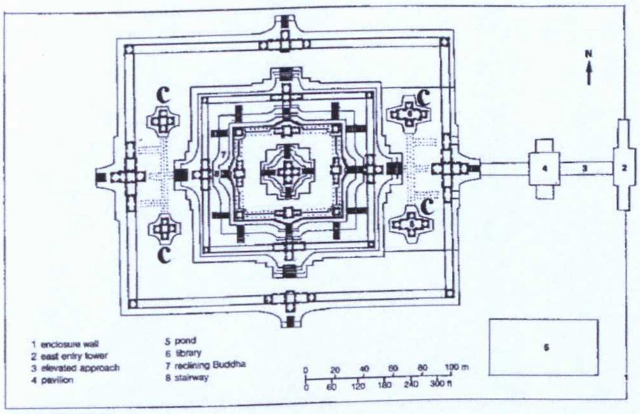
Figure 1.12: Pyramid sanctuary



Plan of Phimeanakas (Freeman and Jacques 1999)

Central Tower of Phimeanakas
(Freeman and Jacques 1999)

Baphuon



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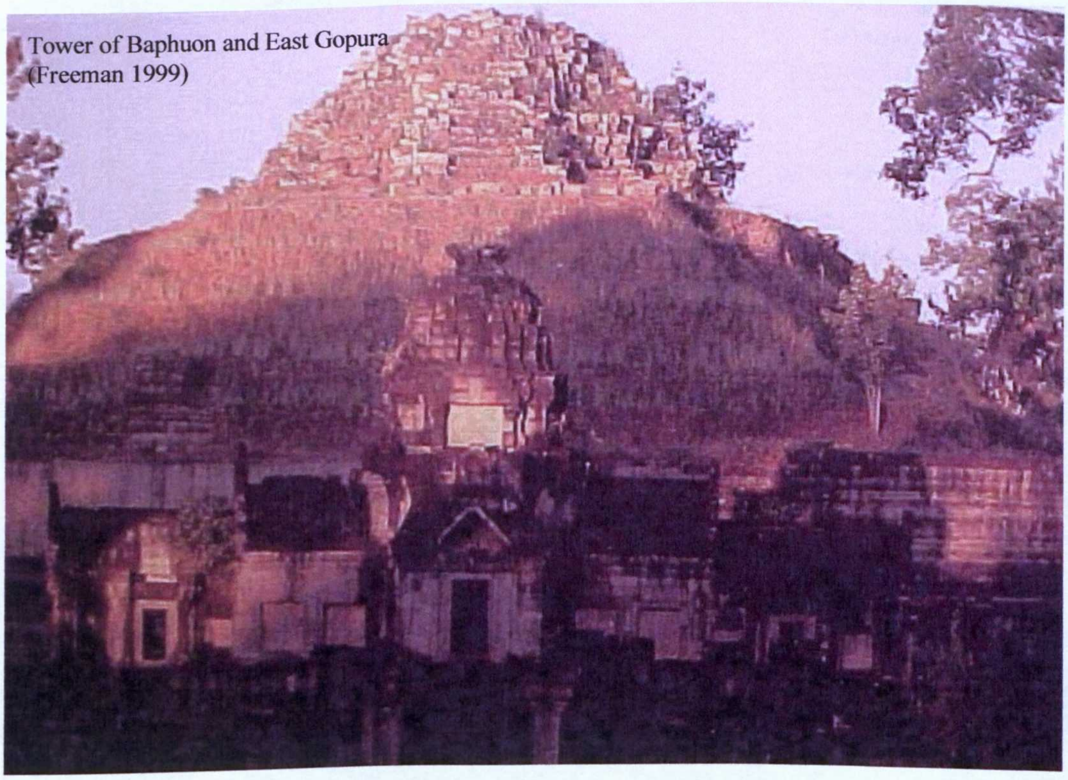
Plan of Baphuon (Rooney 2000)

Figure 1.13:
A complex,
combining three types of architecture


Tower of Baphuon and East Gopura
(Freeman 1999)

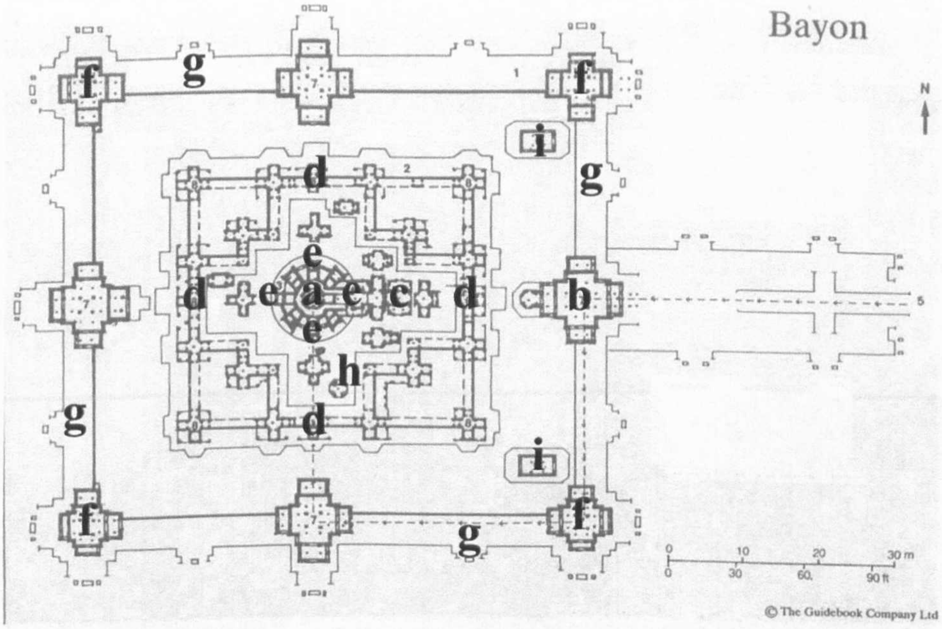


Figure 1.14: **Type of Architecture: Differences in Structural Systems and Locations**

(Based on Plan of Bayon , copied from Rooney 2000)

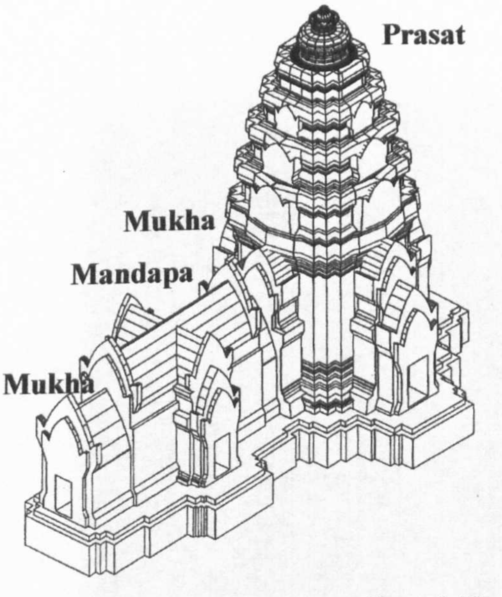


Figure 1.15a:
Locations of *Prasat*, *Mandapa*, and *Mukha*
(Modified from the drawing copied from
Charernsupkul 1998)

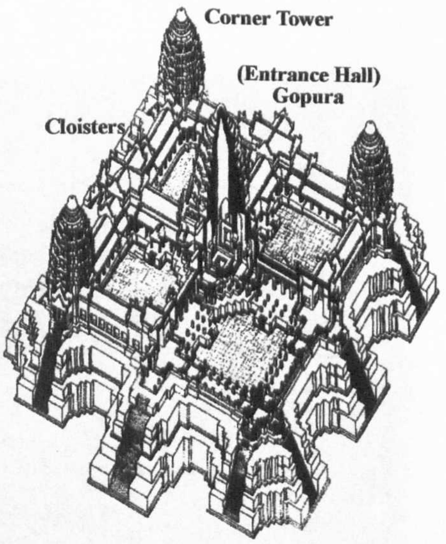


Figure 1.15b:
Locations of Corner Towers, Cloisters, and *Gopura(s)*
(Modified from the drawing copied
from Freeman and Jacques 1999)

Figure 1.16: The Phimai Complex, Nakhon Ratchasima (Korat), Thailand. (in 2000)

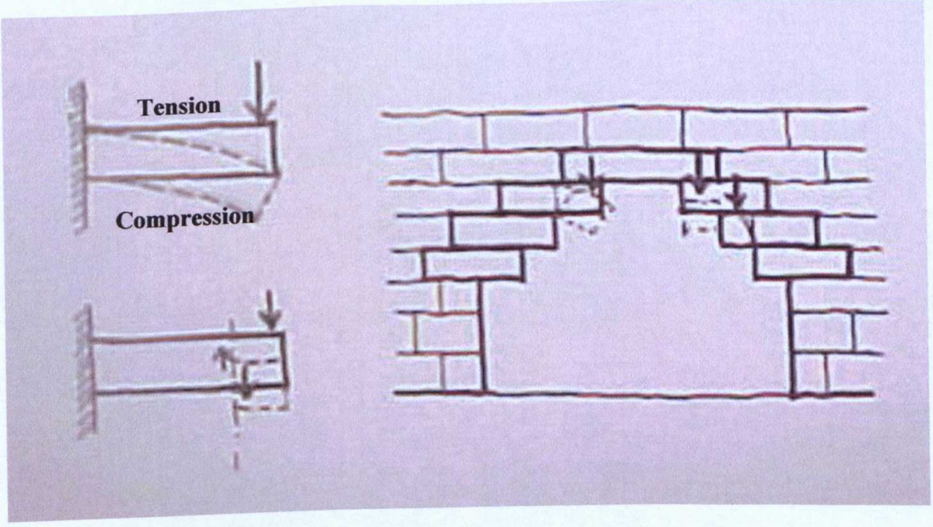


Figure 1.17: Cantilevered effects in corbelled roofs and openings

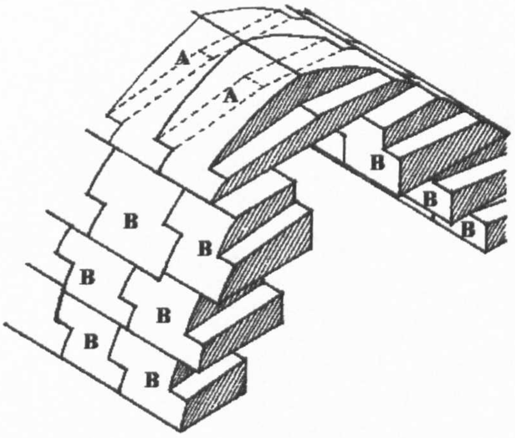


Figure 1.18: Stone corbelled vaulted roof

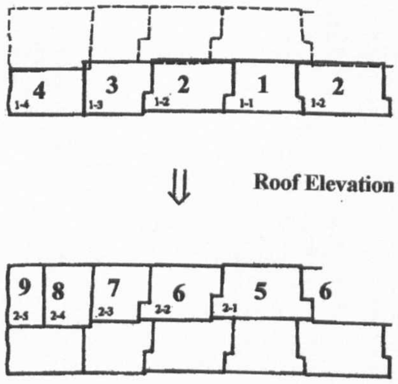


Figure 1.19: Order and direction of stone roofing (JSA 2000)

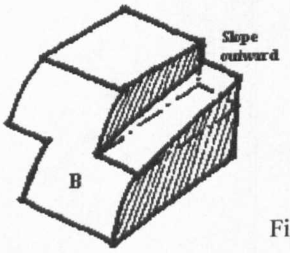


Figure 1.20: A stone block for roofing

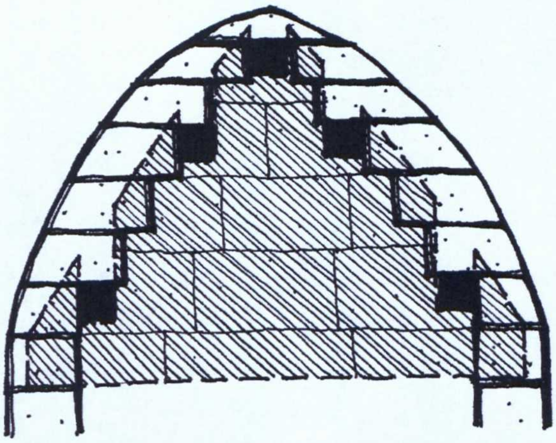
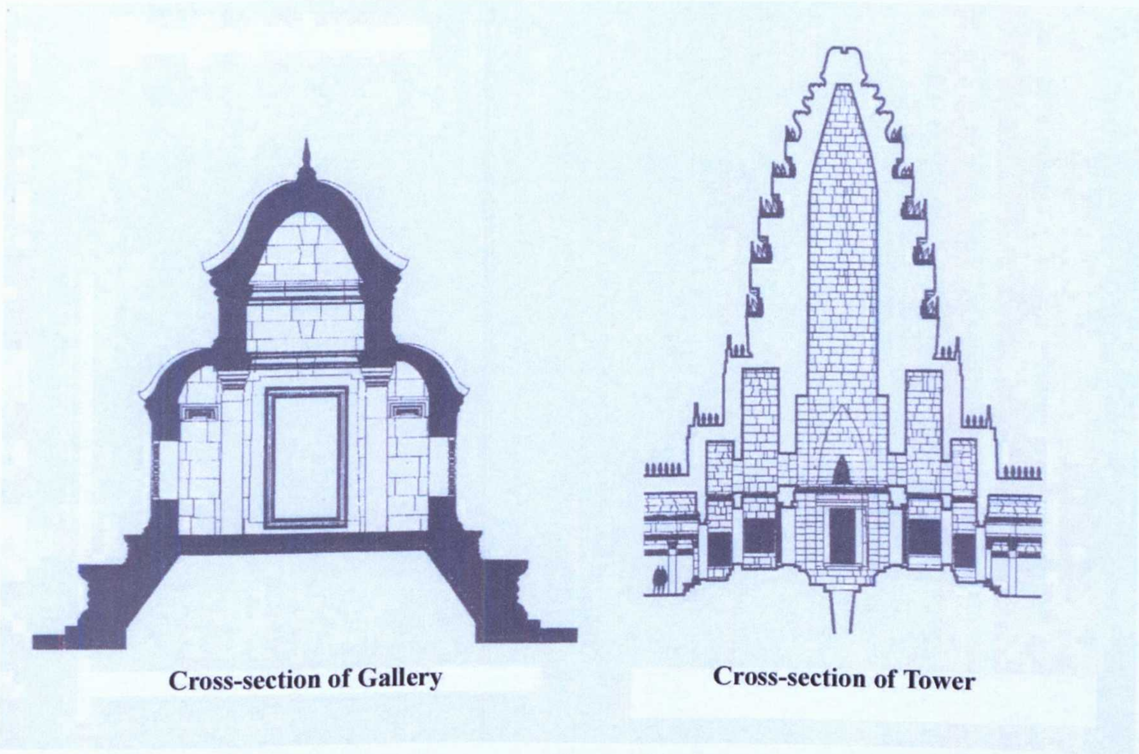


Figure 1.21: Wooden beam inserted in gable

Figure 1.22:
Evidence of wooden beam inserted in gable
(Banteay Srei in 2002)



Cross-section of Gallery **Cross-section of Tower**

Figure 1.23: Cross-section of Khmer architecture
(JSA 2000)

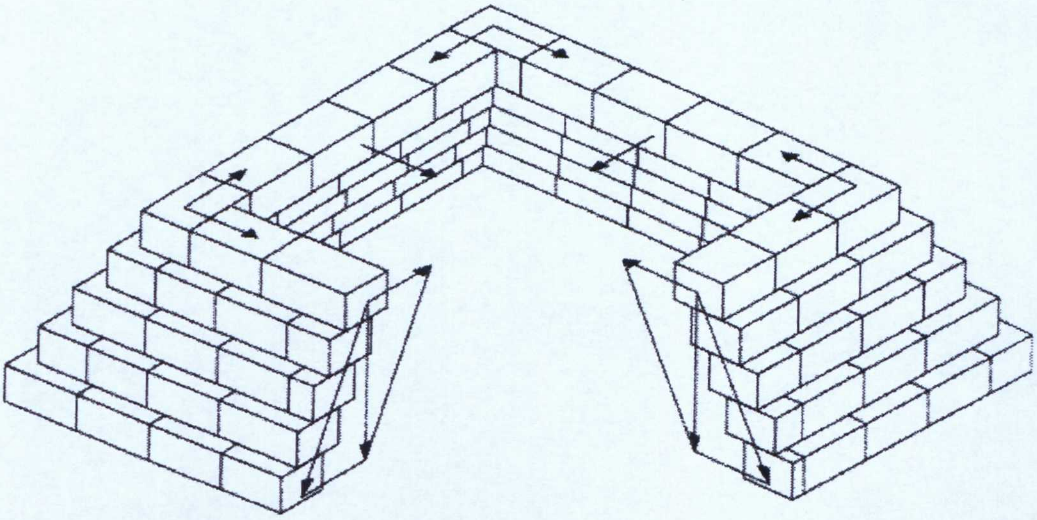


Figure 1.24: Ring effect in each masonry course of Khmer corbelled tower
(Croci 2000)

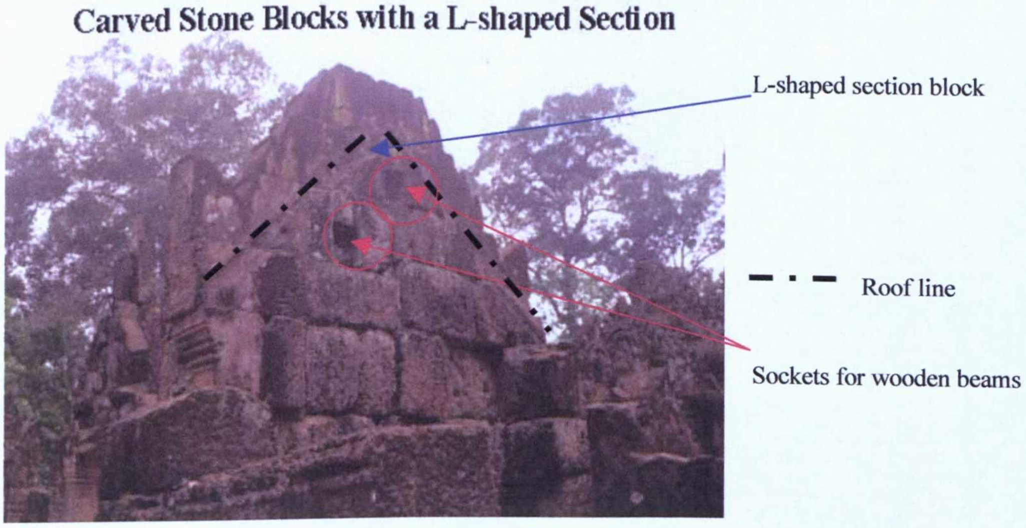


Figure 1.25: Carved stone blocks with a L-shaped section
(Banteay Srei in 2002)

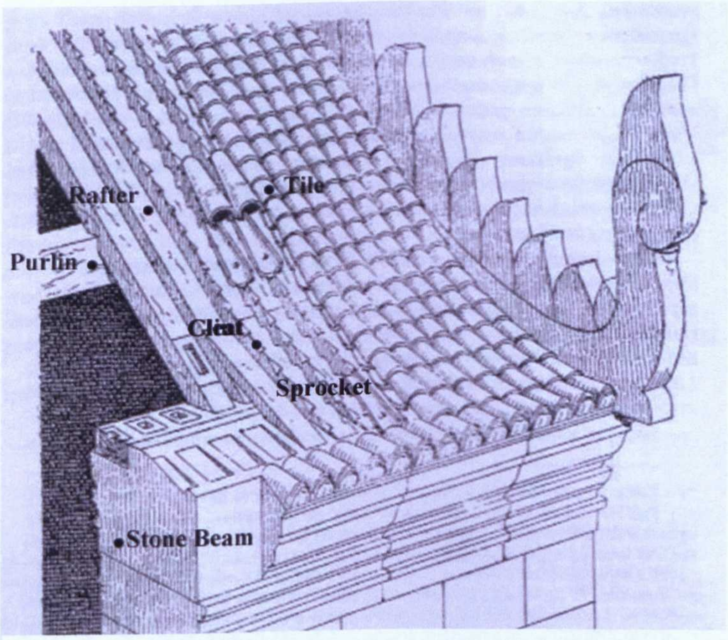


Figure 1.26: Wooden roof structure
(Parmentier 1936)

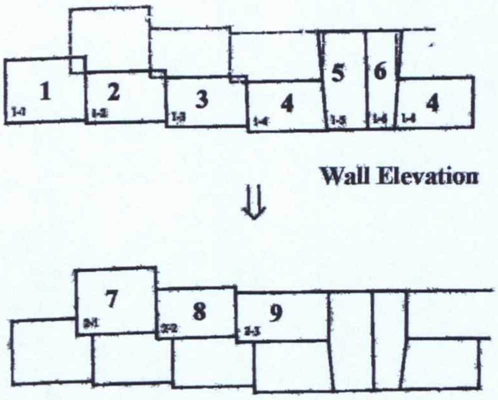


Figure 1.27: Order and direction of stone laying
(JSA 2000)

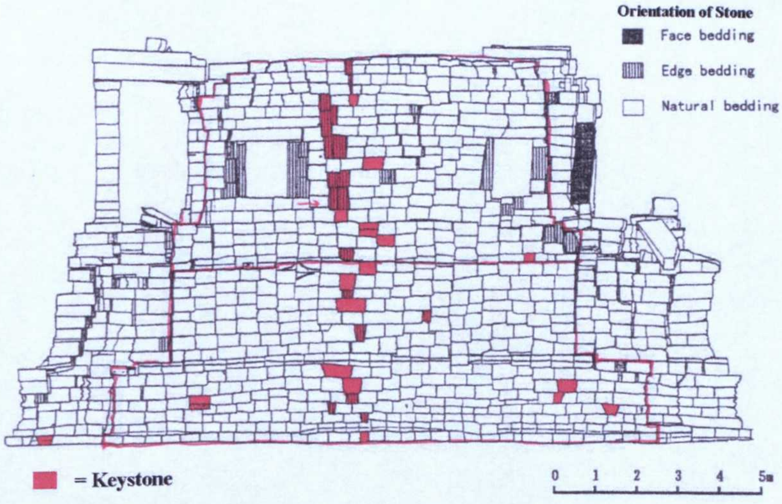


Figure 1.28: Keystones in Khmer wall
(JSA 2000)

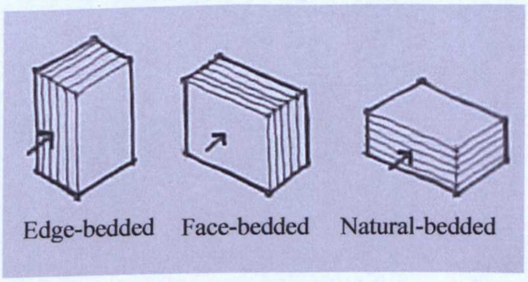


Figure 1.29: Stone orientation in masonry

Steps of Wall Construction

1. Moved the block downward with ropes and a tackle
2. Moved the block horizontally with wooden sticks

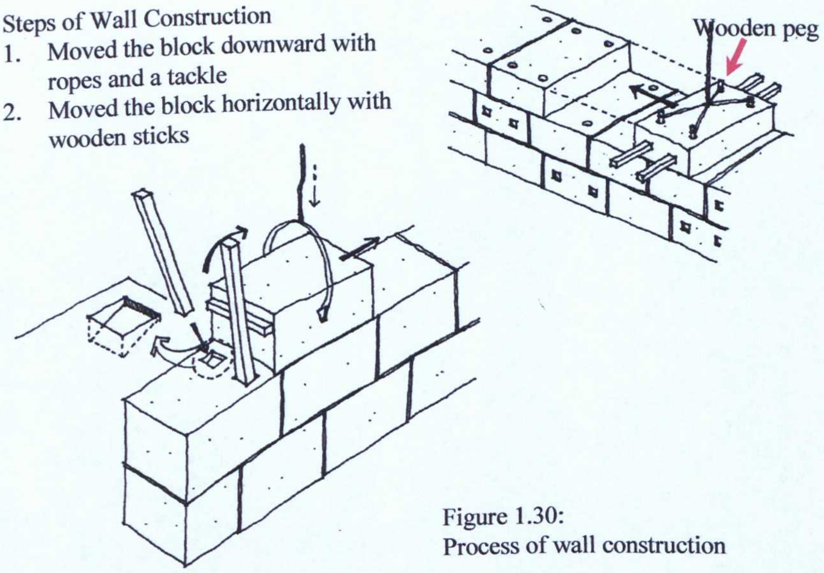


Figure 1.30:
Process of wall construction

Figure 1.31: Wall of Banteay Srei (in 2002)

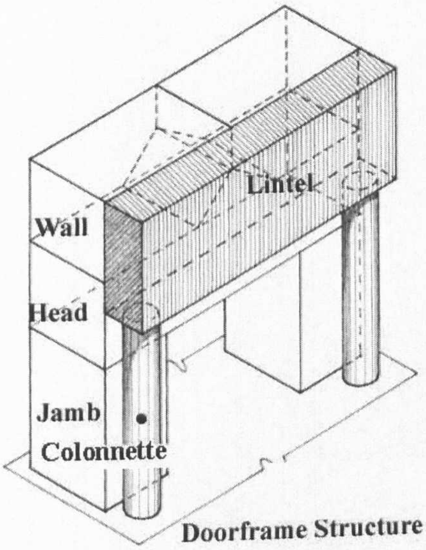


Figure 1.32:
Schematic drawing of Khmer doorframe

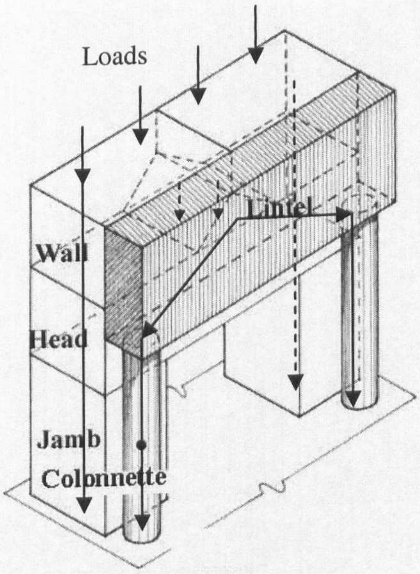


Figure 1.33:
Thrust Diagram in Door Set

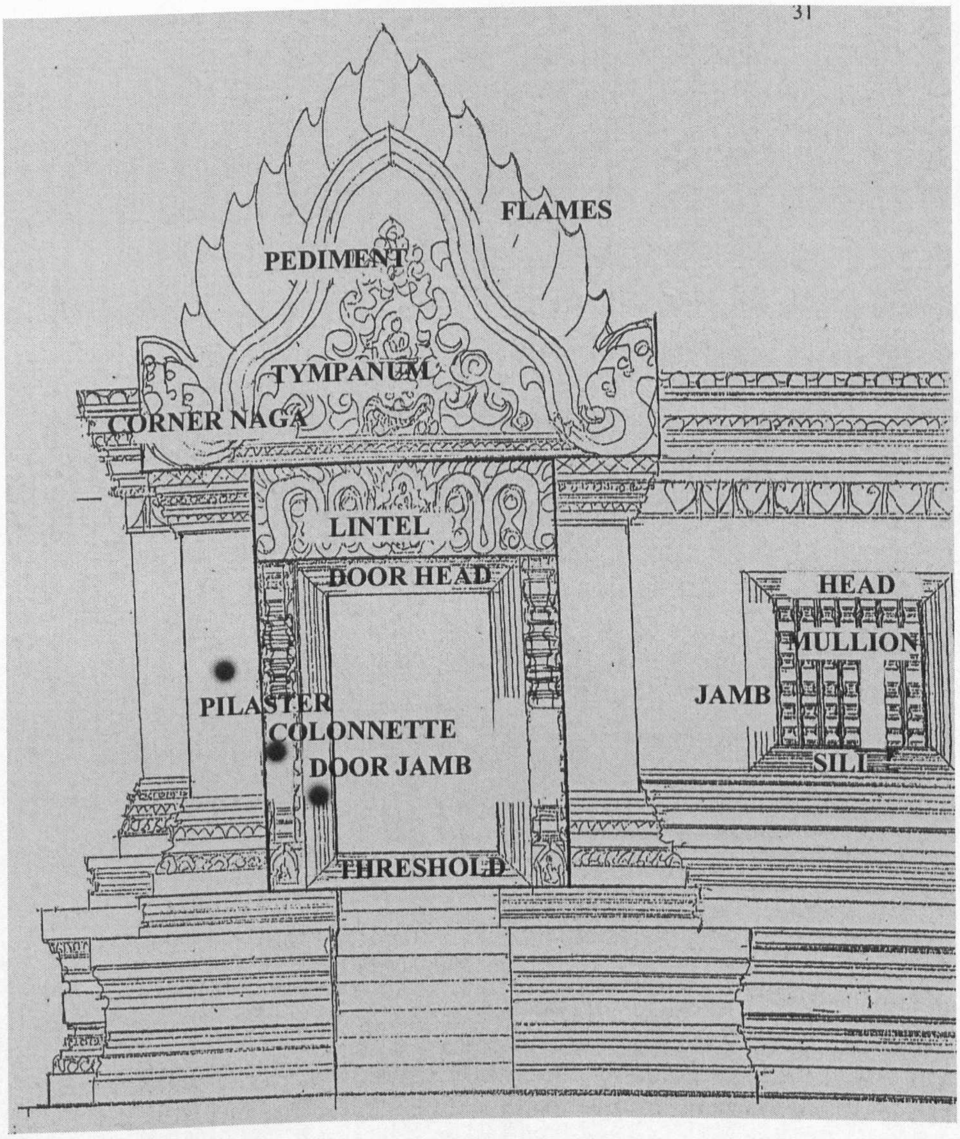


Figure 1.34: Elements of Khmer Opening

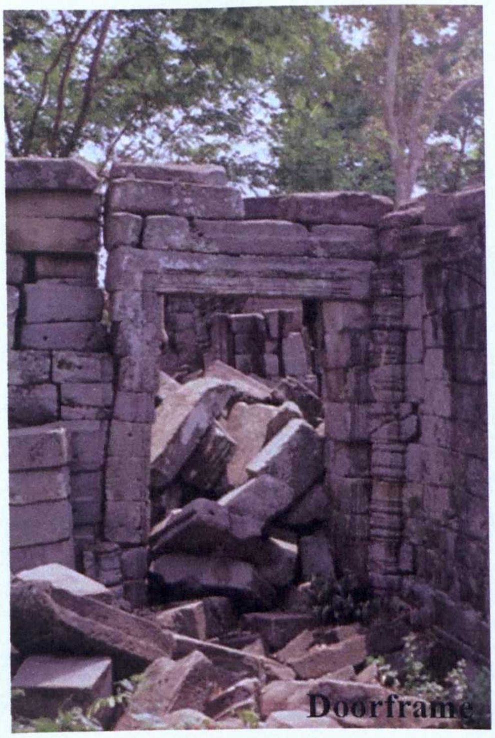


Figure 1.35: Door jamb composed of stone blocks
(Banteay Chmar in 2002)

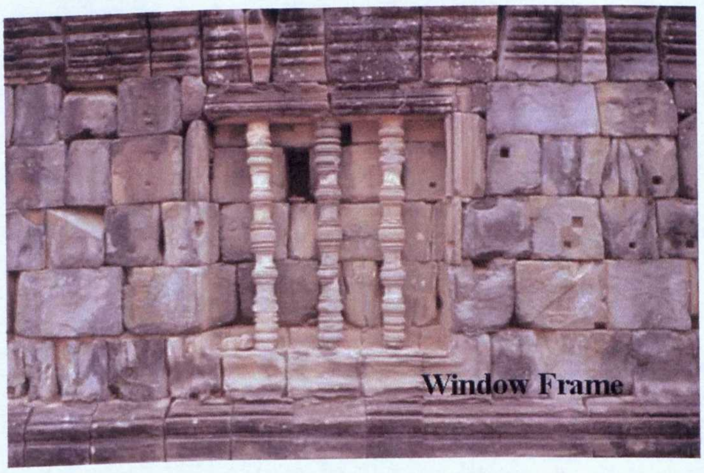


Figure 1.36: Window jambs with supplementing stone blocks
(Banteay Chmar in 2002)

Figure 1.37: Various types of the joint of window frames

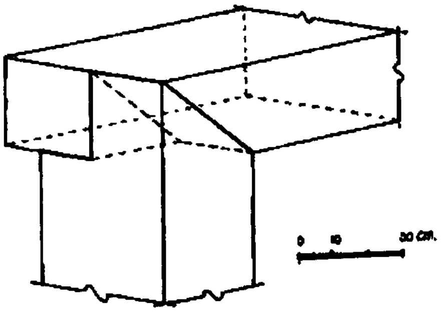


Figure 1.37a

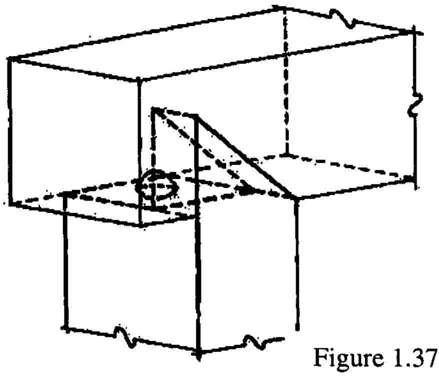


Figure 1.37b

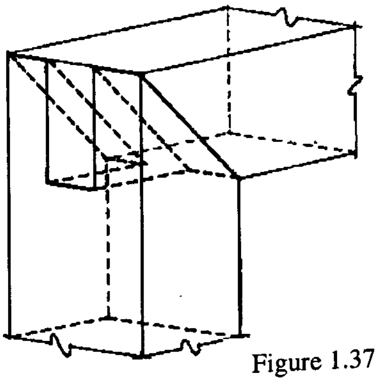


Figure 1.37c

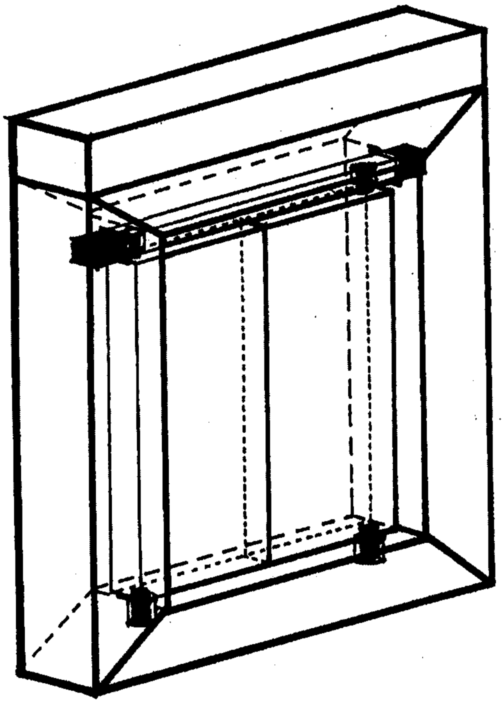


Figure 1.38: Wooden beam holding door panels

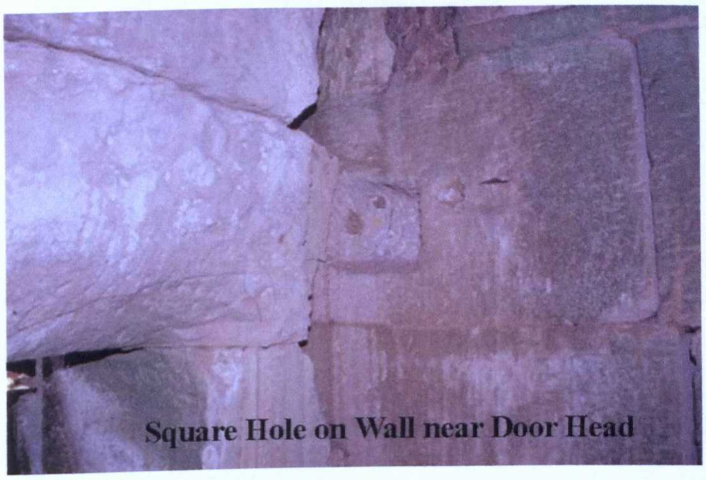


Figure 1.39: Square holes on wall near a door head
(Banteay Chmar in 2002)

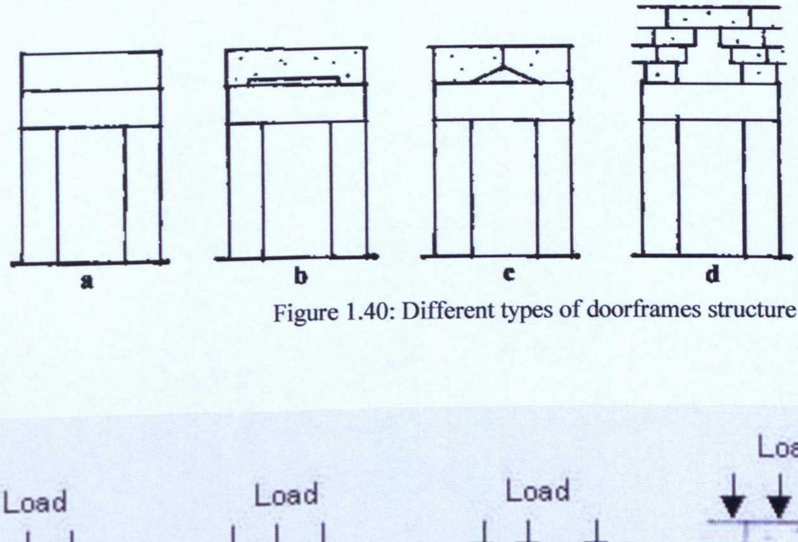


Figure 1.40: Different types of doorframes structure

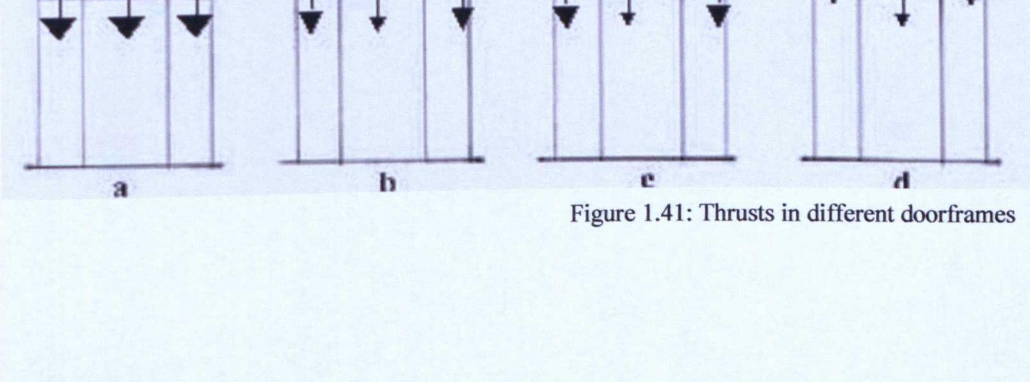


Figure 1.41: Thrusts in different doorframes

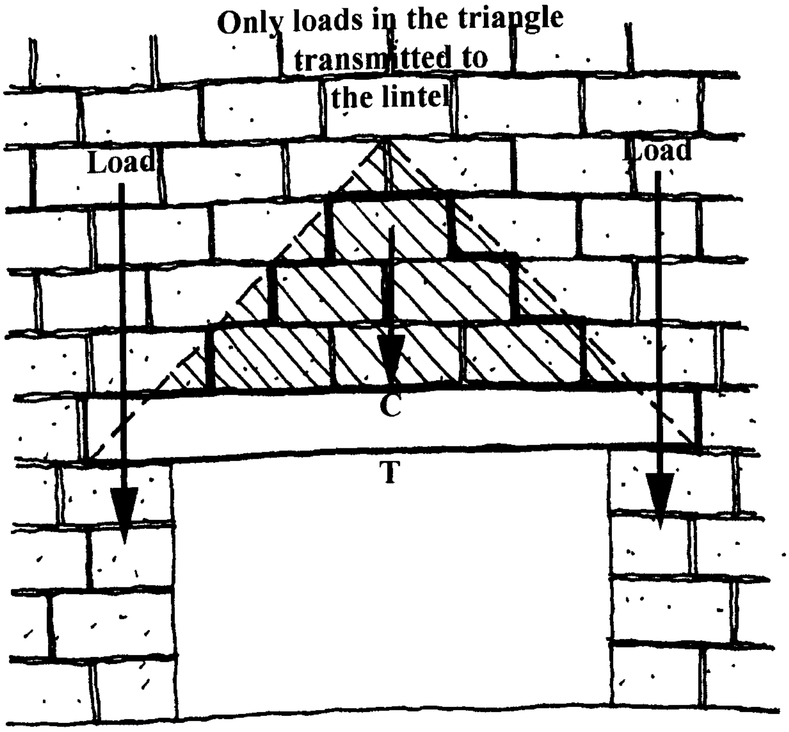


Figure 1.42:
Loads over lintel with corbelled-like effect

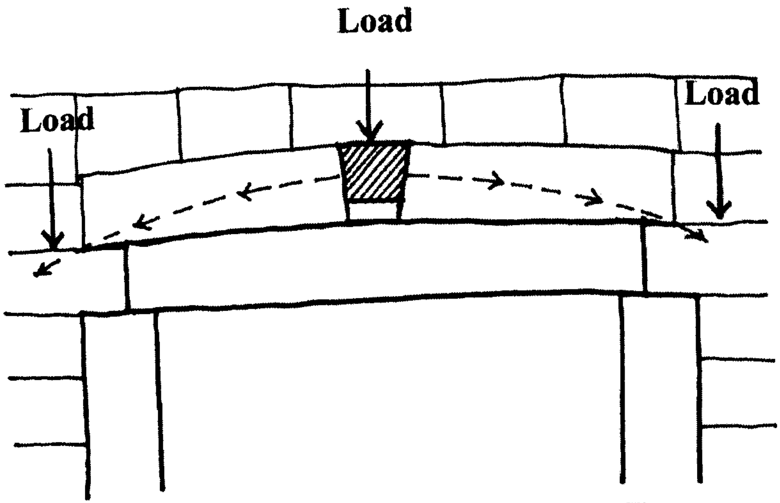


Figure 1.43:
Wedge stone creates an arch-like effect

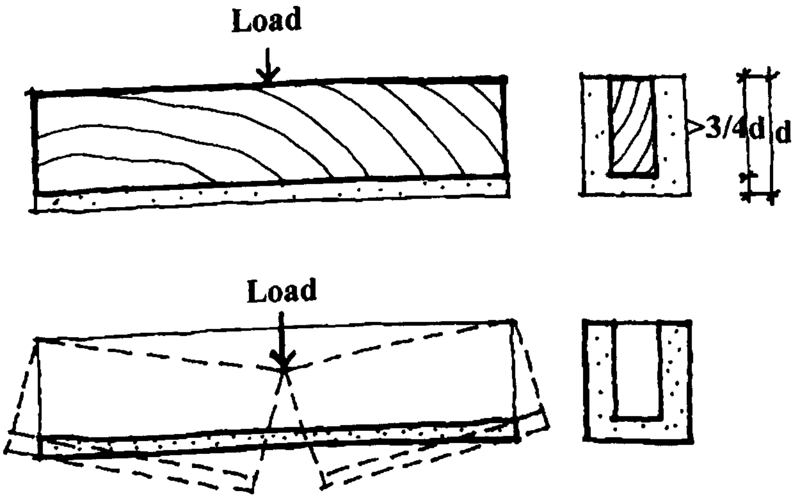
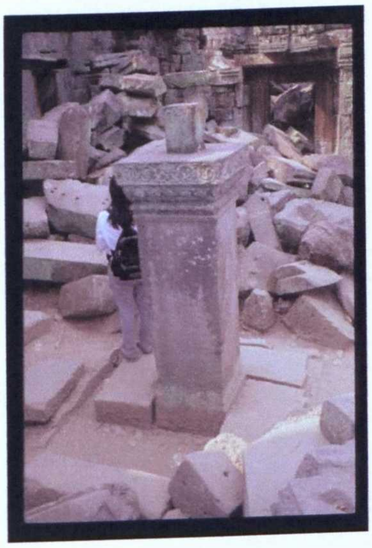


Figure 1.44: Failure of wooden beam strengthening



Tenon at the top of a shaft
(Ta Phrom in 2002)

Tenon at the bottom of a shaft
(Falling column in Banteay Srei in 2002)

Mortise at the base of a column
(Banteay Sret in 2002)

Figure 1.45: Mortise-tenon of column

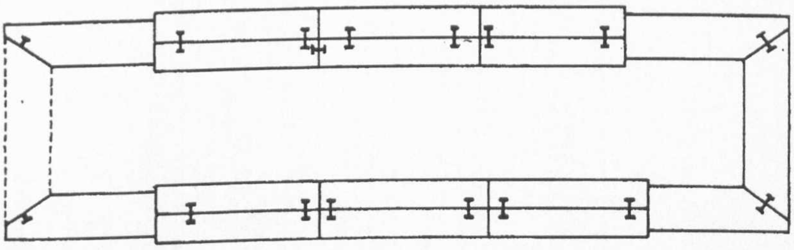


Figure 1.46a: Plan of lower stone beams
(JSA 2000)

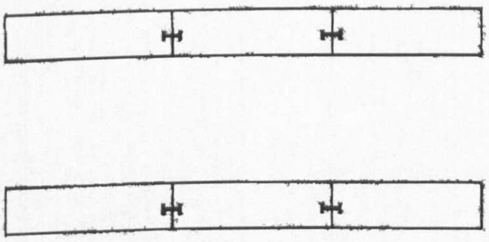


Figure 1.46b: Plan of upper stone beams
(JSA 2000)

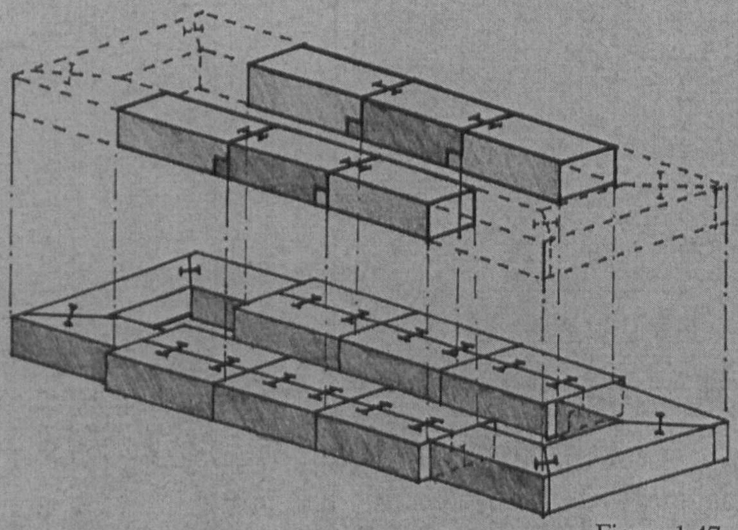


Figure 1.47:
Two-course Beam in Khmer Architecture

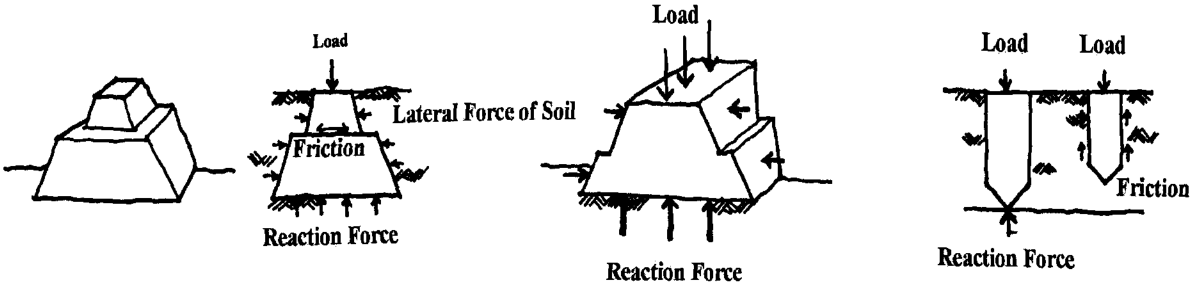


Figure 1.48: Stabilization of foundations and footings

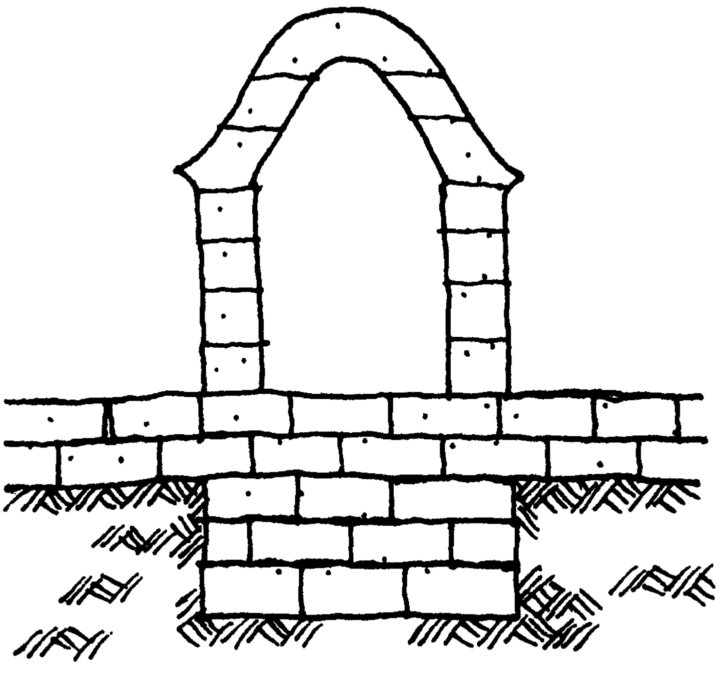
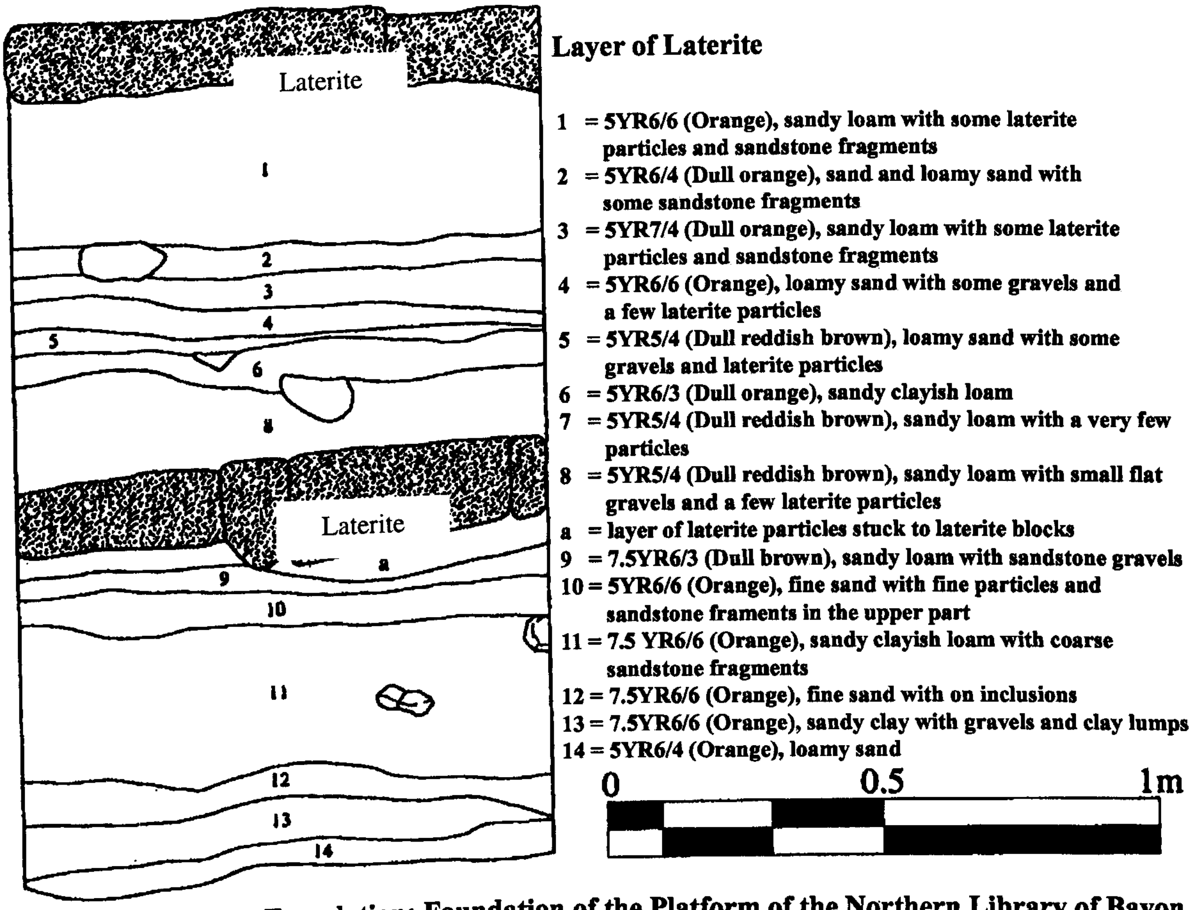


Figure 1.49:
Comparison of courses of platform masonry between interior and exterior

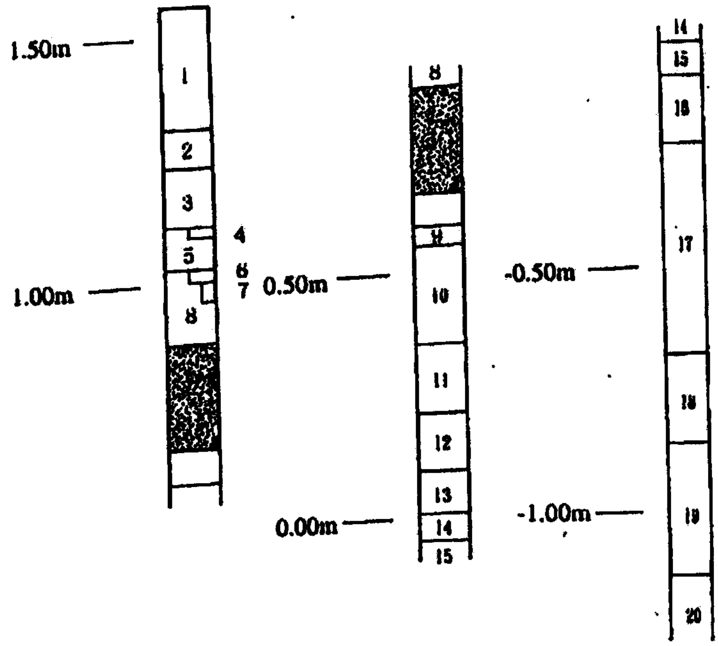
Layer of Sanstone Pavement



Layer of Laterite

1 = 5YR6/6 (Orange), sandy loam with some laterite particles and sandstone fragments
2 = 5YR6/4 (Dull orange), sand and loamy sand with some sandstone fragments
3 = 5YR7/4 (Dull orange), sandy loam with some laterite particles and sandstone fragments
4 = 5YR6/6 (Orange), loamy sand with some gravels and a few laterite particles
5 = 5YR5/4 (Dull reddish brown), loamy sand with some gravels and laterite particles
6 = 5YR6/3 (Dull orange), sandy clayish loam
7 = 5YR5/4 (Dull reddish brown), sandy loam with a very few particles
8 = 5YR5/4 (Dull reddish brown), sandy loam with small flat gravels and a few laterite particles
a = layer of laterite particles stuck to laterite blocks
9 = 7.5YR6/3 (Dull brown), sandy loam with sandstone gravels
10 = 5YR6/6 (Orange), fine sand with fine particles and sandstone framents in the upper part
11 = 7.5 YR6/6 (Orange), sandy clayish loam with coarse sandstone fragments
12 = 7.5YR6/6 (Orange), fine sand with on inclusions
13 = 7.5YR6/6 (Orange), sandy clay with gravels and clay lumps
14 = 5YR6/4 (Orange), loamy sand

Example of Khmer Foundation: Foundation of the Platform of the Northern Library of Bayon



(Continued)
Beneath Ground Level
15 = 5YR6/4 (Dull orange), loamy sand with coarse sandstone fragments
16 = 5YR6/4 (Dull Orange), loamy sand
17 = 5YR5/4 (Dull reddish brown), loamy sand and sand with fine gravels
18 = 5YR4/6 (Reddish brown), sandy loam and clayish loam
19 = 7/5R5/3 (Dull brown), sandy loam and clayish loam
20 = 7.5YR4/3 (Brown), clay: natural soil layer

Cross-section of the Foundation of the Platform of the Northern Library of Bayon

Figure 1.50: Profile and Cross-section of Khmer Foundation
(JSA 2000)

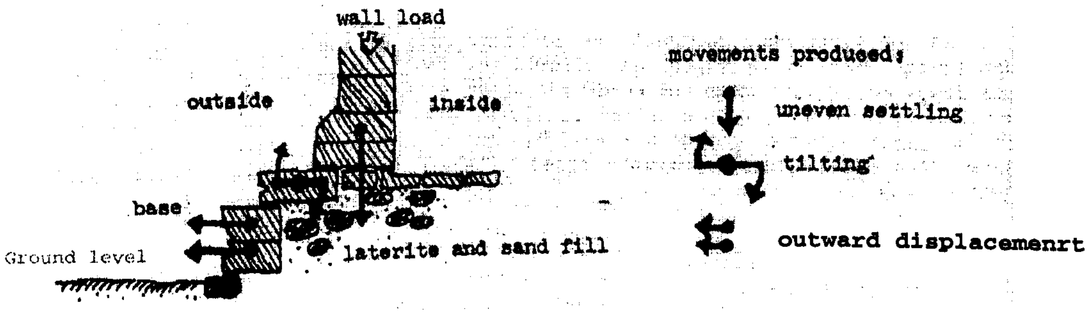


Figure 1.51: Movement of Khmer Foundation
(Pichard 1972, 10)

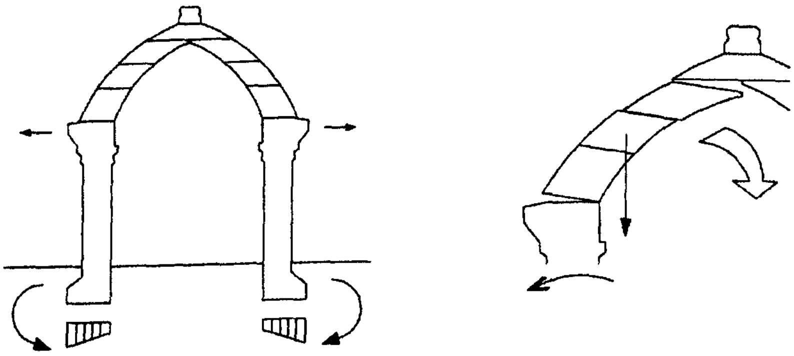


Figure 1.52:
Outward movement of roof support because of uneven subsidence of foundation
(Croci 2000, 126)

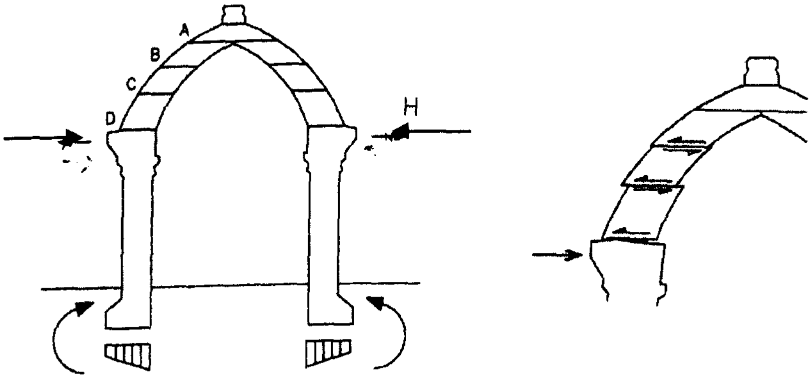
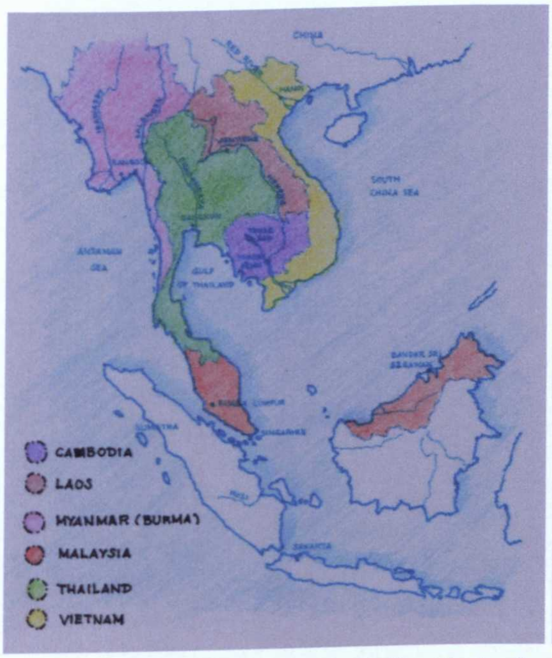
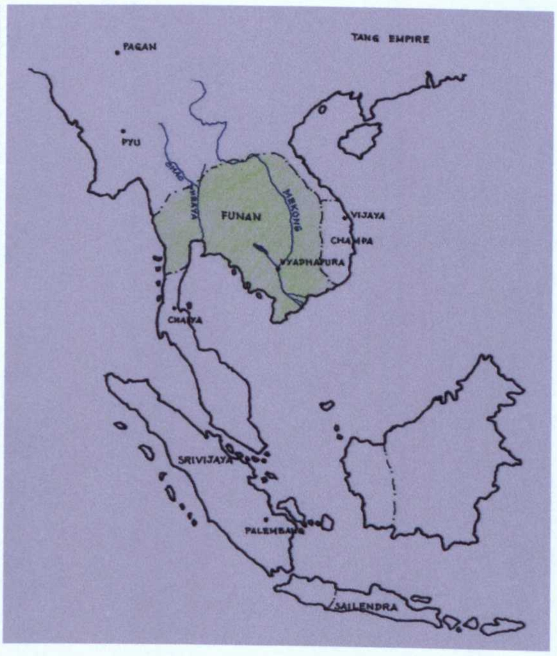


Figure 1.53:
Inward movement of roof support because of uneven subsidence of foundation
(Croci 2000, 126)

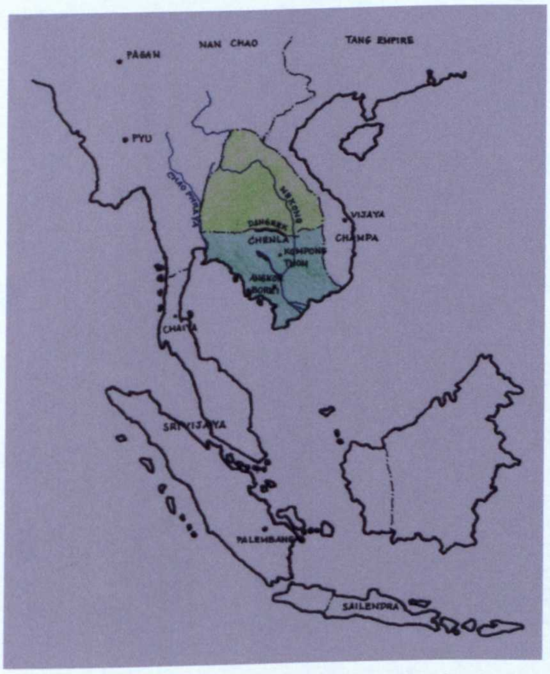
Map 1.1: Indochina Peninsula map and the chronology of Khmer boundaries



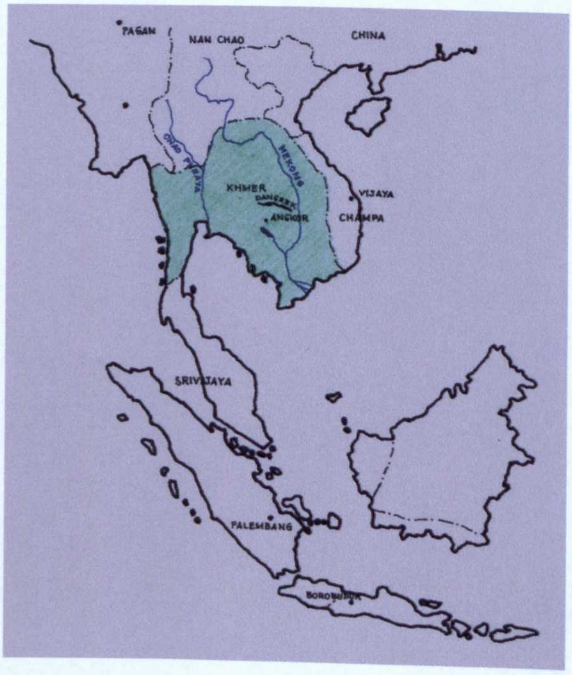
Map 1.1.1: Present-day Indochina Peninsula



Map 1.1.2:
Funan Empire (3rd century)

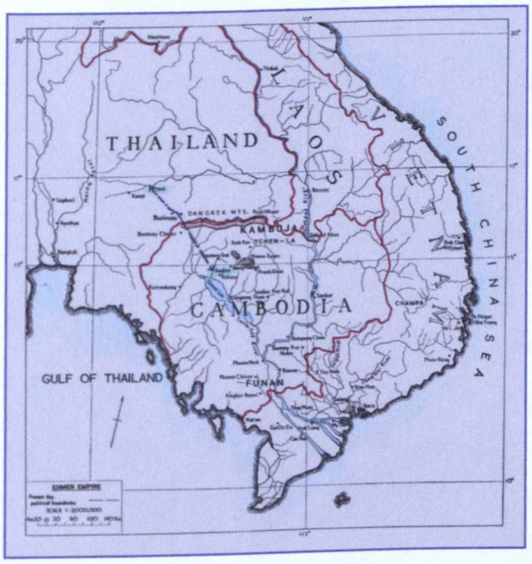


Map 1.1.3: Chenla empire
(the end of 8th century)



Map 1.1.4: Khmer Empire
During the reign of Jayavarman VII
(1181-1220 AD)

Map 1.2: The Imperial Road from Angkor to Phimai (Based on the map of Pichard 1972 drawn on the map copied from Cedès 1966)



CHAPTER II

LATERITE: LITERATURE REVIEW OF LATARITE

Laterite is a natural tropical material derived from a specific type of soil called lateritic soil. It is generally found in the areas located between the north and south latitude of 23° 26' or the tropical zone. Laterites are therefore abundant in eastern, central, and northern parts of South America, in the Sahara and Kalahari Deserts in Africa (especially in the costal regions of Eastern and Western Africa), in South and Southeast Asia, in the north and west of Australia and in Hawaii, Melanesia and South Pacific (Prescott and Pendleton 1966; Bahlman 1978). They have been used in construction since ancient times, particularly being used as a foundation material in historic architecture. In the Khmer architecture of Thailand, laterites were often used as foundations and walls.

In this chapter, the definition, formation, classification and properties of laterites, as described in the literature to date, will be reviewed and discussed. It is to be noted that the information is based on the literature that was available during the period of researching; and the purpose of this chapter is only to introduce readers to laterite; therefore, only the literature about the properties of laterite is considered while the genesis of laterite in nature and what actually changes in the chemical and mineralogical compositions of laterite, from parent rocks to lateritic soils and finally to laterite, will only be discussed briefly, and without mentioning any detail of such chemical weathering.

Most of the available research on laterite reviewed in this chapter focuses only on the properties of laterite when it is still lateritic soil—laterite before complete laterization, or when it is ground and used as gravels for road construction; therefore, the review does not correspond to the aims of this thesis which is to study mature laterite when it is used as a building material. Consequently, the literature review alone cannot answer the questions of the thesis. Hence, from the next chapter onward, I myself will investigate and characterise the properties and decay mechanisms of ancient (mature) laterite that was used for building construction purposes. The analysis and discussion of the characterization and decay mechanisms of mature laterite will then be in more detail.

The term 'tropical' in this chapter means the climates of the tropical zone, which comprise hot rainy, cool dry and hot dry, with average monthly temperatures exceeding 18°C and considerable rainfall, mainly convectional, without any winter season (Clark 2003, 435).

2.1 Definition, classification, formation and properties

> "Laterites are like women. Every engineer who meets them thinks that he understands them and can deal with them but they continue to defy precise description and classification" (Little 1969, 3-11).

2.1.1 Definition and classification

Laterite is a red to reddish brown ferruginous product of weathering inorganic material. It is porous, indurated and concretionary (Little 1969, 3-11; Nichol 2000, 181-185). It is a tropical material and can be found in the equator zone, which covers about fifteen percent of the world's area (Sinsakul nd). Thailand, having of a suitable environment for laterization, is one of the tropical countries that have abundant laterite.

The term 'laterite' is derived from a Latin word 'later' which means 'brick earth'. It was first introduced by Francis Buchanan, a Scottish geologist living in India, in 1807, and has been used to refer to all red soil or ferruginous material from that time onward (Person 1970, 1; Nichol 2000, 181-185). Laterite is soft in its natural environment but can become hard, particularly when exposed to the air. With such properties, it is easily extracted from the ground but thereafter it becomes an indurated product with brick-like hardness through its self-hardening process (Nichol 2000, 181-185).

As quoted at the beginning of this section, the definition of laterite is still debatable and no one authority has given a clear definition that encompasses all laterites. However, there are some universally accepted definitions, for example that of Fermor. He claimed that:

> "Laterite (or rather some varieties of it) is formed by a process that *modus operandi* of which is not discussed here, by which certain rocks undergo superficial decomposition, with removal in solution of combined silica, lime, magnesia, soda, and potash, and with the residual accumulation assisted no doubt, by capillary action, metasomatic replacement, and segregative changes of a hydrated mixture of oxides of iron, aluminium, and titanium, and manganese are designated the lateritic constituents" (Fermor 1911, 454)

Little further described Fermor's 'superficial decomposition' as the weathering occurring to a depth of one hundred feet or so and proposed a definition of laterite, which is compact but clear. He stated that laterite was:

> "Igneous rock tropically weathered in situ which has decomposed partially or totally with a concentration of iron or aluminium sesquioxides, at the expense of silica" (1969, 3-11).

Little's definition includes only laterite derived from igneous rocks and formed *in situ*. His definition proposes the factors that are necessary for the formation of laterite as follows: 1) certain parent rocks must be igneous, 2) the weathering must occur *in situ* under tropical conditions, and 3) the material has to be rich in iron or aluminium oxide with a consequent diminution in the ratio of silica to aluminium or iron oxide. In fact, laterites could also be formed without all these factors. There is another type of laterite formed by colluvium and alluvium, which is discussed below.

Pendleton and Shanasuvana (1946) gave an interesting definition of laterite. They proclaimed that laterite meant an illuvial horizon, largely of iron oxides, with a slag-like cellular or pisolitic structure, and of such a degree of hardness that it may be quarried out and used for building construction (ibid, 423-440). Noticeably, this is the only definition that mentions about laterite as a building material. Furthermore, classifying laterite into two main groups based on its observable hardened pore structure makes the classification of laterite blocks in construction sites without any specific tool possible.

In terms of categorization, some researchers suggest different indicators to classify laterite. Sherman *et al* (1953, 438-446) classified laterites based on their formation, but their system was different from the classification of Little (1969) in certain ways. They considered the locations of formation to divide laterite into five groups as follows: 1) residual laterite formed in places experiencing free drainage; 2) laterite formed by accumulation of iron oxide; 3) transported laterite or the remoulded product of old indurated crusts; 4) groundwater laterite which develops over a permanent water table near the surface; and 5) secondary formatted fossil laterite. On the other hand, Graft-Johnson and Bhatia classifies laterite based on its particle size distribution, which is influenced by the mode of occurrence of lateritic soils (1969, 15). Laterites found on the peneplain are finer than those found in colluviums. The latter (which are the ones usually found and used as construction materials) tend to be gap graded and deficient of sand-sized particles. Graft-Johnson and Bhatia also suggests classifying laterite based on its specific gravity. The specific gravity of laterite varies depending on its particle size distribution and iron content (the degree of laterization) (ibid, 18). The higher the degree of laterization and the coarser the particles, the greater the specific gravity. Gidigasu also classifies laterite based on its particle size as follows: 1) laterite rock, which self-hardens completely and has properties more similar to stone than soils; 2) lateritic gravel and gravelly soil which have similar properties to laterite rock, but no concretion, and 3) laterite fine-grained soil or lateritic soils (Gidigasu 1972 cited by Jintasakul 1989, 19). Unlike others, Ruddock proposed a classification for laterite based on its surrounding context —the depth of laterite samples, water table position, and topography (Ruddock 1967, 359-377). Arulanandan, however, argued that those classifications based on geological or pedological approaches were qualitative and non-universal (Arulanandan 1969, 163-179). He agreed with Little in suggesting that laterite should be classified based on its engineering properties as well as its mineral and chemical composition.

Laterite is composed of sesquioxides of iron and aluminium and possibly a large amount of quartz and kaolinite, but lacks bases or primary silicates. (A sesquioxide is an oxide in which oxygen is present in the ratio of three atoms to two of another element.) Therefore, it can be classified chemically based on the ratio of its silica to metallic sesquioxides, which divides laterite into three groups (Martin and Doyne 1927, 530; Prakash and Basavanna 1969, 165-175). The first group is laterite having a ratio of silica to metallic sesquioxides of less than 1.33. The second group is lateritic soil with a ratio of between 1.33 and 2.00. The last group is non-lateritic soil, whose ratio of silica to sesquioxides is greater than

2.00. Martin and Doyne proposed that the ratio of silica to aluminium oxide is more important than the presence of ferric oxide (Martin and Doyne 1927, 530), and, according to Prakash (1970, 166), the ratio of silica to alumina in laterite must be equal to or less than 1.33. Nevertheless, from an engineering point of view, using the ratio of silica to metallic sesquioxides to classify laterite in the field is unnecessary and non-universal (Little 1969, 3-11).

As discussed above, laterite is composed of sesquioxides of iron and aluminium and possibly a large amount of quartz and kaolinite, but lacks bases or primary silicates. In contrast, plinthite, known as 'laterite before exposure' or underground laterite, is similar to laterite in chemical and mineral composition but is a non-hardened or poorly hardened material formed by incomplete laterization of soils. Plinthite soil, however, may be hardened to form laterite when exposed to wetting and drying. Vallerga *et* al, who classified laterites based on the sources of their chemical composition, also separated laterite from plinthite and lateritic soil, and described laterite as a hardened material formed by the primary weathering of non-transported soils or sesquioxides present in the material; or by the secondary enrichment and cementation of soils—either transported or non-transported—or sesquioxides supplied by lateral groundwater movement (Vallerga *et* al 1969, 109-121).

Laterite may be classified based on its chemical composition and named using its main chemical compound as an adjective (Aleva 1981, 261-268). Examples of the nomenclature of laterite include ferruginous laterite, aluminous laterite, siliceous laterite, manganiferous laterite, for instance.

In Thailand, laterites are classified based on the types of laterization and physical properties (Jintasakul 1989, 21). Since it is lateritic soils that are found in the ground rather than laterite itself, geologists classify lateritic soils on a national scale into two groups—primary lateritic soils and secondary lateritic soils (ibid, 20). Laterites are further classified on a regional scale into two groups based on their laterization. The first group is ground water laterite and the second is pedogenic laterite (Boontan 1984 cited by Jintasakul 1989, 20). In terms of local classification, laterite in Thailand is divided into three groups based on physical appearance—1) massively cemented, cellular laterite, 2) loose, pisolitic laterite and 3) clayey gravelly laterite (Boonsner 1983, 1-5). The Division of Mineral Resources (DMR) in Thailand also applies the last criterion to the classification of laterite in Thailand.

In summary, laterite has been defined in various ways by several scholars. The definitions are different in detail, but the similarity is that they refer to laterite as a natural material derived from tropically weathered rock and mainly composed of silicon dioxide, aluminium and iron oxides. Laterite can be classified based on various criteria. Examples of the criteria that have been used for classifying laterite are summarised in Table 2.1:

Table 2.1: Examples of criteria for laterite classification

Criteria	Researcher	Classification
Formation & location	Vallerga et al (1969)	1.Primary 2.Secondary
	Sherman et al (1953)	1.Residual laterite formed in situ in free drainage conditions 2.Laterite formed by accumulation of iron oxide 3.Transported laterite or remoulded laterite of old crusts 4.Groundwater laterite 5.Secondary formatted fossil laterite
	Jintasakul (1989) (Geologists in Thailand)	1.Primary lateritic soil 2.Secondary lateritic soil
	Boontan (1984) (Thailand)	1.Groundwater laterite 2.Pedogenic laterite
Particle size	Graft-Johnson and Bhatia (1969)	1. Peneplain laterite (fine-grained) 2.Colluvium laterite (coarse-grained)
	Gidigasu (1976)	1. Laterite rock 2.Lateritic gravel with no concretion 3. Lateritic fine-grained soil
Specific gravity	Graft-Johnson and Bhatia (1969)	Varies depending on: - degree of laterization - size particle - amount of iron content
Surrounding factors	Ruddock (1967)	Varies depending on: - depth of laterite - water table - topography

Table 2.1: Examples of criteria for laterite classification (continued)

Criteria	**Researcher**	**Classification**
Chemical composition	Martin and Doyne (1927)	Based on the ratio of silica to sesquioxides 1.Laterite (less than 1.33) 2.Lateritic soils (1.33-2.00) 3.Non-lateritic material (more than 1.33)
	Aleva (1981)	Varies depending on main chemical compound - Ferruginous laterite - Aluminous laterite - Siliceous laterite - etc.
Source of chemical composition	Vallerga et al (1969)	1.Laterite from the primary weathering of non-transported soil and sesquioxides within the parent material 2. Laterite from the weathering of sesquioxides supplied by lateral ground water movement and either transported or non-transported soils
Engineering property	Little (1969)	Varies depending on grades of freshness

Table 2.1: Examples of criteria for laterite classification (continued)

Criteria	Researcher	Classification
Structural form	Vallerga et al (1969)	1.Consolidated pisolitic 2.Unconsolidated pisolites or concretions in a soil matrix 3.Consolidated vesicular or worm hole mass 4.Cemented pre-existing materials
	Maignien (1966)	1.Soft mottled clays or lateritic soils changed to crusts 2.Cellular mottled crusts 3.Concretion or nodules in a matrix of unconsolidated material 4.Consolidated masses of concretions or nodules
	Boonsner (1983), DMR (Thailand)	1.Massive cemented cellular laterite 2.Loose pisolitic laterite 3.Clayey gravelly laterite
	Pendleton and Shanasuvana (1946)	1.Slag-like laterite 2.Pisolitic laterite

It is quite clear that there is no universally acceptable agreement of what the definition of laterite is; therefore, it is inapplicable to give a precise definition to laterite in Thailand, especially ancient laterite, from the literature review alone. Further studies need to be carried out, and the characterization of chemical, physical and mechanical properties of laterite collected from historic Khmer monuments performed in the next chapters will only be the starting point in defining such laterite.

2.1.2 Formation of laterite (laterization)

The process of physical and chemical weathering of iron-rich parent materials into laterite under a tropical climate is called 'laterization'. The process begins with the weathering of iron-rich parent rocks by agents such as acidic rainwater contaminated with organic substances. This combination weathers such rocks into lateritic soils and thereafter into laterite (Graft-Johnson *et al* 1969, 117-128). The process by which lateritic soil, or soft immature laterite, hardens when exposed to the air is mainly associated with the loss of its moisture content and the oxidation of iron compounds to cement its grains (Sinsakul nd.).

According to the definition of Vallerga *et al* (1969) above, it is widely acceptable to classify laterites into two main groups—Primary and Secondary—based on original materials and locations of laterization. Primary laterite is generally formed *in situ* by the residual products of weathering parent rocks. Through laterization during the wet season in a tropical climate, silica and other earth alkalis, such as the hydroxides of calcium and magnesium (Clark 2003, 10-11), in the rocks are leached out, leaving a concentration of ferric oxides or hydroxides with certain amounts of alumina and solid hard crusts agglutinated by iron compounds (Vallerga *et al* 1969, 109-121; Little 1969, 3-11). (Leaching is the process whereby percolating water removes materials from the upper layers of a rock, soil or ore, and carries them away in solution or suspension (Clark 2003, 231).) During the decomposition of parent rocks, the volume decreases considerably: Hong Kong granite, for example, loses one-third of its original volume after it has been decomposed chemically by acid rain (Ruxton and Berry 1957, 9). During dry seasons, the iron compounds, first precipitated as ferric hydrates, are hardened and darkened as 'primary laterite' by dehydration. Dehydration changes the iron hydrates in primary laterite from a yellow to a brown gel, which then crystallises as limonite and haematite. Through this process of weathering, rocks are completely changed into 'laterite'. The colour of laterite can therefore act as a measure of its maturity— the darker the colour, the greater the hardness and maturity of the laterite. In a similar way, exposure to rain, air and sun leads to the oxidation and dehydration of plinthite. The longer the exposure, the harder the laterite product.

Secondary laterite is formed by alluvium or colluvium. Laterites formed by iron compounds that are transported by groundwater or surface drainage are classified within this group. The flow of underground water and surface drainage also brings iron compounds from remote sources of iron-rich rocks and changes the concentration of ferric oxides or hydroxides in the area. Such iron compounds hydrate in wet seasons and dehydrate in dry seasons, leading to hardening of the soil. Generally, the iron compounds are precipitated around the nuclei of quartz or coarse sand, first as hydrated iron and then as hardened dehydrated ferric compounds, which bind the grains.

Laterite is also described as 'indurated clay' (Buchanan 1807 cited by Nichol 2000, 181-185). This is because laterite itself hardens by the loss of water between layers of clay, which is similar to the drying of ordinary ceramic clay or mud bricks. In addition, as discussed above, dehydration of iron compounds, amorphous iron oxides and iron hydroxides, which results in dense crystalline forms, also contributes to the hardening process. Through these wetting and drying cycles, iron compounds move and re-crystallise creating a cementing effect upon the soil grains.

Laterization depends upon three main factors: iron-rich rocks—in the case of *in situ* formation, alternating dry and wet conditions, and a suitable topography (Graft-Johnson *et al* 1969, 117-128). However, the most important factor for laterization is the presence of iron oxides, so laterization generally occurs in places where the terrain can supply large quantities of these (Maignien 1966, 10). Since laterization also requires a high level of rainfall, intensive leaching and a strong oxidising environment, the rate and degree of laterization depends on a suitable environment that provides the following factors: a semi-humid or humid tropical climate; fluctuations of the groundwater table; a flat or nearly flat land surface (10°-15° slope) located above sea level; and a long period of time for the leaching of parent iron-rich rocks (Suwanasing 1971, 74; Sinsakul nd.). A tropical, monsoon climate (one of the most important factors) comprises long alternating wet and dry seasons with short transitional periods, a constant annual temperature of 30 degree Celsius and a large annual rainfall. These conditions result in repeated fluctuation cycles of the groundwater table and therefore the acceleration of chemical weathering of the parent rocks. However, a large amount of rainfall alone does not always guarantee a high rate of laterization. Soils have a limit of saturation; therefore, when the amount of rainfall exceeds the saturation limit of soils, water cannot penetrate to the groundwater level and the excess water will flow into nearby lakes or rivers. Hence, the frequent moderate rain during wet seasons is preferable for laterization to heavy but infrequent rainfall.

In addition to the requirements discussed above, some supplementary factors enhance laterization. High permeability of soils allows groundwater to penetrate and transport sesquioxides of iron and/or aluminium to the area. The presence of plentiful oxygen in groundwater can accelerate the oxidation of iron elements in parent rocks to form the iron oxides necessary for this process.

In summary, laterization is the process whereby parent rocks are weathered to form iron-rich lateritic soils and then harden as laterite when exposed to the environment. According to the literature reviewed in this chapter, the steps in the laterization process could be summarised as follows:

1) During wet seasons, silica and other earth alkalis in the parent rocks are leached out, leaving a concentration of ferric oxides or hydroxides and alumina with some solid hard crusts agglutinated by iron compounds.
2) During dry seasons, the iron compounds, first precipitated as ferric hydrates, dehydrate. The dehydration changes iron hydrate gel to be crystals of limonite and haematite around hard crusts leading to the hardening and darkening of the weathered rock.

Through these steps of weathering rocks are completely changed into 'laterite' (Vallerga *et al* 1969, 109-121; Little 1969, 3-11). The most consistent and possibly the most significant characteristics of hardened laterite, when compared with other material composed of similar chemical composition, are the greater degree of crystallization and more continuity of the crystalline phase of iron oxide minerals (Alexander and Cady 1962, 9).

2.1.3 Properties of laterite

Chemical and mineral compositions

The chemical and mineral composition of laterite is mostly comprised of sesquioxides of aluminium and iron (aluminium oxide as bauxite, $Al_2O_3 . nH_2O$, and haematite or ferric oxide, Fe_2O_3), possibly with large amounts of quartz (SiO_2) and kaolinite (hydrous aluminium silicate, $Al_2Si_2O_5(OH)_4$) and manganese, but with almost no silicates (Vallerga et al 1969, 109-121; Sinsakul, nd.). The amount of iron oxide varies from forty to ninety percent, while that of aluminium oxide may range from five to fifty percent. However, if a laterite is composed of more than sixty percent aluminium, it is called bauxite (Jintasakul 1989, 15).

Laterite may consist of up to thirty percent silica, either in the form of quartz or kaolinite. Less than one percent of other compounds, such as calcium, magnesium, manganese, potassium and sodium, is found in laterite (Young 1976, 12). Sometimes, up to one percent of titanium oxide (TiO_2) is detectable. According to the study of Viswanathan *et al* on laterite from Kerala in India (where the term laterite was first named by Buchanan), laterite is composed of 42.0% kaolinite, 22.4% quartz, 16.6% goethite (iron hydroxide, $FeO(OH)$), 8.8% gibbsite, and 5.6% haematite (Viswanathan *et al* 1985, 375-385).

In Thailand, laterite found in the Korat Basin is composed of 34.31% quartz, 11.35% aluminium oxide, 41.88% ferric oxide, 1.86% calcite, 1.31% magnesium oxide, 0.31% titanium dioxide and 0.16% potassium oxide (Pendleton and Shanasuvana 1946, 423-440). According to a qualitative study of the mineral composition of laterite in the Prachinburi Province in Thailand, laterite contains magnetite, haematite, serpentine, quartz, aluminous minerals, chrome spinel, nickeliferous limonite, illite and kaolinite (Suwanasing 1974, 94). However, there is no quantitative study of the mineral composition of laterite in that research.

Physical characteristics

In terms of physical characteristics, laterite contains hardened aggregates, which are in any combination of four principal forms—1) consolidated pisolitic, i.e. small, spherical, masses; 2) unconsolidated pisolites or concretion in a soil matrix; 3) consolidated vesicular or worm hole masses; and 4) cemented pre-existing materials, such as quartz, in pisolitic or vesicular structure (Vallerga *et al* 1969, 109-121).

According to Maignien (1966), the forms of laterite are grouped as follows: 1) soft mottled clays or lateritic soils which change irreversibly to hardpans or crusts when exposed; 2) cellular mottled hardpans or crusts; 3) concretion or nodules in a matrix of unconsolidated material; 4) and consolidated masses of concretions or nodules.

The simplest characterization of laterite forms was proposed by some researchers (Marbut and Manifold 1926, 414-442; Pendleton 1941, 177-202; Pendleton and Shanasuvana 1946, 423-440). They divided laterite into two groups—slag-like cellular laterite and pisolitic laterite. As previously discussed, classifying laterite into two main groups based on its observable hardened pore structure makes the classification of laterite blocks on construction sites without any specific microscopic tool easier, especially if the characterization is carried out by conservators with non-geological background. Nevertheless, it should be noted that, apart from Sinsakul, the other scholars classified the physical composition of laterite qualitatively without mentioning the sizes of aggregates. Sinsakul (nd.) states that when laterite is a concretion of rounded, pea-like, aggregates with a size larger than millimetres in diameter it is called 'pisolitic laterite', while that composed of ooliths, small round grains which are smaller than two millimetres in diameter, is called oolitic laterite.

In general, the factors controlling the form of laterite produced are the environmental conditions during the laterization. Such environmental factors are climate, temperature, humidity, pH, the degree and rate of precipitation or laterization, topography, vegetation, the location of laterite (the depth from ground level that affects the degree of weathering) and the types of parent rock (Graft-Johnson and Bhatia 1969, 13-43; Little 1969, 3-11). However, it is still debatable as to whether certain factors are able to enhance a certain form of laterite. For example, pisolite may be formed by sand matrix (Pendleton 1941, 177-202) or by centripetal enrichment of materials in groundwater fluctuating zones (Pullan 1967 cited by Jintasakul 1989, 65). In terms of the origin and location of laterization, laterite formed *in situ* is usually found in irregular shapes consisting of fresh iron oxide (neo-ferran), which fills the gaps (so-called 'void neo-ferran'), angular-shaped quartz grains and patches of goethite. Laterite formed by colluvial materials is composed of cracking round-shaped quartz grains whose cracks are filled with iron oxide (so-called 'ruin-quartz'), irregular-shaped goethite patches, and cementing materials (goethite and fresh iron oxide) filling the voids between grains (so-called 'void geothan' and 'void neo-ferran') (Zauvah 1983, 667-673).

In terms of colour, laterite is usually red or brown, but may also be ochre or a mixture of colours including purple and black caused by the presence of iron oxides and/or manganese. Haematite, or iron oxide, varies in colour and generally acts as a colouring agent in rocks and organic materials. It appears either black, iron-coloured with metallic lustre, red or brownish red, as earthy grains or sometimes as pebbles in laterite. When combined with iron in laterite, aluminium, which is usually white, changes to be dark brownish red; and silica, combining with the hydroxide of iron, changes to rusty colour (Sinsakul nd.). Therefore, the colour of laterite may vary from reddish brown (5YR 5/6 on the Munsell Scale), which is found generally, to dark brown (7.5YR 3/4), dark red (7.5YR 3/8), and yellowish brown (10YR 6/8) found in laterite from the Saddleback Mountains in Australia (Young 1976, 14; Ball and Gilkes 1985, 1-14). However, the colour of laterite may change when exposed to wet-dry cycles leading to greater laterization. As discussed above, the longer the exposure, the darker the colour, and, consequently, the more mature and harder the laterite becomes.

Specific gravity is another physical property used to identify laterite. It is the ratio of the weight or mass of a given volume of a substance to that of an equal volume of another substance (water for liquids and solids, air or hydrogen for gases) used as a standard (Agnes and Laird (eds.) 2002). The specific gravity (and density) of laterites is dependent on the amount of iron oxide; the more the iron oxide the greater specific gravity (Sinsakul nd.). Generally, it ranges from 2.5 to 3.6 (Bahlman 1978, 12). On average, laterite in Thailand has a specific gravity of 3.0 (Jintasakul 1989, 14).

Laterite is irreversibly hardened when exposed to alternate cycles of wetting and drying. Noticeably, the irreversible hardening of laterite makes it different from lateritic soils, which harden upon drying but soften easily when re-exposed to wetting. This is because particles of lateritic soils are bound with only secondary iron cements, while those of laterites are bound with ferric oxides. However, according to Martin and Doyne, the ratio of silica to aluminium oxide in laterite is more important than the presence of iron oxide (1927, 530). Thus, such a ratio can generally be used to differentiate laterite from lateritic soils. As discussed above, the silica to alumina ratio of laterite is 1.33 or less while the ratio of lateritic soil is 1.33-2.00 (Prakash and Basavanna 1969, 165-175). If the soil contains more than twice the amount of silica than alumina, it is non-lateritic.

Because laterite is the end product in a breakdown process, its weight and volume is always less than that of parent rocks, plinthite or immature laterite, but the porosity is significantly greater. This is because during the process of laterization, fine-grained constituents are removed from the parent materials and only particles agglutinated by iron oxide remain. This is especially true under alkaline conditions (pH much greater than 7) where silica becomes more soluble and is rapidly leached out leaving a high concentration of iron and aluminium compounds in the resulting materials. After laterization, therefore, the amount of iron and aluminium oxide is considerably increased while that of silica (whose weight and volume are greater than iron or aluminium oxide) appreciably decreases resulting in the significant reduction of weight and volume. Since only coarse iron oxide-agglutinated particles remain, large pores and voids exist between grains leading to the large porosity of laterite mentioned above.

Mechanical properties

As far as my research has reviewed, there is no study on the mechanical properties of ancient laterite. Some researchers studied the mechanical properties of laterite as if it was a soil and therefore apply tests usually applied to characterise the properties of soil. Some research reviewed such property of laterite when used as gravels in road construction which is not relevant to the study of laterite when used as blocks in dry masonry in Khmer architecture. Since the focus to this thesis is to mainly study of laterite used as a building material, the mechanical properties of laterite, compressive strength in particular, will be investigated and discussed thoroughly in Chapter VI of this thesis.

2.2 *Summary*

Laterite is a natural material found in tropical countries around the world. It is the product of the chemical, and possibly physical, weathering of parent igneous or sedimentary iron- and aluminium-rich rocks, such as granite and ferruginous sandstone, through a process called laterization. The information about laterite properties obtained from the literature review can be summarized briefly as follows:

1) Iron compounds in laterite are derived either from the weathering rock *in situ* or can be transported from other remote iron-rich areas.
2) Therefore, it is widely acceptable to classify laterites into two main groups—Primary and Secondary. Primary laterite is generally formed *in situ*, while secondary laterite is formed by alluvium or colluvium whereby iron compounds transported by groundwater or surface drainage.
3) Laterization is the process of the weathering of parent rocks to form lateritic soils and the hardening of lateritic soils to form laterite.
4) The rate and degree of laterization depends on a suitable environment with the following factors: a semi-humid or humid tropical climate; fluctuations of the groundwater table; a flat or nearly flat land surface located above sea level; and a long period of time for the leaching of parent iron-rich rocks
5) Through laterization during wet seasons in a tropical climate, silica and earth alkalis in the rocks are leached out, leaving a concentration of ferric oxides or hydroxides with certain amounts of alumina and solid hard crusts including quartz grains cemented by iron compounds.
6) Laterite, lateritic soil indeed, hardens when it is exposed to the environment for a period of time.
7) The process of hardening involves a reduction in the moisture content in the soil and the oxidation of iron compounds in laterite simultaneously. Therefore, oxygen supply and dry conditions are required. Not only are aggregates cemented with iron oxide, but kaolin and quartz in voids that have already been leached out are also replaced by goethite (Sinsakul nd.).

8) The classification of the physical appearance of laterite is usually based on its pore structure, texture and forms. However, the division of laterite into two groups—slag-like cellular laterite and pisolitic laterite—is the simplest way. Within pisolitic group, laterite can be subdivided into pisolitic and oolitic laterite depending on its aggregates' size.
9) Laterite is mainly composed of iron oxide and aluminium oxide, possibly with the presence of silica as quartz grains.
10) Iron oxide in laterite is usually in the forms of haematite (Fe_2O_3) and sometimes goethite ($Fe_2O_3 . H_2O$).
11) Aluminium oxide in laterite is usually in the forms of bauxite ($Al_2O_3 .nH_2O$) and sometimes gibbsite ($Al_2O_3 .H_2O$).
12) Some scholars use the ratio of silica to sesquioxides (ferric oxide and aluminium dioxide) of less than 1.33 to differentiate laterite from lateritic soils (1.33-2.00).
13) Another difference between laterite and lateritic soils is that the former hardens chemically and irreversibly.
14) Laterite contains very little organic materials.
15) Laterite is usually in the range of red in colour. This colour derives from the richness of its iron oxide.

Although the research that has been reviewed in this chapter can provide useful information as an introduction to laterite, it focuses only on the properties of laterite as lateritic soil or immature laterite rather than studying mature laterite when it is used as a building material and following-up its decay mechanisms. None of this research discusses the mechanical strength of mature laterite, for example. Therefore, in order to answer the questions of the thesis, from the next chapter onward, I myself will investigate and characterise the properties and decay mechanisms of ancient (mature) laterite that was used in Khmer building construction. The analysis and discussion of the characterization and decay mechanisms of mature laterite will then be in deeper detail and provide a basis for decision making in the conservation of ancient laterite.

CHAPTER III

THE EFFICACY OF STANDARD TESTS FOR THE CHARACTERIZATION OF LATERITE

The characterization of a material involves the study of that material in order to identify and describe its distinctive properties and thereafter to apply the results to categorise such material and to use it suitably according to its properties. Although several scholars and researchers (Little 1969; Nichol 2000; Sinsakul nd; Persons 1970; Pendleton and Shanasuvana 1946; and so on) have studied the properties of laterite around the world, only few of them have discussed the properties of laterite after having been used in building construction for a long period—they only focussed on laterite in the ground or laterite used for road construction. Amongst the properties of materials used in building construction, strength for withstanding loads is one of the most important, but laterite has hardly been studied for this quality. The aim of this thesis is to study the laterite used in Khmer architecture in Thailand thoroughly and one of the questions raised in this thesis is whether laterite is suitable to be used as a building material; therefore, to explore this question fully, laterite in Thailand needs to be studied thoroughly, especially with regard to its structural strength. The earliest stage of research for this thesis requires the selection of appropriate tests for such characterization and an ensuring pilot study to distinguish inherent properties from those resulting from extrinsic factors, in particular environmental factors.

In this chapter, the process of selection of tests for characterising laterite is discussed followed by a programme for analysing the characteristics of selected laterite samples collected from various Khmer architecture sites in Thailand. Data collected from these tests will then be analysed and discussed. The characterised properties of selected laterite and previously studied sandstone are also compared as a preliminary study. Lastly, the effectiveness of the selected tests and their necessity and suitability for characterising laterite are evaluated. However, it is to be noted that the purpose of this chapter is only to evaluate the efficacy of selected standard tests for the characterization of laterite in order to select the effective tests to be carried out in Chapter VI.

3.1. A pilot testing programme for laterite characterization

As previously discussed, laterites are products of the decomposition of rocks that contain minerals of different degrees of weathering. Once lateritic soils laterise or fresh laterites become mature, they display stone-like behaviour because of their irreversible self-hardening property. As a result, despite laterite being derived from soil, general soil classifications and tests, which generally consider the soil particle size distribution and the liquid-plastic limit of soils, such as Atterberg Limits and California Bearing Ratio, are not applicable to classify laterite because soil tests assume a granular semi-cohesive material, while laterite is a porous solid. In addition, such tests are inadequate for predicting the particular engineering properties of laterites, ancient laterite in particular, especially for predicting the short- and long-term behaviour of laterites undergoing repetitive loading.

Because laterite hardens and has stone-like properties after having been exposed to the air for a period, tests for characterising stone recommended by international organization such as the American Society for Testing Materials (ASTM), the Italian NORMAL (Normativa Manufatti Lapidei) committee and the RILEM (International Union of Testing and Research Laboratories) committee are more appropriate.

It is to be noted that this thesis is a research continued from my Master's thesis studying sandstone used in Khmer architecture (Watsantachad 2001); therefore, the tests for the characterization of such sandstone will be first selected as a pilot testing programme in this thesis in order to compare the preliminary results obtained from this pilot testing programme with the characteristics of the studied sandstone. Thus, the determination of tests selected in my previous thesis is here reviewed again.

3.1.1. Determination of tests to be applied

The characterization and analysis of building stone enables an understanding of the physical, chemical and mechanical properties of the material (as well as its mechanisms of deterioration and the assessment of its deteriorated condition which will be discussed in Chapter V). In order to select testing protocols, previous research and testing standards will be reviewed and summarized. This summary will provide general information about the important properties as well as decay mechanisms that should be tested, and offer several tests that have been successfully applied for stone performance evaluations. Availability of the testing equipment was also taken into account when selecting a pilot testing programme for my previous and this thesis.

The articles reviewed were selected from the most recent books and proceedings of the International Congress on Deterioration and Conservation of Stone available in the library of University of Pennsylvania in 2000-2001 (see Table 3.1 and the list of literature in Appendix II) with a condition that the selected articles had to study sandstone, and other types of stone if possible. The review of thirty articles on stone testing and assessment showed that not every research programme identified and tested all the physical, chemical and mechanical characteristics including mineralogical and petrographic properties of the stone type under investigation. Rather, the choice of tests depended on the researchers' purposes. In terms of physical properties, researchers most often tested for water absorption and porosity (both 60%) and mineralogy (50%) as well as colour and petrography (both 33.3%) of stone. All the thirty articles reviewed characterised the physical properties of stone. Eighteen of the articles studied water absorption and seventeen articles referred to the characterization of the stone porosity. Fifteen articles characterised mineralogy and ten articles studied on the colour and petrography.

Table 3.1: Summary of literature review

* This table is adapted from Apendix IV in the author's Master thesis (Watsantachad 2001, 168). The list of the reviewed literature can be found in Appendix II

Ref No	Year	Author	Country	Material	Subject of Study																																																																																							
					Physical																																						Chemical				Mechanical					Decay Mechanism																																
					Colour						Hardness			Porosity						Pore Distrb		Permea		Water Absorption						Dil'n		Density				Mineralogy					Petrography			Mcr. Str	Thermal Expans												Salt Identification									Deterioration Condition									Moist Cont'			Air Flow		Weathering Resistance									
					Photospectroscopy	Munsell System	FT-IR	XRD	PLM	Not Mentioned	Scratching	Drilling Resistance	Penetrometry	Mercury Porosimetry	Calculation	Standard Test	SEM	Optical Microscopy	Not Mentioned	Mercury Porosimetry	Not Mentioned	Nuclear Magnetic Resonance	Water Vapor Transmission	Total Immersion	Capillary Action	Water Drop Absorption	Water Evaporation	Water Penetration (Rilem Tube)	Not Mentioned	Standard Test	Not Mentioned	Helium Pycnometer	Ultrasound	Standard Test	Not Mentioned	XRD	SEM	PLM	AAS	Not Mentioned	Thermo Mechanical Analysis	PLM	Not Mentioned	SEM-EDS	Thermal Gravimetry	Not Mentioned	Other	FT-IR	SEM-EDS	XRD	Not Mentioned	Compressive Strength Test	Tensile Strength Test	Flexural Strength Test	Linear Strain Claculation	Young Modulus Calculatin	XRD	FT-IR	DTA-TGA	Qualitative Anlysis	Solubility	Titration	Photometry	Others (AAS, IC, Calcimetry, etc.)	Not Mentioned	Visual Observation	XRD	SEM	Biaxial Flexural Strength	Ultrasonic Velocity	Schmidt Hammer	Drilling Resistance	FT-IR	Not Mentioned	Thermocouple&Moisture Sensor	Microwave	Not Mentioned	Schonlin -Apparatus	Not Mentioned	Artificial Aging (Not Specified)	Natural Weathering	Salt Crystallization	Acid Rain/ Atmospheric Gas	Ozmeter Aging	UV Radiation Weathering	Secreted by Lichen	Wet-Dry Cycling	Freeze-Thaw Cycling	Abrasive Resistance
9.1P135	2000	Matovic	Yg	Fresh Sandstone						*									*		*								*						*				*																		*									*																								
9.1P181	2000	Sahlin	Swd	Siliceous Sandstone											*										DIN 52123-A							DIN 52102-RE.VA								*							*							DIN 52112-A																										*											CEN TC246/WI014
				Calcereous Limestone																																														DIN52105																																									
9.2P3	2000	Baccaro	Ita	Sandstone																																*						*		*				*	*									*						*																											
				Limestone																																																																																					
				Cement Mortar																																																																																					
				Efflorescence																																																																																					
9.2P361	2000	Leroux	Fr	Sandstone															*																																*																																						
			Ger	Limestone																																																																																						
			Port	Marble																																																																																						
			Ita	Siliceous Chalk																																																																																						
9.2P395	2000	Mazova	Cze	Sandstone						*																														*			*																																															20	
				Spongolite																																																																																				
				Traventine																																																																																							
9.2P413	2000	O'Corner	Aus	Siliceous Sandstone	*																	*											*							*	*				*			*				*																														*	*								
9.2P513	2000	Twilley	USA	Micaceous Sandstone			*	*	*							RL1972												RL1972						RL'72		*	*	*				*						*		*							*										*	*					*																	
9.2P561	2000	Messori	Ita	Stone & Plaster							*		*	*										*		*																																*	*	*		*			*																										
9.2P765	2000	Wendler	Tha	Clay Rich Sandstone								*													*				*		*															*								*		*								*				*	*			*			*												*		
	1999	Lotzmann	USA	Sandstone															*																							*																																*																		
	1999	Pleyers	USA	Sandstone																								*																																																																		
7P1033	1992	Wheeler	USA	Siliceous Sandstone						*									*		*																																	ASTM C674																																			*				
				Calcitic Limestone																																																																																					
7P1073	1992	Valdeon	Spn	Dolomite															*					NM7/81	RL/NM		NM7/81													*			*																																																			
				Limestone																																																																																					
				Sandstone																																																																																					
7P1083	1992	Baronio	Ita	Sandstone																					*				*											*			*				*					*		*	*																													80					*	50	
				Soft-mud Brick																																																																																						
				Lime Putty Mortar																																																																																						
7P1103	1992	Wendler	Ger	Clay Rich Sandstone								*													*			*		*																							*									*	*	*														*											
7P1113	1992	White	Bel	Sandstone															*						*																																																								*		*	*	*		*		42	*
7P1231	1992	Moropoulou	Grc	Calcereous Sandstone				*	*					*						*			*	*																			*								*	*																																	*							
7P1327	1992	Calatayud	Spn	Calcereous Sandstone		*																																		*			*																																													10					20		
7P1335	1992	Santamaria	Spn	Calcereous Sandstone				*	*					*																						*																																							*								15					20		
7P1343	1992	Rizzi	Ita	Calcereous Sandstone		*																																																																																				
6P86	1988	Theoulakis	Grc	Sandstone																								RL						RL		*	*	*	*																							*									*									*		*	*									
6P236	1988	Fitzner	Ger	Sandstone										*			*	*						*																																																												*						*	
6P330	1988	Alessandrini	Ita	Sandstone		*								*										*	*		*									*		*						*																							*																*	6h		*			260	
				Limestone																																																																																					
				Marble																																																																																					
6P356	1988	Heiman	Aus	Sandstone										*									*						*							*	*													*	*		*	*	*																	*	*											*							
6P367	1988	Derkowska	Pol	Sandstone																																									*																																*												
				Limestone																																																																																				
				Mortar																																																																																					
				Brick																																																																																					
				Wood																																																																																					
6P466	1988	Cabalova	Czec	Sandstone															*										*						*			*				*									*	*																																			*						
6P524	1988	Aussel	Fr	Stone															*																*																																																								
6P563	1988	Domaslowski	Pol	Sandstone																					*																												*		*																																								
				Limestone																																																																																					
6P712	1988	Hauff	Ger	Sandstone										*									*													*		*																*																																							
	1983	Furlan	Swz	Calcereous Sandstone										*										*																				*								*	*	*	*																																								
				Note 1	1	3	1	3	3	3	1	2	1	8	1	1	1	1	8	1	2	1	3	6	8	1	2	4	5	1	1	1	1	2	3	7	3	5	1	7	1	3	6	3	2	1	2	3	2	2	2	9	3	8	2	1	3	2	1	1	1	1	1	4	1	1	1	3	1	1	1	2	1	1	1	1	2	1	1	3	1	8	3	1	2	1	4	5	2
				Note 2	10						3			18						3		4		18						2		7				15					10			3	3		2	5				14					8									7									4			2		15									
				Note 3	10.0	30.0	10.0	30.0	30.0	30.0	33.3	66.7	33.3	44.4	5.6	5.6	5.6	5.6	44.4	33.3	66.7	25.0	75.0	33.3	44.4	5.6	11.1	22.2	27.8	50.0	50.0	14.3	28.6	28.6	42.9	46.7	20.0	33.3	6.7	46.7	10.0	30.0	60.0	100.0	66.7	33.3	100.0	60.0	40.0	40.0	40.0	64.3	21.4	57.1	14.3	21.4	37.5	25.0	12.5	12.5	12.5	12.5	12.5	50.0	12.5	14.3	14.3	42.9	14.3	14.3	14.3	28.6	14.3	14.3	25.0	25.0	50.0	50.0	50.0	20.0	6.7	53.3	20.0	6.7	13.3	6.7	26.7	33.3	13.3
				Note 4	30																																												5				14					22																																				
				Note 5	33.3						10.0			60.0						10.0		13.3		60.0						6.7		23.3				50.0					33.3			10.0	10.0		6.7										36.4										31.8								18.2			9.1		68.2									
				Note 6	30																																																																																							
				Note 7	33.3						10.0			60.0						10.0		13.3		60.0						6.7		23.3				50.0					33.3			10.0	10.0		6.7	16.7				46.7					26.7										23.3								13.3			6.7		50									

Note 1 : **Number of article mentioning**
Note 2 : **Total No.of article mentioning**
Note 3 : **% of method mentioned within mentioning articles**
Note 4 : **Total of articles mentioning**
Note 5 : **% of article mentioning in each subject**
Note 6 : **Total of articles reviewed**
Note 7 : **% of property mentioned in all articles**

In addition, international researchers also studied the chemical compositions and the mechanical properties of stone. From fourteen articles that referred to the mechanical strength of stone, the two mechanical properties that were studied the most frequently are compressive and flexural strength. Nine of the articles (64.3%) measured the compressive strength while eight of them (57.1%) measured the flexural strength of the studied materials (see Table 3.1).

In considering the decay mechanisms of stone (which will be discussed in detail and tested in Chapters IV and V), the weathering resistance capacity was the most popular test applied to fresh or untreated weathered or non-weathered stone. Fifteen out of twenty-two articles (68.2%) applied artificial weathering conditions to investigate effects of the weathering agents on the studied materials. Additionally, eight of the thirteen articles that studied decay mechanisms (61.5%) identified salts in the studied materials while seven articles (53.8%) investigated the conditions of material deterioration. When all the reviewed articles are considered, 50% of the articles tested the weathering resistance of materials, 26.7% focused on the identification of salt contents and 23.3% studied the condition of material deterioration (see Table 3.1).

Different methods and tools were applied by the various researchers to investigate these properties. For testing the water absorption by capillary action (44.4% of all research into water absorption) and by total immersion (33.3% of them) were the most utilized methods to measure the water absorption capacity of stone. The most popular method for measuring the porosity of stone is mercury porosimetry, used in eight of the thirty reviewed articles (26.7%). X-ray diffraction and polarized light microscopy were the most frequently methods for analysing the mineralogical composition of the stone (46.7% and 33.3% of the reviewed articles that carried out the mineral analyses applied these methods). To identify the colour of stone, 30% of the reviewed articles that identified the colour of studied materials applied at least one of these tools—Munsell Colour Chart, X-ray diffractometer and polarised light microscope. For petrographic identification, most of the researchers did not name the tools or methods used in their research while only three of ten researchers stated that they used polarised light microscopes. In order to evaluate the mechanical strength of stone, tests were made mostly following the standard tests recommended by DIN or ASTM. (See Table 3.1)

In order to determine the appropriate tests for my pilot testing programme, account was taken not only of this summary of the literature, but also other of researchers' suggestions and some recommendations from many standard sources, including RILEM, NORMAL and ASTM. NORMAL 16/84 recommends optical examination, thin section analysis and scanning electron microscopy to determine mineralogy, petrography and deterioration morphology. NORMAL 20/85 recommends some tests for change in weight and colour, water vapour permeability, depth of penetration, hydric dilatation and ultrasonic and/or sonic velocity for instance. It also specifies some artificial weathering tests that should be able to simulate the environmental conditions to which the stone is exposed, including the cycles of acid rain or mist, wet-dry, freeze-thaw, salt crystallization, thermal expansion, salt spray and ultraviolet radiation. The combination of two or three of these tests is recommended.

The international RILEM 25 P.E.M. Committee proposes structure-defining (or characterization) tests: porosity accessible to water, bulk and real densities, vapour permeability and pore size distribution by suction and mercury porosimetry analysis (RILEM). It suggests that some water effects in stone should be analysed: movement of water including the coefficients of saturation and water vapour conductivity; the coefficients of water absorption under low pressure and water absorption; linear strain due to water absorption; and water drop absorption. This standard also recommends the tests for compressive, tensile and bending strength, modulus of elasticity, adhesion strength, surface hardness and abrasive resistance. The durability of the stone can be tested with artificially or naturally weathered aging. Lastly, in this standard, miscellaneous tests, such as the external aspect of the stone, the sampling method, thermal expansion and electrical conductivity, are also recommended.

The American Society for Testing Materials provides various standard tests for testing the properties of stone and other materials. They publish books containing updated standard tests for materials every year. For instance, to calculate the porosity of stone, they recommend a standard test, ASTM C97, while they recommend ASTM E96 to test the permeability of stone. ASTM C99 and C170 are recommended to measure the mechanical strength of stone or other porous materials.

Selection of the pilot tests

Since this thesis is concerned with an understanding of the physical and mechanical properties of laterite as an ancient building material, particularly when used in conjunction with sandstone, it seemed important to understand its compressive and flexural strength and how far these were determined by physical structure (in particular porosity and its effect on water absorption and permeability) and chemical composition. It was important to correlate the attributes of physical and chemical structure with mechanical performance and to see whether laterite that had been recently quarried differed in its properties from that which had been exposed for several centuries in archaeological contexts.

A brief summary of the review of the various methods employed by other researchers in the field of stone testing and assessment is given in Table 3.2. In devising my own series of tests, account was taken not only of the effectiveness of the previous work, but also of the expense and the availability of specialist equipment. For instance, although XRD is considerably effective to characterise the mineralogy and chemistry as well as the colour of stone, it was expensive and unavailable at the time of the test being carried out. Another example was to apply the Munsell soil colour chart to identify the colour of laterite. It is the cheapest and easiest method if compared with other instrumental methods. The soil colour chart is also more suitable to be used with laterite than other stone colour charts because laterite, derived from soils, has colours closer to soils than to stone. In addition, as previously stated, since one of the purposes of carrying out the tests is to compare the properties of laterite with those of sandstone used in Khmer architecture in Thailand which were tested in 2001 (Watsantachad 2001, 30-43), the same standard tests, mostly recommended by ASTM, which were applied to test such sandstone, were applied again for testing laterite, if applicable. The pilot testing programme to be carried out in this chapter is summarised in Table 3.3.

Table 3.2: Summary of tests for characterization of laterite

Tested Properties	**Tested area**	**Applied test**	**Advantages**	**Disadvantages**
Mineral/ chemical composition	Stone sample	X-ray diffraction (XRD)	- Able to characterise the stone including chemical composition and particular minerals	- Expensive method - Unable to identify any mineral or compound that constitutes less than 10% of the stone - Takes time to prepare the mounting sample, and also to obtain the result
Mineral/ chemical composition	Stone sample	Infrared spectrometry	- Able to identify and quantify organic and some inorganic elements in the stone - Quick sample preparation	- Expensive - Unable to identify compounds that have the same component or organic matrix - Unable to identify most mineral oxides and sulphides
Chemical composition	Stone sample	Wet chemical analysis	- Able to analyse chemical composition of the stone quantitatively	- Needs experienced analysts
Micro structure/ Mineral composition	Stone sample	Optical Microscopy	- Able to obtain both information about the stone microstructure and composition and the surface alterations	- Destructive - It takes time to obtain the data due to vacuum impregnation of the sample before being prepared into thin sections
Morphology/ Chemical composition	Stone sample	SEM-EDS	- Able to simultaneously investigate the morphology and chemical composition of the stone	- Very small observed area - Unable to obtain the data quantitatively
Mineralogical composition	Stone sample	UV-fluorescence	- Rapid, inexpensive and readily available analytical tool for the stone weathering, minerals and salts identification	- Unable to differentiate colours between the fluorescence and the intensities of reagent grade crystalline powders of some salts.

Table 3.2: Summary of tests for characterization of laterite (continued)

Tested Properties	Tested area	Applied test	Advantage	Disadvantage
Colour	Surface	Observation based on the Munsell System	- Useful to quantify visual impressions - Used as reference values for later assessment	- Subjective
Compressive Strength	Stone cube	Compressive strength test	- Useful to indicate the differences in compressive strength between various sized stones and/or between examples of the same type of stone - Able to quantify compressive strength values in different stone conditions	- Expensive - Unable to test in situ - Destructive due to the large number of samples tested
Flexural Strength	Stone cube	Three point bending test	- Useful to indicate the differences in modulus of rupture between various sized stones and/or between examples of the same type of stone - Able to quantify flexural strength values in different stone conditions	- Expensive - Unable to test in situ - Destructive due to a large amount of required sample - Product's individual variations may cause deviation from the accepted values

Table 3.2: Summary of tests for characterization of laterite (continued)

Properties	**Tested area**	**Applied test**	**Advantage**	**Disadvantage**
Water absorption	Stone sample	Water absorption test with RILEM Tube or Water (micro) Drop Absorption	- Easy to test either in situ or in the laboratory	- Possible to have multiple errors due to the interruption of absorption process or ineffective elimination of adhering water or unstable environmental conditions
	Stone sample	Water absorption by total immersion	- Useful to analyse stone's water absorption capacity - The result obtained can be useful for calculating stone's porosity - Simple and cheap	- Unable to qualify pore size and distribution
	Stone sample	Water absorption through capillary uptake	- Useful to analyse stone's ability to draw water into its pores and the highest level to which water can be drawn - Simple and cheap	- Not mentioned in the reviewed articles
Porosity	Stone sample	Calculation from water absorption result	- Simple - Useful to quantify the percentage of stone porosity	- Possible to have inaccurate result due to error in the immersion test
	Stone sample	Mercury Porosimetry	- Useful to identify and quantify the percentage of stone porosity and pore distribution	- Expensive
Water permeability	Stone sample	Water vapour transmission test	- Useful to determine the vapour transmission capacity of the stone	- May have some error data due to unstable environmental conditions

Table 3.3: Summary of tests applied in this research for characterising laterite properties

Property to be tested	**Test/method to be adapted/applied**	**Required sample**
Mineral composition	Transmitted-light microscopy	Thin section slides
Chemical composition	Wet chemical analysis	200 grams of sample
	SEM-EDS	Small pieces of sample
Colour	Munsell colour chart	Randomly selected sample
Porosity	ASTM C97: Standard test methods for absorption and bulk specific gravity of dimension stone	Five 2x2-inch cube (about 5x5-centimetre)
Water absorption	ASTM C97 and NORMAL 7/81: Water absorption by total immersion	Five 2x2-inch cube (about 5x5-centimetre)
	Ex.10-Teutonico and NORMAL 11/85: Water absorption through capillary uptake test	Five 2x2-inch cube (about 5x5-centimetre)
Water permeability	ASTM E96: Standard test methods for water vapour transmission of materials	Three 3 7/8" diameter and 1"- thick cylinders (about 10-centimetre diameter and 2.5-centimetre thick) and one same-size cylinder as a dummy
Compressive strength	ASTM C170: Compressive strength test	Five 2x2-inch cube (about 5x5-centimetre)
Flexural strength	ASTM C99: Standard test methods for modulus of rapture of dimension stone	Five 4x8x2¼-inch bar (about 10x20x5.5-centimetre)

3.1.2. Locations of selected sites

In order to study laterite used in Khmer architecture in Thailand, laterite samples collected from four different locations (three ancient sites and one freshly quarried) were tested and investigated. The freshly quarried matarial was tested in order to preliminarily compare its characteristics and properties with those of ancient laterite so that changes occurring in laterite after a long period of exposure to the elements could be examined. At this stage, the criteria of site selection were the accessibility of the site and the availability of samples to be collected in the site. Since most Khmer monuments in Thailand are located in the Northeast, two provinces of this region were selected; the Nakhon Ratchasima and the Roi Et Provinces with a permission of the Fine Arts Department in Thailand to access to the sites (see Map 3.1 on page 116). The availability of samples in the site means that the site had broken laterite blocks unable to be reused in restoration and the blocks were to be collected easily. With this criterion, three laterite complexes, the *Ku Pone Rakang* and *Ku Kantanam* complexes in Roi Et, and the *Prang Ban Prang* complex in Nakhon Ratchasima, were selected (see Figure 3.1 on page 160). A criterion of selecting fresh laterite was that the laterite came from the same region as the ancient one. However, freshly quarried laterite from the Sa Kaew Province in the East of Thailand was finally collected because of its availability. Therefore, the fresh laterite was sourced as close to the study area as possible but was not within the region of the study sites.

In the Roi Et Province, the *Ku Pone Rakang* complex was the selected site (see Figure 3.1a). It was used as an *arogayasala* (a hospital), during the reign of Jayavarman VII. It is located in the Ban Kukasing Village in the Kasetvisai District. ('Ban' in Thai means a village.) From its remains, Ku Pone Rakang was categorized as belonging to the Bayon artistic style and the Post-Angkorian architectural style dedicated to Mahayana Buddhism dated around the thirteenth century AD. Its chief building material is laterite, with some sandstone and brick used as structural elements. Conforming to the typical plan of an arogayasala, the complex is composed of a main sanctuary surrounded by a boundary wall with a gopura or entrance tower to the east. Within the boundary, there is a banalaya (library) located to the southeast and a laterite square pond to the northeast of the sanctuary. At present, the condition of this site is critical. Most of the monuments in the complex have collapsed and are covered by soil and trees (mainly *Urticaceae*) and evidence of looting is obvious in the main sanctuary. Despite being exposed to the environment for eight hundred years, laterite blocks that remain at this site are still in a sound condition. Although the complex has been excavated and laterite and stone blocks have been numbered and removed from the position in which they originally fell, only broken laterite blocks with unknown provenance were selected for these tests in order to avoid using any ancient material that could be re-used. The same method was applied to the other selected sites. The samples collected from this site were numbered as Sample 1.

The second site in the Roi Et Province is the *Ku Kantanam* complex located in the Ban Ku Kantanam Village in the Pone Sai District (see Figure 3.1b). Built of laterite in the thirteenth century, it was also used as a hospital in the reign of Jayavarman VII comprising all architectural elements needed in this type of architecture. However, laterite of this site is in a sound condition. The samples collected from this site were numbered as Sample 2.

The selected site in the Nakhon Ratchasima Province is the *Prang Ban Prang* complex (see Figure 3.1c). It is located in the Ban Prang Village within the Huay Talang District. Built in the reign of Jayavarman VII about the thirteenth century, it was used as a hospital like the two other sites and it therefore is of a similar layout and size. The current condition is sound, but only a few architectural parts remain. There are no trees remaining in the area of the complex. Laterite samples collected from this complex seemed to be in a better condition than the other two sites, and they were numbered as Sample 3.

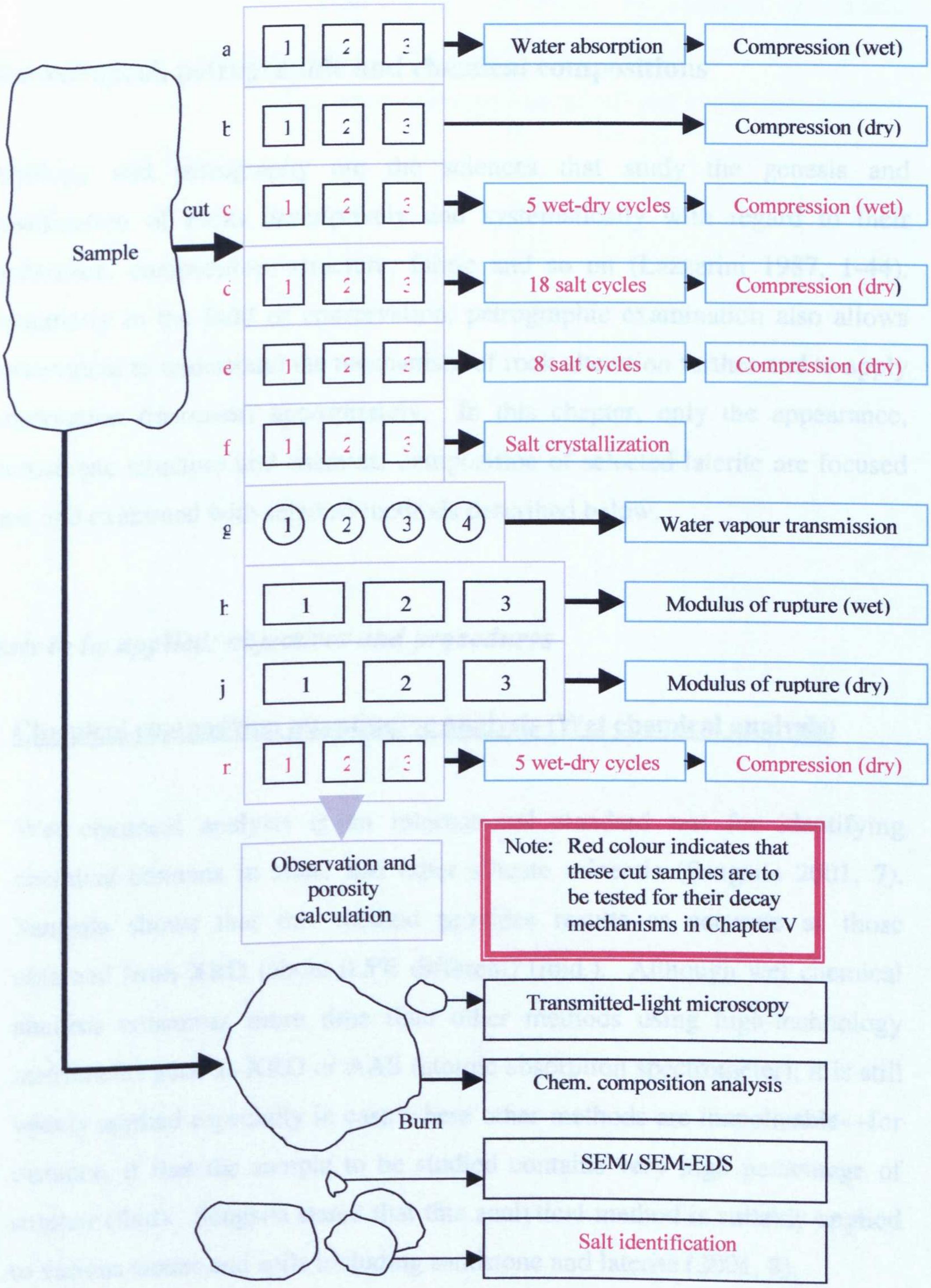
Finally, newly quarried laterite samples to be tested were collected from a quarry in the Sa Kaew Province. They had been exposed to the air for two months before being cut. Noticeably, their pores and large voids are filled naturally with a packed clay-like material (while sand-like or loose clay-like material fills the voids of laterite collected from the ancient sites). The fresh laterite samples were labelled as Sample 4.

Map 3.1: Map of Thailand
(http://www.infoplease.com/atlas/country/thailand.html)

3.1.3. Sample preparation

Regarding the sample preparation process, all laterite samples were cut into shapes according to the requirement of each standard test. (The details of each test are discussed below.). A stone cutting machine with a twelve-inch diamond disc water-cooled blade was used. After being cut, the samples were briefly washed to eliminate any surface soil wash and then oven-dried completely at 60°C before being tested for their porosity measurement. (The recommendation of NORMAL 7/81, the test for water absorption, suggests drying and weighing the sample until two successive weighings carried out after 24 hours in time do not vary more than 0.1 % of the sample weight.). All cut samples were then tested for their percentage of porosity with a total immersion test. The rest of laterite samples were sent to the Division of Mineral Resources in Thailand for their petrographic analyses (see Diagram 3.1 for the graphical explanation of the sample preparation).

Diagram 3.1: Each sample preparation for the pilot tests in this chapter
(To be noted that the samples to be tested for decay effects in Chapter V were prepared simultaneously with the samples for the tests in this chapter, but the selection of such tests will be discussed in Chapter V)



3.2. Properties of laterite to be characterised

3.2.1. Mineralogical, petrographic and chemical compositions

Petrology and petrography are the sciences that study the genesis and classification of rocks descriptively and systematically with regard to their appearance, composition, structure, fabric and so on (Lazzarini 1987, 1-44). Particularly in the field of conservation, petrographic examination also allows conservators to understand the mechanism of rock alteration further and to apply conservation treatments appropriately. In this chapter, only the appearance, microscopic structure and chemical composition of selected laterite are focused upon and examined with selected methods described below.

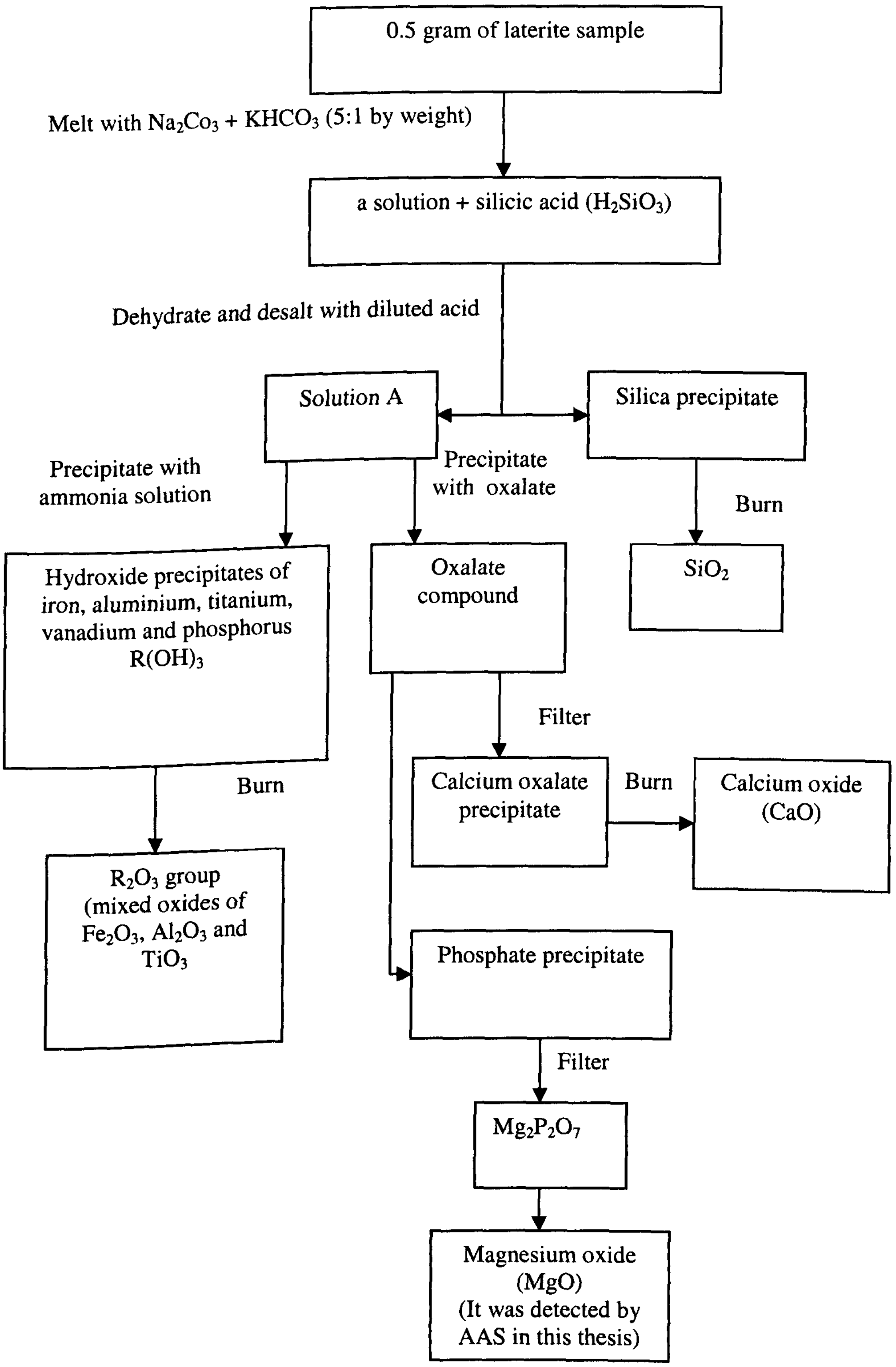
Tests to be applied: objectives and procedures

1) **Chemical composition quantitative analysis (Wet chemical analysis)**

Wet chemical analysis is an international standard test for identifying chemical contents in stone and other silicate minerals (Sangsila 2001, 7). Sangsila shows that this method provides results as accurate as those obtained from XRD (about 0.5% different) (ibid.). Although wet chemical analysis consumes more time than other methods using high-technology instruments such as XRD or AAS (atomic absorption spectrometer), it is still widely applied especially in case where other methods are inapplicable—for instance, if that the sample to be studied contains very high percentage of sulphur (ibid). Sangsila stated that this analytical method is suitably applied to various stones and soils including sandstone and laterite (2001, 8).

To analyse the chemical compositions of selected laterite, 200 grams of each sample were sent to the Department of Mineral Resource in Thailand and sampled systematically to obtain 0.1-0.3 gram for testing. The procedure of the wet chemical analysis of ferric oxide, aluminium oxide, titanium dioxide, calcium oxide and manganese oxide is displayed briefly in Diagram 3.2. (However, it is to be noted that in this thesis the Division of Mineral Resource detected potassium oxide, sodium oxide and manganese oxide with AAS (Atomic Absorption Spectroscopy) instead of using the wet chemical analysis method.)

Diagram 3.2: Procedure of wet chemical analysis (adapted from the description of Sangsila 2001, 9-10)



2) Transmitted- and polarised-light microscopy

Polarised light microscopy (PLM) is generally the most useful and economically feasible examination method for conservators (Palenik (unpublished) cited by Watsantachad 2001, 30). It is used to observe the optical characteristic properties of materials, including size, shape, surface, colour, transparency, refractive index, crystal system, and dispersion of the optic axial angle on a single particle. It can reveal almost any phase of a sample—whether in thin section, cross section or dispersed— and the image observed with the microscope can be identified by listing its characteristics, comparing with reference to a photo-micrographic atlas, or referring to a known sample (McCrone 1984, 1403).

To prepare samples for microscopy, the selected laterite samples were sent to the Division of Mineral Resources in Thailand to be made into thin sections. A 30 micron-thick standard thin section of each was mounted without blue dye saturation. Thereafter, transmitted polarised light microscopy, with a magnification of 4X, was used to observe the micromorphologic and physical characteristics of the laterites. This test was carried out by the microscopic team of the Division of Mineral Resources.

3) Scanning electron microscopy

Scanning electron microscopy (SEM) is used frequently to analyse the micro-textural and elemental composition of masonry materials. It can reveal some of the physical and chemical properties of the stone, including the size, orientation and arrangement of its composite minerals and pores, and deposition of any new material (e.g. consolidants). Due to a very small amount of sample required, SEM can be considered as a non-destructive method that helps us to understand decay mechanisms. It can show the alterations of the mineral composition, the widening of pore spaces and the loosening of particle binders that are the indicators of stone weathering. In order to supplement the SEM result, X-ray diffraction analysis is required to give a more accurate result of the mineralogical composition (Weber and Zinsmeister 1991, 20).

The samples analysed were small pieces of laterite and materials within laterite large pores. A scanning electron microscope, with 300, 500 and 3000 magnifications, in the Scientific and Technological Equipment Centre in Silpakorn University was used to observe the microstructure of the samples. SEM-EDS (scanning electron microscopy aided by energy dispersive X-ray analysis) was also be used to identify chemical compounds composed in each sample qualitatively.

4) Colour analysis with the Munsell colour system

The Munsell colour system is widely accepted as the most practical method for characterising stone colour. The system arranges the three attributes of colour—hue, chroma and value—into orderly scales of equal visual steps (Winkler 1994, 91). Hues in the Munsell system are divided into five principal colours—red (R), yellow (Y), green (G), blue (B) and purple (P); and they are subdivided into ten steps—1 to 10 from faintest to strongest. Chroma indicates the saturation of the colour scaling from /0 for a neutral grey to /14. Lastly, value indicates the degree of lightness or darkness of a colour in relation to a neutral grey scale ranging vertically from 0/, pure black, to 10/, pure white.

In this test, the Munsell soil colour chart was applied to analyse the colour of laterite samples under standard light conditions in Bangkok at one o'clock in the afternoon. The samples were washed to eliminate dust and debris and naturally dried before being analysed.

Result

Table 3.4: The percentage of chemical compounds in tested laterites

Sample	Chemical Compound (%)									Ratio	
	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	MnO	SiO_2:Al_2O_3	SiO_2:Fe_2O_3
1	45.68	2.31	39.12	0.00	0.22	0.04	<0.01	0.01	0.50	19.77	1.17
2	42.75	2.87	44.25	0.12	0.19	0.03	<0.01	0.06	0.14	14.90	0.97
3	27.80	12.65	46.02	0.00	0.17	0.06	<0.01	0.03	0.23	2.20	0.60
4	28.48	17.45	41.38	0.16	0.15	0.01	<0.01	0.06	0.26	1.63	0.69

Table 3.5: Mineral composition in tested laterites

Sample	Mineral					Grain			Quartz & voids
	Cement	Iron Oxide	Quartz	Feldspar	Others	Shape	Size	Sorting	
1	Fe_2O_3	y	y	a few		angular-subangular	0.05-0.3 mm	poor	>30%
2	Fe_2O_3	y	y	n		angular-subangular	0.03-0.3, 0.5-0.7 mm	poor	>25%
3	Fe_2O_3	y	y	n		angular-subangular	0.03-0.5 mm	poor	>25%
4	Fe_2O_3	y	y	n		angular-subangular	0.03-0.5, 0.7 mm	poor	>25%

Sample 1:

From the optical microscopic observation, the laterite sample 1 is composed of consolidated pisolites and greyish white sand grains as a pre-existing material in a wormhole cementation matrix. Within the cementation, several black mottles are present and some pores in size ranging from 0.5 to three millimetres can be observed. Wormholes or large voids are filled with pale brownish white material (expected to be clay). The overall colour of Sample 1 is strong brown (7.5YR-5/6) mottled with black.

From the chemical composition analysis carried out by the Department of Mineral Resources, the laterite sample no. 1 is mainly composed of 45.68% quartz and 39.12% ferric oxide, with some aluminium oxide (2.31%) and a few feldspar constituents. Microscopic analysis revealed the binding cement in this laterite to be iron oxides. Because of its quartz predominance, Sample 1 is siliceous laterite with the ratio of silicon dioxide to aluminium oxide of 19.77 and to ferric oxide of 1.17 and to sesquioxides of 1.10 (see Table 3.4).

From a transmitted-light microscopic observation of a thin section carried out and reported by the Division of Mineral Resources, the laterite appears poorly sorted (see Table 3.5). Quartz grains range from angular to sub-angular shape in the size of 0.05 to 0.3 millimetre with fairly poor packing. There are numbers of sub-rounded or sub-angular grains of ruin-quartz, particularly big grains. Pores also randomly exist with a visual porosity about greater than 30%. (The percentage of porosity is analysed in more detail in the porosity analysis section.) The colour of cementation ranges from brownish orange to brown. The brown cementation tends to appear in the area surrounding large quartz grains, while the brownish orange one is scattered regularly in other areas.

From the scattered electron images (SEI) taken by a scanning electron microscope (SEM), the grains of Sample 1 are bound fairly loosely by a cementing material with gaps (about five microns wide) between the solid cementation and the grains. Holes from the loss of grains can be observed, and their surface is level reflecting the smooth texture of the lost grains. A zoomed SEI shows that Sample 1 is moderately porous mainly consisting of pores larger than ten microns wide and a few pores smaller than five microns wide. From the EDS analysis, Sample 1 comprises iron, silica, aluminium, potassium, and titanium. (Although the EDS analysis is also quantitative, the chemical composition analysis provides a more accurate result. This is because the latter analyses the ground sample prepared from a systematic sampling method while the former only tests several tiny spots on small pieces of laterite. Therefore, only the qualitative result showing detected elements is taken into account.) The material filling the voids consists of not only the same main elements found in the solid part, but also a carbon element. Such carbon possibly came from microorganisms or other organic materials. Since there is no trace of tree roots or other organic materials except fungi, it can be concluded that this carbon is the result of fungi detection. There is no trace of potassium, titanium or calcium.

The absence of calcium confirms that the material is not calcium carbonate. From the element analysis together with the SEI, the filling material is possibly a clay.

Sample 2:

From the optical observation, Sample 2 consists of reddish brown pisolites in a wormhole cementation mass. Within the cementation, a few pores (less than those presenting in Sample 1) in the size ranging from 0.5 to five millimetre can be observed. Wormholes or large voids (greater than 0.5 millimetres wide) are filled with a pale brownish white material and sometimes with reddish orange powder. The overall colour of Sample 2 is reddish yellow (7.5YR-6/6).

Sample 2 is mainly composed of 42.75% quartz and 44.25% ferric oxide, with some aluminium oxide (2.87%). Like Sample 1, microscopic analysis revealed the binding cement in this laterite to be iron oxides. Sample 2 is siliceous ferruginous laterite because it comprises the most ferric oxide with a comparable amount of silicon dioxide. The ratios of silica to aluminium oxide, to ferric oxide and to sesquioxides are 14.90, 0.97 and 0.91 respectively (see Table 3.4).

According to the transmitted-light microscopic observation of a thin section carried out and reported by the Division of Mineral Resources, the laterite is poorly sorted (see Table 3.5). There are two different quartz grain sizes. One ranges from 0.03- to 0.3-millimetre wide and the other size ranges in diameter from 0.5 to 0.7 millimetre. All grains are angular or sub-angular with fair packing. A number of pores also randomly exist with a visual porosity greater than 25%. The colour of cementation is brownish orange.

From the SEI, the grains of Sample 2 are bound more tightly to the cementing material, compared to those of Sample 1. The grains are sub-angular to sub-rounded, but their texture is not as smooth as those of Sample 1. The SEI also shows that Sample 2 is less porous than Sample 1 and mainly consists of pores smaller than ten microns wide. However, when looked closely, such pores are not cylindrical but shallow and irregular. In addition, the other 3000x SEI shows the area where few pores are present. From the EDS analysis, similarly to Sample 1, Sample 2 is also composed of silica, iron, aluminium, potassium and titanium. Likewise, the material filling the voids consists of silica, iron, aluminium and carbon elements with the presence of fungi. This filling material is therefore possibly considered the same type as that of Sample 1.

Sample 3:

From the optical observation, Sample 3 consists of reddish brown pisolites and brownish orange pebbles in a wormhole cementation matrix. However, if compared with the others, the wormholes in Sample 3 present less frequently. In some areas, fine sand grains can be observed. Within the cementation, a few pores (less than those presenting in Sample 1 and 2) in the size ranging from 0.5 to two millimetres can be observed. Wormholes or large voids (greater than a 0.5-millimetre diameter) are also filled with pale brownish white material and sometimes with reddish or bright brownish orange powder. The overall colour of Sample 3 is strong brown (7.5YR-5/6)

According to the analysis report of the Department of Mineral Resources, Sample 3 is mainly composed of 46.02% ferric oxide, with less silicon dioxide (27.80%) and more aluminium oxide (12.65%), compared with the first two samples. There is no feldspar present. The binding cement in this laterite consists of iron oxides. Therefore, Sample 3 is obviously ferruginous laterite based on its main mineralogical composition. The ratios of silica oxide to aluminium oxide, to ferric oxide and to sesquioxides are 2.20, 0.60 and 0.47 respectively (see Table 3.4).

According to a transmitted-light microscopic observation of a thin section carried out and reported by the Department of Mineral Resources, the laterite number 3 is also poorly sorted (see Table 3.5). The size of its grains ranges from 0.03- to 0.5-millimetre. All grains are angular or sub-angular with fair packing and some of the big grains are ruin-quartz. A number of pores also randomly exist with a visual porosity greater than 25%. The colour of cementation is brown with some spots in reddish orange.

From the SEI, the grains of Sample 3 are bound excessively loosely to the cementing material, compared with the other samples. There are wide gaps around the grains. The grains are sub-angular to angular with fairly smooth texture. The SEI shows that Sample 3 is moderately porous, and from the 3000x image, most of the pores are larger than six microns and cylindrical in shape. From the EDS analysis, Sample 3 is composed of silica, iron, aluminium, titanium and manganese, but there is no presence of potassium. Similarly, the material filling the voids consists of silica, iron, aluminium and carbon elements with the presence of fungi. This filling material is therefore possibly considered the same type as that of Sample 1 and 2.

Sample 4:

From the optical observation, Sample 4 is in a form of cemented vesicular or wormhole mass with no consolidated pisolite present. Fine-grained sand can be observed. A few pores (less than those presenting in the others) in the size ranging from 0.5 to one millimetre exist. Wormholes or large vesicular voids (greater than a 0.5-millimetre diameter) are also filled with pale brownish or reddish brownish white material. The overall colour of Sample 4 is yellowish red (5YR-5/6).

Sample 4 is mainly composed of ferric oxide (41.38%), with some amount of silicon dioxide (28.48%) and aluminium oxide (17.45%). There is also feldspar present. The binding cement in Sample 4 is iron oxides. Like Sample 3, Sample 4 is obviously ferruginous laterite based on its predominant ferric oxide constituent. The ratios of silica oxide to aluminium oxide, to ferric oxide and to sesquioxides are 1.63, 0.69 and 0.48 respectively (see Table 3.4).

According to a transmitted-light microscopic observation of a thin section carried out and reported by the Department of Mineral Resources, the laterite of Sample 4 is also poorly sorted (see Table 3.5). The size of its grains ranges from 0.03 to 0.5 millimetre. All grains are angular or sub-angular with fair packing, and appreciably blended with ferric oxide—in a higher degree than those of the others. A numbers of pores also randomly exist with a visual porosity about greater than 25%. The colour of cementation is brownish orange.

From the SEI, the grains of Sample 4 are bound more tightly to the cementing material with a narrower gap around them, compared with those of Sample 1. The grains are sub-angular, but their texture cannot be identified since the cementing material covers most of grain surface. Sample 4 is considerably porous consisting of pores in various sizes—ranging from smaller than one micron to larger than ten microns. From the EDS analysis, Sample 4 is composed of silica, iron, aluminium and titanium. Neither potassium nor manganese is detected. The material filling the voids substantially consists of silica, iron and aluminium. Unlike those in the other samples, there is no carbon, but potassium and titanium are detected. There are no microorganisms observed.

Conclusion

The chemical composition examinations of the selected laterite samples reveal that their main chemical components are the same—silicon dioxide, ferric oxide and aluminium oxide. However, the amounts of those compounds in each sample are different creating different ratios in each of silica to aluminium oxide or to ferric oxide. Martin and Doyne proposed that the ratio of silica to aluminium oxide is more important than the presence of ferric oxide (1927, 530), and, according to Prakash and Basavanna (1969, 166), the ratio of silica to alumina in laterite must be equal to or less than 1.33. However, the ratios of silica to aluminium oxide in all the selected samples, which were undoubtedly laterite, are greater than 1.33 (so falling outside Prakash and Basavanna's classification), while their ratios of silica to ferric oxide are less than 1.33. These results therefore raise doubts as to whether or not Martin and Doyne's, or even Prakash's, criteria of laterite classifications are universally applicable to all laterite. If the ratio of silica to ferric oxide can be used as a criterion (the smaller the ratio, the more laterite-like the material, particularly when the ratio is less than 1.33), Sample 3 appears as the most laterite-like example followed by Sample 4, Sample 2, and Sample 1, respectively and none of them can be considered as plinthite or lateritic soils. Moreover, the ratio of Sample 4 may confirm that only two months of exposure is adequate to harden a plinthite into a laterite. However, it should be noted that if the ratio of silica to ferric oxide is not acceptable as a criterion, this conclusion is invalid.

If the optical microscopic observation results are compared, in terms of the colour of the sample cementations, those of Sample 1 and 3 have closely similar colours optically (if the block mottles in Sample 1 are disregarded). The colour of Sample 2's cementation is slightly brighter, but that of Sample 4 is the brightest. According to Vallerga et al, the darker colour identifies the greater maturity of laterite (1969, 109-121). Therefore, it may be concluded that Sample 1 and 3 had been exposed to the air for a same length of time giving them the more maturity than Sample 2, which may have had a shorter exposure period. Undoubtedly, Sample 4 had been dug and exposed to the air for two months before being tested, resulting in the brightest colour. Regarding the structure of the samples, Sample 3 has the densest slag-like structure followed by Sample 4 and 1. Sample 2 is the most continuously vesicular, resembling lace.

In terms of microorganic contamination in laterite, regarding the presence of carbon in all samples except Sample 4, being freshly cut laterite, it is possible that microorganisms had not yet deposited on laterite recently dug and cut. Therefore, microorganisms, if present, possibly occur after the laterite host has been dug and exposed for a length of time.

Nevertheless, the conclusion obtained from the result of these tests is possibly valid either only for these laterite samples or for other laterite. To confirm this conclusion, a larger number and/or more various location of laterite tested is required (as described in Chapter VI). The most important reason to carry out these tests is to evaluate whether they are applicable for testing the mineralogical, petrographic and chemical compositions of laterite. The clear results prove that these tests are effective and may be applied to characterise laterite generally. However, the suitability and efficacy of these test methods will be discussed thoroughly in the discussion section at the end of this chapter.

3.2.2 Water absorption capacity and porosity analyses

Tests to be applied: objectives and procedures

1) Water absorption by total immersion and porosity calculation

One method to characterise such a porous material as stone is to measure its water absorption capacity and percentage porosity. The water absorption capacity is the maximum amount of water absorbed by a material under the cited conditions, expressed as a percentage of the dry mass of the sample (Teutonico 1988, 35). The measurement can be carried out by total immersion of the laterite samples in deionised water at room temperature. The data obtained are reported in terms of the percentage of absorbed water to the weight of the dry sample. The water absorption capacity is then calculated and reported as the percentage of maximum quantity of absorbed water to the weight of the sample when redried after total immersion. The procedure of the test is based on ASTM C97 and NORMAL 7/81.

In order to supplement the analysis of the susceptibility to water of laterite, a test for water evaporation is also conducted. The same samples tested for total immersion are used. After the immersion, all samples are oven-dried at 40°C and weigh at elapsed times of five, ten, fifteen, thirty, and sixty minutes, and then, at every 24-hour interval until two successive weighings carried out after 24 hours show a difference of less than 0.1 % of the sample weight.

2) Porosity calculation

Porosity of a material is the fraction of the total volume of a solid that is occupied by pores (Teutonico 1988, 45). The percentage of porosity that can be obtained by calculation will indicate the percentage of pores in the material. The procedure is based on ASTM C97. The real and apparent density can be calculated after both real and apparent volumes have been measured using the Principle of Archimedes method, which is the method of measuring the volume of overflowing water that is replaced by an object put into its container as the apparent volume of the object. (In terms of material properties, apparent volume is the volume of a material including its pore space while real volume is the apparent volume minus the volume of its pore space accessible to water.)

The porosity can be calculated as follows:

$$\epsilon = 1 - \rho_a / \rho_r$$

Where: ϵ = Porosity

ρ_a = Apparent density

ρ_r = Real density

Porosity calculation is the easiest method to measure the porosity of a material when compared with other high-technology methods, especially when advanced instruments are not available. It can be carried out following the same procedure as that of water absorption using a total immersion test and is therefore used here. Each sample is first dried and weighed to give its original dry weight. Thereafter, the samples are immersed in water. When the saturation is reached, they are weighed and then redried to measure their weight again. Finally, the data obtained from the measurements will be used to calculate their porosity.

3) Water absorption by capillary action

Generally, the capillary rise of water is the most frequent and typical water absorption mechanism that occurs in stone (Weber and Zinsmeister 1991, 26). Under the influence of the surface tension of pores and capillary forces, water or any solution is transported into the pores causing a 'rising damp' effect on stone or any porous material. To measure the capillary action of a porous material, dried samples of such material are first put on glass beads in a container, and water is poured into the container until about one centimetre of the samples is immersed. The levels of water rising on the samples are recorded at specified intervals. The procedure is based on Experiment 10 in *a laboratory manual for architectural conservators* (Teutonico 1988, 43).

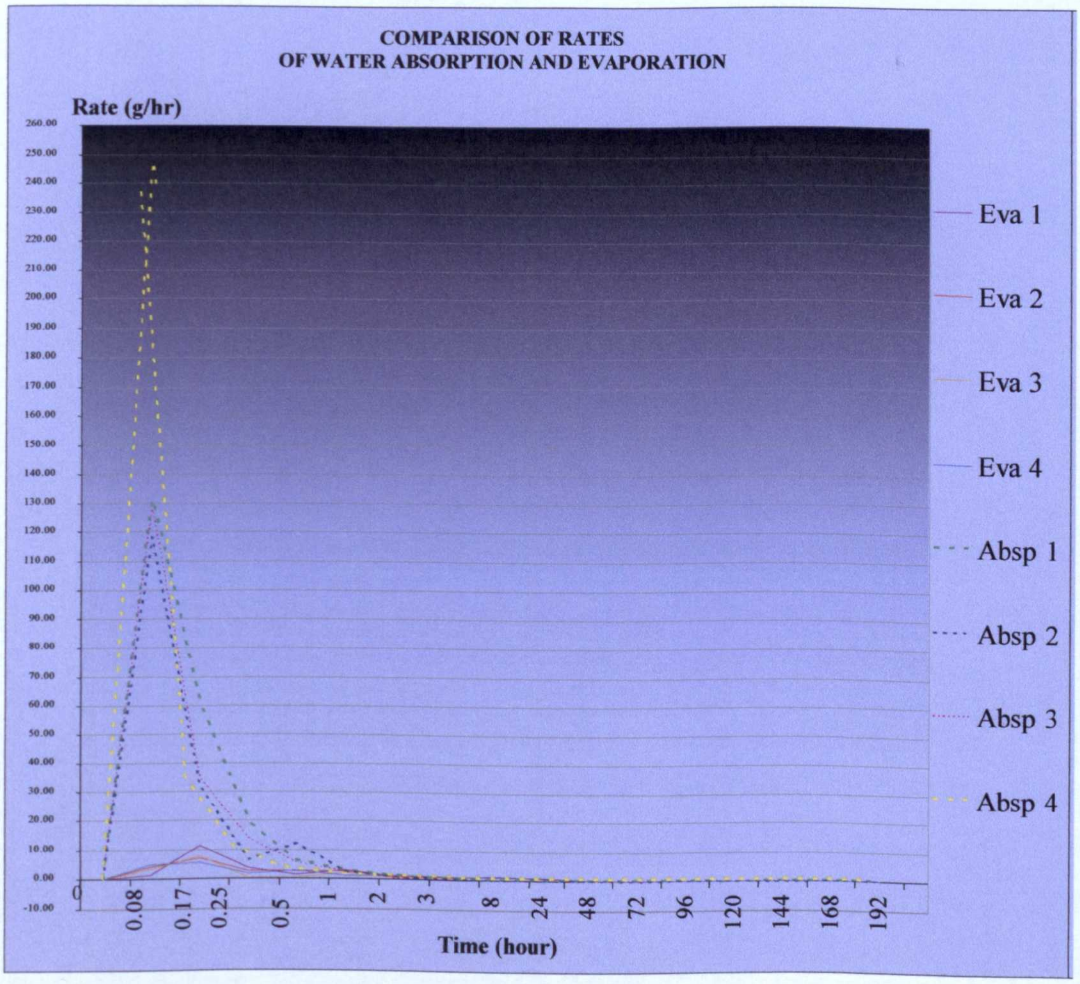
Results (See Data Set 1 in Appendix III)

1) Water absorption and porosity calculation

Table 3.6: Averages of the percentage porosity and water absorption capacity (WAC) and the rate of water absorption (WA) and evaporation (WE) of tested laterites
(See the number of cases and the standard deviation of each data average Data Set 4 in Appendix III)

Sample	% Porosity	%WA	WAC	Max Rate WA (g/hour)	Max Rate WE (g/hour)
1	21.47	8.98	10.40	131.40	11.20
2	16.54	6.09	7.37	118.60	7.00
3	20.64	8.27	9.10	128.00	7.60
4	24.76	12.31	13.66	247.80	5.40

Chart 3.1: The comparison of rates of water absorption and evaporation



Sample 1:

With an average porosity of 21.47%, the average maximum quantity of water that Sample 1 could absorb is 8.98% of its average original dry weight with its water absorption capacity of 10.40. The rate of water absorption was high in the first five minutes of immersion, and then decreased significantly in the next five minutes (see Table 3.6 and Chart 3.1). The rate continued decreasing afterwards, after fifteen minutes of continuous immersion. The percentage of water absorption became almost stable after six days (increasing at a rate of about 0.02%) and the rate of water absorption became completely nil after eight days of immersion. However, the change of weight between two consecutive weighings every twenty-four hours had been less than 0.1% after four days' immersion, which could be considered that the sample had already been saturated regarding the recommendation of ASTM. Therefore, it is concluded that Sample 1 was saturated after four days' immersion.

Sample 2:

With an average porosity of 16.54%, the average maximum quantity of water that Sample 2 could absorb is 6.09% of its average original dry weight with its water absorption capacity of 7.37. The rate of water absorption was high in the first five minutes of immersion, and then decreased significantly (by about 70%) in the next five minutes (see Table 3.6 and Chart 3.1). The rate continued to decrease. The percentage of water absorption became almost stable after seven days (increasing by only 0.02% increasing) but the rate of water absorption had been zero since the fourth day of immersion. After twenty-four hours of immersion, the change of weight between two consecutive weighings every twenty-four hours was less than 0.1%. Therefore, it may be concluded that Sample 2 was saturated after one day's immersion.

Sample 3:

With an average porosity of 20.64%, the average maximum quantity of water that Sample 4 could absorb is 8.27% of its average original dry weight with its water absorption capacity of 9.10. The rate of water absorption was appreciably high in the first five minutes of immersion, and then decreased significantly afterward (see Table 3.6 and Chart 3.1). The rate became almost stable after two days and reached zero after eight days' immersion with the fairly stable percentage of water absorption a day earlier (or seven days' immersion). From the seventh day onward, the change of weight between two consecutive weighings every twenty-four hours was less than 0.1%. Therefore, it may be concluded that Sample 3 was saturated after seven days' immersion.

Sample 4:

With an average porosity of 24.76%, the average maximum quantity of water that Sample 4 could absorb is 12.31% of its average original dry weight with its water absorption capacity of 13.66. The rate of water absorption was extremely high in the first five minutes' immersion, and then decreased rapidly in the next five minutes (see Table 3.6 and Chart 3.1). The rate continued decreasing after fifteen minutes' immersion onward. The rate of water absorption became consistently zero after ten days' immersion but the percentage of water absorption became stable after eleven days. After seven days' immersion, the change of weight between two consecutive weighings every twenty-four hours was less than 0.1%. Therefore, it may be concluded that Sample 4 was saturated after seven days' immersion.

2) Water absorption by capillary action

It was not possible to record the level of rising water in all samples because either water rose too fast to be recorded or the colour of wet and dry laterite were so undifferentiated that the levels of rising water were unidentified. However, in less than three minutes, all samples were completely wet—when putting blotting paper on the top of the samples, the paper was all saturated. The reasons why this phenomenon happened will be discussed in the conclusion.

3) Water evaporation

Sample 1:

The rate of water evaporation of Sample 1 reached the highest (11.20 grams/minute) after having been oven-dried for ten minutes. Thereafter, the rate decreased significantly (see Table 3.6 and Chart 3.1). It took four days to dry completely.

Sample 2:

The rate of water evaporation of Sample 2 was fairly high (4.20 grams/minute) within the first five minutes of drying and reached the highest (7.00 grams/minute) after having been oven-dried for ten minutes. It took four days to dry completely (see Table 3.6 and Chart 3.1).

Sample 3:

Water had started evaporating from Sample 3 at a fairly sharp rate (3.20 grams/minute) since the first five minutes of drying and reached the highest (7.60 grams/minute) in the next five minutes. Thereafter, the rate dropped significantly. It also took four days for Sample 3 to dry completely (see Table 3.6 and Chart 3.1).

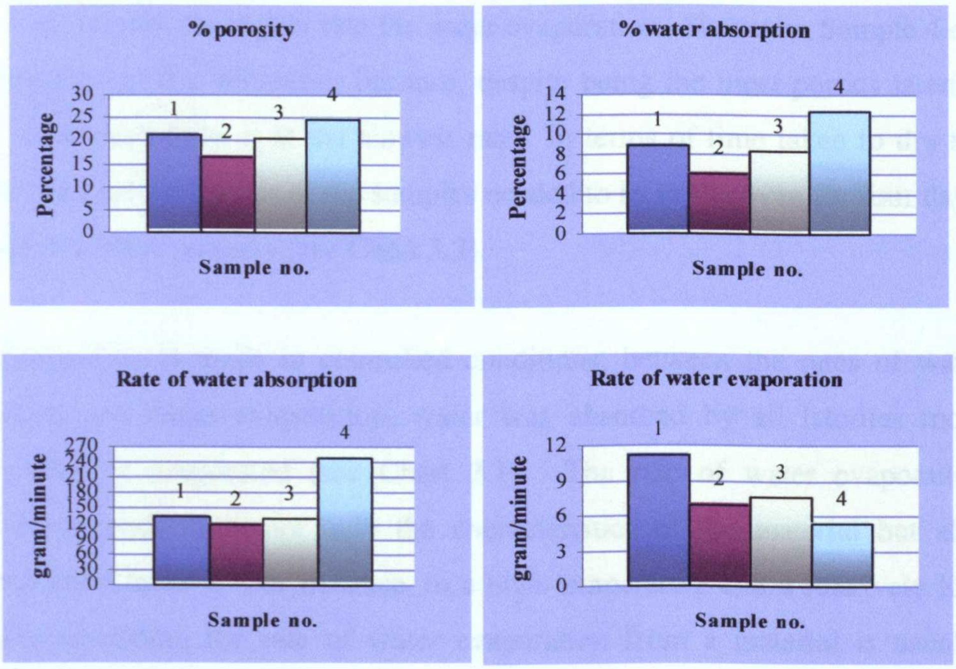
Sample 4:

The rate of water evaporation of Sample 4 was fairly high (5.00 grams/minute), which nearly reached to its peak, within the first five minutes of drying and reached the highest (5.40 grams/minute) after having been oven-dried for ten minutes. Afterward, the rate decreased to zero within four days (see Table 3.6 and Chart 3.1).

Conclusion

To compare the tested samples, Sample 4, with its greatest water absorption capacity (WAC), absorbed the largest amount of water compared with its own weight, while Sample 2 had the least WAC, absorbing the minimum amount of water. Sample 1 absorbed slightly more water than Sample 3 because of its higher WAC (see Chart 3.2).

Chart 3.2: The comparisons of the percentages of water absorption and porosity, and rates of water absorption and evaporation of laterite samples



Testing water absorption by capillary uptake failed because water was brought up to the top of the samples by capillary action so fast that recordings and measuring were impossible. Thus, it was impossible to compare the speed at which the samples absorbed water by this capillary action test and, therefore, it may be concluded that the test of water absorption by capillary action is inapplicable to laterite.

Although water was taken into the pores by capillary action very fast, the samples were not saturated because it was the material, possibly clay, filling in the large pores of the laterite that transported water up to the top of the samples in a very high speed, while the pores of laterite had not been filled by water. According to the fact that smaller pores have more capillary effect, clay, for example, having much smaller pores than laterite, could absorb water in a higher speed, resulting in a very fast water capillary action in the laterite.

We can see that the laterite samples dried out at different rates. The rate of water evaporation tended to vary depending on their percentage porosity; the more porous the laterite, the higher rate the water evaporation. However, Sample 4 did not demonstrate this behaviour because, despite being the most porous laterite, water evaporated from it at the slowest rate. In terms of time taken to dry the laterite completely, all sets of the samples needed to be in the oven for four days, regardless of their porosity (see Chart 3.2).

If a comparison is made in controlled conditions, between the rates of water absorption and water evaporation, water was absorbed by all laterites more rapidly than it evaporated (see Chart 3.1). The rate of water evaporation probably depends upon not only the characteristics of the material but also environmental factors. For instance, in a high-temperature and a relatively low humidity condition, the rate of water evaporation from a material is usually high—higher than the rate in a cold and humid condition (Massari et al 1993, 28). The effects of environmental factors on material decay are discussed in Chapter IV.

In terms of the efficacy of the standard tests applied to characterising the water absorption capacity and the porosity of laterite, the results show that only the water absorption by total immersion test and the porosity calculation from the result of the water absorption by total immersion test are effective, while the water absorption by capillary action fails and may not be applied to test laterite and the water evaporation test has to be redone in a control condition. Therefore, only the water absorption by total immersion test and the porosity calculation are applied for testing laterite samples in Chapter VI.

3.2.3. Permeability of stone analysis

Tests to be applied: objectives and procedures

1) <u>Water vapour transmission test</u>

A critical property of porous materials is permeability. This is the ability of the materials to transmit liquid or gas from one place to another. Normally, under conditions of stable temperature and consistent pressure ratios, a balance between the moisture content of the materials and atmospheric moisture will occur. However, whenever one has a lower water vapour pressure than the other, it will absorb the water vapour from the other. Testing simulates this phenomenon, using a porous material as a transmitter between a beaker full of water and the atmosphere. The water vapour pressure inside the beaker is higher than that of the air, so that the water vapour will be transmitted through the material disk to the atmosphere. The more porous the material is, the more water vapour diffuses through the disc (Weber and Zinsmeister 1991, 81).

According to the definition of terms found in Terminology C168 explained in ASTM E96-95 of the standard test methods for water vapour transmission of materials, the water vapour permeability test indicates the rate of water vapour transmission through a unit area of a flat transmitter of unit thickness induced by a unit vapour pressure difference between two specific surfaces, under specified temperature and humidity conditions. Although this test can be used to characterise a porous material, it is better applied to evaluate an appropriate conservation treatment method by comparing the water vapour transmission capacities of a material before and after being treated thus.

The test in this chapter is based on ASTM E96. The selected laterite samples are cut into cylinders with a four-centimetre diameter and two and a half-centimetre thickness. Four disks of each laterite samples were tested—three discs placed over beakers containing one hundred and eighty millilitres of water and the other as a dummy without water in the beaker. The discs and disposable beakers are first weighed before being assembled together and sealed with paraffin. Each assembly is then weighed before being placed in the desiccator. Thereafter, the assemblies are weighed at elapsed times of five, ten, fifteen, thirty, and sixty minutes, and then, at every 24-hour interval for two weeks or until the rate of weight change recorded is stable (at six consecutive weighings). The data from the record are plotted as a weight-time graph to obtain the slope of the graph line displaying the rate of water vapour transmission.

The water vapour transmission (WVT) of the samples is calculated as follows:

WVT = G/ t . A (grams/hour/square centimetres)

Where: G = Weight change (grams)

t = Time (hours)

G/t = Slope of the straight line (gram/hour)

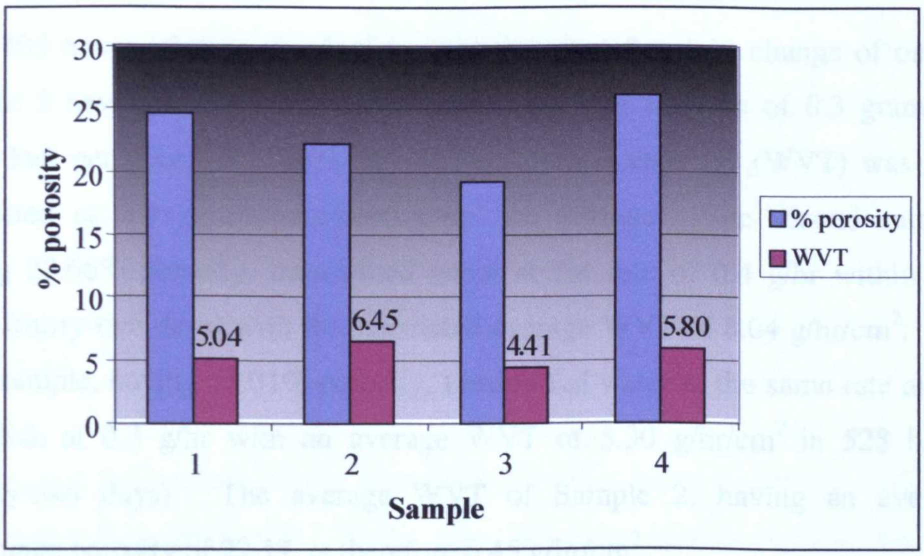
A = Surface area of the disc (square centimetres)

Result (See Data Set 2 in Appendix III)

Table 3.7: Averages of the percentage porosity and the rate of water vapour transmission of the tested laterite (see the number of cases and the standard deviation of each data average Data Set 4 in Appendix III)

Sample	% Porosity	WVT (g/hour/cm^2)
1	24.60	5.04
2	22.17	6.45
3	19.13	4.41
4	26.06	5.80

Chart 3.3: Averages of the water vapour transmission capacity (WVT) of the tested laterite in relation to their average percentage porosity



Sample 1:

After 528 hours (twenty-two days) of testing, the rate of weight change of one disc of Sample 1, having 15.64% porosity, became stable at the rate of 0.2 grams of water loss per hour. Its water vapour transmission capacity (WVT) was then calculated as 4.37 gram/hour/centimetre^2 on average. The second sample, having 25.70% porosity, transmitted water at the rate of 0.3 g/hr within 428 hours (seventeen days) with the calculated average WVT of 5.32 g/hr/cm^2. The other sample, having 32.46% porosity, transmitted water at the same rate of 0.3 g/hr with the average WVT of 5.42 g/hr/cm^2 in 492 hours (twenty days). The average WVT of Sample 1, having an average percentage porosity of 24.60, is therefore 5.04 g/hr/cm^2.

Sample 2:

After 405 hours (sixteen days) of testing, the rate of weight change of one of Sample 2 having 24.85% porosity became stable at the rate of 0.3 grams of water loss per hour. Its water vapour transmission capacity (WVT) was then calculated as 6.01 gram/hour/centimetre^2 on average. The second sample, having 23.66% porosity, transmitted water at the rate of 0.4 g/hr within 769 hours (thirty-two days) with the calculated average WVT of 8.04 g/hr/cm^2. The other sample, having 18.01% porosity, transmitted water at the same rate as the first disk at 0.3 g/hr with an average WVT of 5.30 g/hr/cm^2 in 528 hours (twenty-two days). The average WVT of Sample 2, having an average percentage porosity of 22.17, is therefore 6.45 g/hr/cm^2.

Sample 3:

After 299 hours (twelve days) of testing, the rate of weight change in one disc in Sample 3, having 23.51% porosity, became stable at the rate of 0.3 grams of water loss per hour. Its water vapour transmission capacity (WVT) was then calculated as an average of 5.67 gram/hour/centimetre^2 on average. The second disc, having 17.82% porosity, transmitted water at the rate of 0.2 g/hr with a calculated average WVT of 3.83 g/hr/cm^2. The other sample, having 16.06% porosity, transmitted water at the same rate as the second disk of 0.2 g/hr with the average WVT of 3.73 g/hr/cm^2 in 646 hours (twenty-six days). The average WVT of Sample 3, having an average percentage porosity of 19.31, is therefore 4.41 g/hr/cm^2.

Sample 4:

After 299 hours (twelve days) of testing, the rate of the weight change of disc one of Sample 3, having 26.71% porosity, became stable at the rate of 0.3 grams of water loss per hour. Its water vapour transmission capacity (WVT) was then calculated as 6.00 gram/hour/centimetre^2 on average, and the second disc, having 24.83% porosity, transmitted water at the rate of 0.3 g/hr with the calculated average WVT of 5.91 g/hr/cm^2. The third disc, having 26.63% porosity, transmitted water at the same rate of 0.2 g/hr with the average WVT of 5.49 g/hr/cm^2 but in 528 hours (twenty-two days). The average WVT of the forth disc in Sample 4, having an average percentage porosity of 24.60, is therefore 5.80 g/hr/cm^2.

Conclusion

In these results Sample 2 had the greatest WVT followed by Sample 4, Sample 1 and Sample 3, respectively. If the rates of water vapour transmission are compared, water vapour is transmitted through most of laterite samples at the same rate, 0.3 g/hr. Only a few samples allowed vapour to transmit at a slightly lower or higher rate. Sample 3 allowed transmission at the lowest rate, two of the three discs yielded the transmission at the rate of 0.2 g/hr, while Sample 2 yields the highest rate—two discs at 0.3 g/hr and the other at 0.4 g/hr.

Although the standard test based on ASTM E96 is effective to measure the water vapour transmission rate of the laterite samples, it may not be necessary to carry out this test when only the basic characterization is needed. As previously discussed, the test is an effective tool to evaluate the effectiveness of conservation treatment reagents; therefore, laterite, which is proved in Chapter VIII that there is no need of any conservation reagents, may not require a measurement of its water vapour transmission rate. Therefore, this test is not carried out in Chapter VI. It is to be noted that whenever the measurement of the permeability of laterite is required, the test based on ASTM E96 can still be a good option.

3.2.4. Compressive strength analysis

Tests to be applied: objectives and procedures

1) Compressive strength test

Compressive strength is the load per unit area under which a block fails by shear or splitting (Winkler 1973b, 39). The results obtained from the compressive strength test can be useful for comparing material strength in different orientation (e.g. parallel and perpendicular to the bed in case of sedimentary rocks); between different types of materials or the same material with different deterioration states.

In this thesis, the test followed ASTM C 170 to compare the compressive strength amongst the laterite samples collected from different sites. Although the standard recommends the use of least five stone cubes of a size not less than two inches in each condition (wet and dry), in this chapter only three 2x2x2-inch (or about 5x5x5-centimetre) laterite cubes of each sample per condition were tested due to the limited amount of available samples. Before testing for the dry condition, the cubes were dried in the oven at 60 ± 2°C for 48 hours or until their weights were stable. (Regarding the ASTM standard (C170-87), at the 46th, 47th and 48th hour, each cube was weighed to ensure that the weight was the same, or until three successive hourly weight readings were the same. The recommendation of NORMAL 7/81, the test for water absorption, is to dry and weigh the sample until two successive weighings carried out after 24 hours in time do not vary more than 0.1 % of the sample weight.) Then the cubes were allowed to cool in a desiccator at room temperature (32± 2°C). Before testing for the wet condition, the other laterite cubes were immersed in deionised water (32 ± 2°C) for 48 hours. Thereafter, they were tested immediately after being removed from the immersion and wiped with wet paper to eliminate the surface water.

The test were performed at the Faculty of Architecture in the Silpakorn University in Thailand using an Instron Testing Machine 1125 calibrated at a cross head speed of 0.05 inch/minute, and the chart speed at 2.0 inch/minute. The preferable rate of loading should not greater than 100 psi (690 kPa)/second.

The calculation of the data is as follows:

$$C = W/A$$

Where: C = Compressive strength of the sample (psi)

W = Total load on the sample at failure (pound)

A = Calculated area of the bearing surface (inch^2)

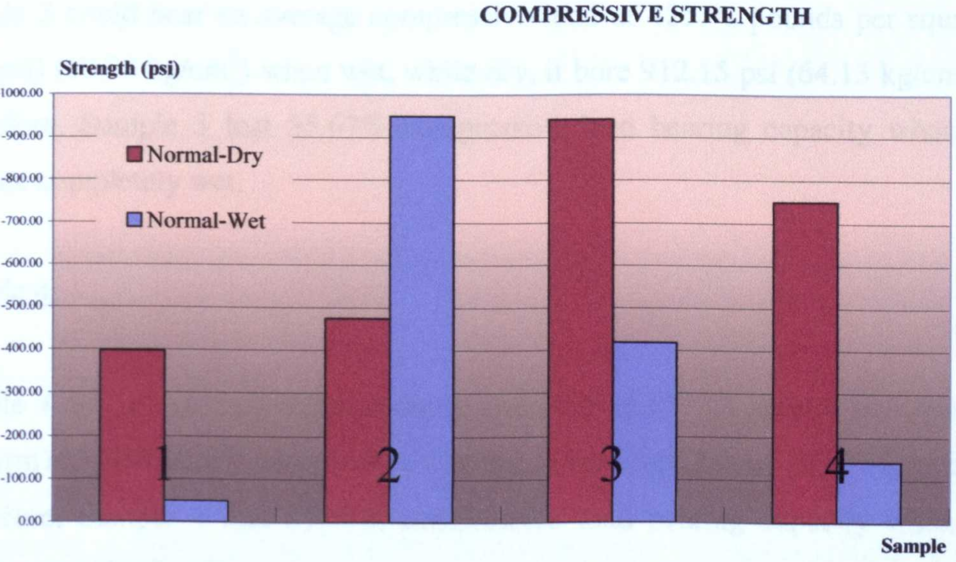
Result (See Data Set 3 in Appendix III)

Table 3.8: Averages of the compression strength of tested laterites in different conditions compared with their percentage porosity (see the number of cases and the standard deviation of each data average Data Set 4 in Appendix III)

Sample	% Porosity	Wet Comp Strength (psi)	% Porosity	Dry Comp Strength (psi)
1	20.59	-49.31	18.19	-396.87
2	16.54	-942.71	21.00	-480.80
3	20.64	-425.93	22.09	-912.15
4	24.76	-137.98	26.27	-748.17

Note: The compressive strength is generally displayed in a negative value.

Chart 3.4: The comparison of compressive strength of the laterite samples



Sample 1:

Sample 1 could bear an average compressive load of 49.31 pounds per square inch (psi) (3.47 kg/cm^2) when wet, while dry, it bore 396.87 psi (27.90 kg/cm^2). Therefore, Sample 1 lost 87.39% compressive load bearing capacity when it became completely wet.

Sample 2:

Sample 2 could bear an average compressive load of 942.71 pounds per square inch (psi) (66.28 kg/cm^2) when wet, while dry, it bore 480.80 psi (33.80 kg/cm^2). In contrast to Sample 1, Sample 2 gained about 100% greater compressive strength when it became completely wet.

Sample 3:

Sample 3 could bear an average compressive load of 425.71 pounds per square inch(psi) (29.93 kg/cm^2) when wet, while dry, it bore 912.15 psi (64.13 kg/cm^2). Therefore, Sample 3 lost 55.67% compressive load bearing capacity when it became completely wet.

Sample 4:

Sample 4 could bear an average compressive load of 137.98 pounds per square inch (psi) (9.70 kg/cm^2) when wet, while dry, it bore 748.16 psi (52.60 kg/cm^2). Therefore, Sample 4 lost 81.08% compressive load bearing capacity when it became completely wet.

Conclusion

In this comparison, Sample 2 when wet could bear the greatest load followed by Sample 3, 4, and 1, respectively; and, when dry, Sample 3 was the strongest succeeded by Sample 4, 2, and 1. (See Chart 3.4) Noticeably, Sample 1, either in a wet or dry condition, bore the least compressive stress.

Since different sets of sample provided dissimilar results of compressive strength in different conditions, it is impossible to predict the mechanical behaviour of laterite whether it loses or gains greater compressive strength when wet. In fact, a wet or dry condition may not significantly affect the strength of laterite. This curious result demands that compressive strength of laterite be examined in the light of other characteristics and additional environmental factors (See Chapter VI) and a greater number of samples should be tested in order to obtain a statistical conclusion.

The results show that laterite has measurable compressive strength and the machine used in this test is effective to measure it. Therefore, this test is carried out again in Chapter VI.

3.2.5. Flexural strength analysis

Tests to be applied: objectives and procedures

1) **Flexural strength test**

Flexural strength or modulus of rupture is the other mechanical property of a material that characterises the bending or flexural resistance caused by a combination of compressive, tensile and shear load (Winkler 1973b, 44). The test for this strength compares the modulus of rupture between the various orientations of stone within the same type, in the case of sedimentary rocks, or indicates differences between various types of stone or material.

Following ASTM C99, five or more 4x8x2¼-inch (about 10x20x6-centimetre) stone samples should be prepared for each direction of stone for each test condition. (In the case of laterite, it does not have bedding planes; therefore, there is no direction of stone laying.) However, due to the limited availability of the laterite samples, only three 2x4x1-inch (about 5x10x2.5-centimetre) samples for each condition were prepared. The testing machine should be as accurate as 1% or lower for the range of 10 to 1000 ft^3 of applied load. The length of the blade pressing at the middle of the samples should be at least as long as the width of the samples. The test was conducted at the same place as the compression test using an Instron Testing Machine 1125 calibrated at a cross speed of 0.05 inch/minute and a chart speed of 5 inch/minute. The gauge length was two inches. The rate of load applied should not greater than 1000 ft^3/minute (4450 N/minute).

The calculation of the data obtained from the test will be as follows:

$$\mathbf{R = 3Wl/2bd^2}$$

Where: R = Modulus of rapture (psi)
W = Breaking load (pound)
l = Length of span (inch)
b = Width of sample (inch)
d = Thickness of sample (inch)

Result (See Data Set 3 in Appendix III)

Table 3.9: Averages of the flexural strength of tested laterites in different conditions (see the number of cases and the standard deviation of each data average Data Set 4 in Appendix III)

Sample	Wet flex strength (psi)	Dry flex strength (psi)
1	0.00	0.00
2	-24.18	-59.65
3	0.00	-36.93
4	0.00	0.00

Conclusion

The test shows that the laterite samples were nearly unable to bear almost any flexural load. Regardless of the different sets, there were only four of twelve samples able to withstand the flexural stress up to 134.22 psi (9.44 kg/cm^2) while the rest broke before performing their load bearing capacity. If a comparison is made between the wet and dry samples, the latter bore greater loads.

Since the data obtained was insufficient and unsuccessful in indicating the lack of flexural strength of laterite, the calculation of the correlation between this property and other characteristics is not relevant. The results of the test were so emphatic that the tensile weakness of the material must have been very clear to Khmer builders and it is unsurprising that it is never found in tension in Khmer architecture: lintels and friezes are always in sandstone. Therefore, this test is omitted in Chapter VI.

3.3 Discussion and conclusion

3.3.1. A comparison of the properties of studied laterite and sandstone

Since laterite in Khmer architecture was always used with sandstone or substituted for it, a comparison of the properties of laterite and the stone used in Khmer architecture is necessary and thus discussed here as a preliminary study. The results obtained from the tests in this chapter and from the tests carried out as a part of my Master's thesis (Watsantachad 2000), studying the properties of and conservation techniques for sandstone used in Khmer construction, are displayed in Table 3.10:

Table 3.10: The comparison of properties of sandstone and laterite

Property		**Sandstone**	**Laterite 1**	**Laterite 2**	**Laterite 3**	**Laterite 4**
Mineral	Quartz	40-50%	45.68%	42.75%	27.80%	28.48%
	Feldspar	10-25%	n/a	n/a	n/a	n/a
	Calcite	n/a	n/a	n/a	n/a	n/a
	Clasts	20-40%	n/a	n/a	n/a	n/a
	Cement	Iron oxide	Iron oxide	Iron oxide	Iron oxide	Iron oxide
	Grain size	0.025-0.07, 0.07-0.1 mm	0.05-0.3 mm	0.03-0.3, 0.5-0.7 mm	0.03-0.5 mm	0.03-0.5, 0.7 mm
	Sorting	Poor	Poor	Poor	Poor	Poor
Physical	Porosity	12.78-13.06% (0.5-42% generally)	18.69%	15.34%	15.94%	22.40%
	WAC	4.59	10.40	7.37	9.10	13.66
	%WA	4.57	8.98	6.09	8.27	12.31
	Rate WA	High in the first five minutes (25.84 g/h or 2.15% of TWA). In eight hours, 78.25%of TWA was absorbed, stable within 12 days	High in the first five minutes (131.40 g/h or 39.91% of TWA). In half an hour 69.93% of TWA was absorbed, stable within 8 days	High in the first five minutes (118.60 g/h or 49.09% of TWA). In half an hour 79.97% of TWA was absorbed, stable within 4 days	High in the first five minutes (118.60 g/h or 42.72% of TWA). In half an hour 68.76% of TWA was absorbed, stable within 8 days	High in the first five minutes (247.80 g/h or 62.48% of TWA). In half an hour 76.35% of WA was absorbed, stable within 8 days

Table 3.10: The comparison of properties of sandstone and laterite (continued)

Property		Sandstone	Laterite 1	Laterite 2	Laterite 3	Laterite 4
Physical	Rate WE	n/a	High in the first ten minutes (11.20g/h or 3.20% of TWE). In one day 84.54% of TWA had evaporated, stable within 4 days	High in the first ten minutes (7.00g/h or 3.68% of TWE). In one day 85.28% of TWA had evaporated, stable within 4 days	High in the first ten minutes (7.60g/h or 3.70% of TWE). In one day 77.20% of TWA had evaporated, stable within 4 days	High in the first ten minutes (5.40 g/h or 2.32% of TWE). In one day 80.19% of TWA had evaporated, stable within 4 days
	WVT	0.99-2.16	5.04	6.45	4.41	5.80
	Capillary Rise	2.60 cm in an hour	5 cm in three minutes	5 cm in three minutes	5 cm in three minutes	5 cm in three minutes
Mechanical	Comp Strength	-2300 psi (wet) -11825 psi (dry)	-50.08 psi (wet) -397.05 psi (dry)	-950.46 psi (wet) -474.85 psi (dry)	-417.81 psi (wet) -942.43 psi (dry)	-142.12 psi (wet) -751.22 psi (dry)
	Flex Strength	-294.42 psi (wet) -1252.07psi (dry)	0 psi in both conditions	-24.18 psi (wet) -59.65 psi (dry)	0 psi (wet) -36.93 psi (dry)	0 psi in both conditions

The comparison reveals that both laterite and sandstone are composed of poorly sorted quartz cemented with iron oxide. However, the percentage of quartz varies. Quartz grains in laterite are much larger than in sandstone which was tested. The porosity of the studied laterite ranges from about 15% to 22% which is greater than the porosity of the studied sandstone (12.78-13.06%). In addition, sandstone in general has porosity ranging from 0.5-25.0% (Weber and Zinsmeister 1991, 19); therefore, the percentage porosity of laterite and sandstone are somewhat incomparable. The rates of water absorption and water vapour transmission of laterite are much greater than sandstone possibly because laterite mostly contained large pores. But Weber and Zinsmeister suggest that macro pores do not significantly contribute to capillary rise (1991, 26). Hence, other factors should be sought to explain this phenomenon. According to the data obtained from SEM-EDS, it is possible that it was the clay filling in the pores, itself having much smaller pores than laterite, that contributed to the capillary rise of water in laterite.

In terms of mechanical strength, sandstone bore much greater loads than laterite. Dry sandstone could bear more than 10,000 psi (703.07 kg/cm^2) and can be considered as a strong material while dry laterite resisted only less than 1,000 psi (70.31 kg/cm^2)—this amount of load bearing capacity is considered as a very weak material according to Winkler (1994, 44). In addition, laterite was unable to withstand flexural forces; while dry sandstone could bear up to 1250 psi, latrite could bear at most just over 59 psi. Pore size distribution and structure of materials may have been the causes of the difference. Sandstone is a sedimentary rock composed of cemented quartz grains and dense micro pores, but laterite is derived from soils, mainly composed of large pores and continuous networks of ferric and aluminium oxides with some loosely cemented quartz grains. Therefore, the sandstone structure is denser and, because of more firmly cemented quartz, stronger than laterite. This fact possibly leads to the greater load bearing capacity of sandstone.

3.3.2. The efficacy of the carried out standard tests

The calculations using the SPSS programme show that there are significant correlations amongst the porosity, the water absorption capacity, the percentage of water absorption and the rate of water absorption of laterite; as well as the significant correlations between the percentage of silicon dioxide and the dry compressive strength and the significant correlations between the wet compressive strength and the percentage of water absorption and the water absorption capacity (see Data Set 5 in Appendix III). This latter correlation is also reflected in the significant correlation between the ratio of silicon dioxide to ferric oxide and the dry compressive strength. Preliminarily, it may be concluded that the porosity and water absorption capacity, the chemical composition and the strength of laterite are the important properties that require characterization because they affect the other properties of laterite. However, the tests described in this chapter were pilot ones in which only three samples of each set of laterites were studied. To characterise the properties, especially the porosity and compressive strength, of laterite more thoroughly and statistical accurately, testing a larger number of samples was therefore carried out and the results are discussed in Chapter VI.

The results obtained from the pilot testing programme revealed that the analysis through wet chemical analysis method and AAS seems to be effective in characterising the chemical properties of laterite. Although the microscopic observations could reveal the main mineral compositions and their sorting, the results were only qualitative. As well, the visual porosity observed by microscopes was fairly approximate. When EDS was used, chemical compositions could be detected quantitatively but it was inaccurate because only some spots of the samples were tested without any systematic sampling method; so only qualitative results can be trusted. By contrast, the chemical composition analysis with wet chemical analysis method yielded accurate and useful results.

To measure the porosity of a laterite, laboratory tests, the basic total immersion test for instance, have to be conducted since visual observation is very subjective and unreliable. Vesicular or wormhole laterite sometimes looks relatively porous, while in fact it has a moderate percentage of porosity. Underestimation or overestimation of porosity may lead to a wrong prediction of other characteristics and properties of a laterite. The pilot study revealed that applying the total immersion test and thereafter calculating the obtained results could effectively measure the percentage porosity of laterites. However, this method could only measure the percentage of micro pores of the samples because water was not retained in large pores when the samples were taken out from the immersion tray and weighed. Therefore, although this recommended method is effective, some procedures may need to be adapted in order to measure successfully the total porosity of laterites which are mainly composed of large pores. Therefore, in Chapter VI, an adapted method for measuring the overall porosity of laterite is proposed and carried out, together with the standard one.

Since the rates of water evaporation and water vapour transmission of laterites did not correlate with other properties significantly and rather depended upon the environment, it can be concluded that it is not necessary to measure these rates in order to predict the strength of laterites and therefore out of the focus of the study in Chapter VI.

The pilot study revealed that only compressive strength could be measured, while laterites had so little flexural strength that they were unable to withstand flexural loads leading to the unsuccessful flexural strength test. As previously discussed, the result of the test were so emphatic that the tensile weakness of the material must have been very clear to Khmer builders and it is unsurprisingly that it is never found in tension in Khmer architecture. Therefore, this flexural strength test is omitted in Chapter VI and only the compressive strength test is carried out to measure the mechanical strength of laterites.

The purpose of the study is to investigate whether or not laterite is suitable to be used as a structural element in buildings; therefore, the mechanical strength characteristic of laterite is the most important property that should be focussed upon. Hence, tests of material strength and tests of other properties correlated with laterite strength are selected. The pilot test showed that chemical composition affected the compressive strength of laterite while the porosity and possibly other physical properties are relevant. Therefore, the tests on the compressive strength and chemical composition, together with the effective porosity analysis and observable physical characteristics of laterite as a supplement are used in the main focus of this study: the analysis of laterite from the Ban Prasat Complex, in Chapter VI.

However, mechanical strength is just one of the characteristics indicating whether or not laterite is suitable to be used as a structural building material, while how long it will last also depends upon other factors. In reality, laterite properties are only intrinsic factors, which either protect it or allow extrinsic environmental decay agents to harm it. The decay mechanism of laterite, which will be discussed and analysed in Chapter IV and V, will indicate if the characteristics and properties studied in this chapter contribute to the durability of laterite exposed to the environmental decay agents.

Figure 3.1:
Images of the selected sites
(in 2003)

Figure 3.1a:
Ku Pone Rakang
Roi Et
(in 2003)

Figure 3.1b:
Ku Kantanam
Roi Et
(in 2003)

Figure 3.1c:
Prang Ban Prang
Nakhon Ratchasima
(in 2003)

CHAPTER IV

ENVIRONMENTAL DECAY MECHANISMS

In the previous chapter, the efficacy of standard tests to be applied to characterise laterite was evaluated. However, only the properties of laterite were discussed in that chapter, while its decay mechanisms have not yet mentioned. In fact, laterite, as a natural material used in buildings, is inevitably exposed to and eventually affected by the atmosphere and environment. Whether or not laterite can survive in such an environment depends on its properties, its susceptibility to decay and its environmental decay agents, such as water, salts and vegetation.

In order to characterise the decay mechanisms of a building material, not only the atmosphere, but also other environmental decay agents, both natural and unnatural, need to be identified, and their effects on such material studied. Therefore, in this chapter, the sources and decay effects of each environmental agent present in Thailand (particularly in the northeast and the east where the studied sites are located) will be listed and discussed. However, how laterite is affected by such agents will be investigated and discussed in the next chapter, and the effects of the environment on laterite in reality will be assessed and analysed in Chapter VI and VII.

It is to be noted that because laterite is a porous material that has yet to be studied in terms of the alterations that occur after environmental exposure, the sources of potential decay agents and their effects will be based on existing records for other materials, particularly sandstone that was also used in Khmer construction.

4.1 Environmental Agents and their effects

4.1.1 Definitions of terms

There are many terms used for describing the changes of materials, especially stone, when they are exposed to natural and anthropogenic environments (Viles et al 1997, 95-109). These terms include alteration, deterioration, damage, decay, degradation and weathering. 'Alteration' is defined as changes in material properties; 'deterioration' as the alteration of material by damage factors leading to distress and decay; and 'weathering' as the naturally occurring processes of alteration (ibid). Viles et al, in their workshop, differentiated the terms based on the scale of occurrence. They used the term 'degradation' when the alteration of a material occurs at the micro scale (centimetres or less); 'distress' at the meso scale (centimetres to metres); and 'decay' at the macro scale (whole buildings) (ibid). However, in architectural fields, we usually use the term 'material decay' and 'structure or building damage, which give us more understanding of the pathology of alteration. For example, Croci defines 'decay' as the alteration of material properties while he uses 'damage' when buildings are structurally altered or deformed (2000, 41). Sir Bernard Feilden, in contrast, used only the term 'decay' to specify any change occurring in buildings, regardless of the scale of its effect, throughout his book, especially in Part II: Causes of decay in materials and structure (1982, 89-181). Indeed, he did not give any definition of 'decay' but only referred decay to any alteration in buildings.

From another point of view, decay is defined as the state or process of decomposition, structural or physical deterioration, or declining in quality of a material, while weathering is the change of appearance or texture of a material only by long exposure to the atmosphere (Soanes and Stevenson (eds) 2004). Therefore, according to the Concise Oxford English Dictionary, decay is caused by various environmental agents, but weathering indicates only the changes caused by atmospheric agents. However, Schaffer define these two terms in different ways. He proposes that 'weathering' is used to describe the changes developed by the action of the weather and yield pleasant effects to the material, while 'decay' refers to undesirable changes associated with dangerous and ugly forms of weathering (2004, 3). From my point of view, using the word 'desirable', 'pleasant' and 'ugly' may lead to misunderstandings. All of them are related to one's preference and hence likely subjective. In geological terms, weathering refers to the process of the degradation of igneous rocks and the purification or refinement of sedimentary ones (Keller 1957, 5; Yuwaniyom 1988b, 100-113). From this point of view, weathering is related to tangible science, particularly physical and chemical alteration, which is clearer for one to understand and define an alteration occurring in stone more objectively than Schaffer's.

So far, there seems to be no standardization in either the exact meaning or application of the terms used for describing material alterations (Viles et al 1997, 96). Therefore, each researcher should give the definition of these terms used in their research to set up a ground basis of understanding for their readers. In this chapter and throughout the thesis, I only divide the scale of laterite's properties and alteration into two, macro and micro. Macro scale refers to the one that can be observed visually and micro scale as the one unobservable and needs special tools to investigate. Being an architect, and partially based on Croci's definitions and the International Congresses on Deterioration and Conservation of Stone which use the term 'deterioration' to define decay problems of stone, I only use the term 'decay' or 'deterioration' to refer to the alteration of materials at either micro or macro scale; and use 'damage' when the alteration occurs in buildings structurally, definitely as physical alteration at macro scale. In my opinion, dividing the alteration of a building only into two main aspects can help architects, who are usually familiar with only three main aspects of buildings—design, material and structure, to have a clear vision of types of building alterations and can themselves identify such alterations in the same way.

Another term used in this chapter is 'environment'. 'Environment' is the conditions that surround and influence things on earth (Agnes and Laird (eds.) 2002). Since building materials are in contact with the environment, they are decayed naturally and inevitably by environmental agents. The environmental agents include water (the most important), climate and temperature variation, air, soil and its subsidence, vegetation, the terrain where buildings are located, animal and human interventions, and salts.

4.1.2 Environmental decay agents

Variation of climate and temperature

Variation in temperature alone can cause materials to change physically, and sometimes chemically. Materials expand when the temperature increases and contract when it decreases. When a material is exposed to the sun, the surface becomes hotter than the underlying mass while at night the surface becomes colder than the material beneath, and these temperature differences cause unequal expansion leading to stresses developing in the material (Schaffer 2004, 43; Feilden 1982, 94). Cracking of the material is the result. Stresses created by thermal change in a material depend on five factors—the magnitude of absolute dimensional change in it; its elasticity; its capacity to creep or flow under load; its degree of restraint to the movement by its connection to other structural elements; and the change of moisture content by evaporation (Feilden 1982, 95). However, how much a material will be affected by the fluctuation of temperature also depends upon its thermal conductivity, thickness, heat capacity, coefficient of expansion and diffusivity—the ratio of conductivity to heat capacity (Feilden 1982, 94; Schaffer 2004, 43). The diffusivity of building materials, such as stone, is generally lower than that of metals; hence, the stresses created by thermal fluctuation in stone is higher than in metals (Schaffer 2004, 43).

The peak temperature on the surface relies on the conductivity, albedo and insolation, which is the amount of solar radiation reaching the surface, but the temperature at five centimetres below much depends on only the thermal conductivity of the material (Winkler 1994, 49). Thermal conductivity is the rate at which heat passes through a specified material (ibid, 49-50). Therefore, the peak temperature difference between the surface and at the five-centimetre depth of a stone with a higher thermal conductivity is less than that of other stones with lower thermal conductivities. Therefore, the higher the thermal conductivity, the greater the heat absorbed by the stone. As a result, the difference in temperature in the afternoon and at night, and at the surface and the beneath it, is less. Consequently, there are fewer effects of temperature variation on such stone with higher thermal conductivity. Generally, the thermal conductivity of denser rocks is higher than of porous ones (Winkler 1994, 50).

In addition, the rate and degree of expansion or contraction also depend on the expansion coefficient of each material. It is possible that materials are weathered or cracked because the adjacent materials have different expansion coefficients, resulting in different rates and degrees of expansion and contraction, and consequently stresses are exerted on materials that expand and contract at lower rates and degrees. Even within stone, when the component minerals have different linear coefficients of expansion in different directions, stresses are developed leading to micro cracks in the stone (Schaffer 2004, 42).

In Thailand, according to the mean values of maximum and minimum temperature, the highest differences of temperature in daytime and at night occur in the northeast in summer from the middle of February to the middle of May, and in the east in winter from the middle of October to the middle of February. The differences are 12.2°C in the northeast and 9.8°C in the east. However, if we look specifically at the lowest and highest daily temperature of the provinces where the selected sites are located, the temperature in the Nakhon Ratchasima Province reached 42.7°C on the seventh of April 1979 and 3.6°C on the thirty-first of December 1975, giving a difference in highest and lowest daily temperature of 39.1°C. Unfortunately, there is no record of the minimum and maximum daily temperatures in the same season or in the same day. The comparison of the temperature change within one day is, therefore, impossible. The best comparison that could be conducted based on the existing records is to compare the maximum and minimum mean temperature of each season in each region to obtain the highest temperature difference as described above.

As previously discussed, as well as the different ambient temperature by day and by night, the thermal conduction of materials also is relevant to the severity of decay caused by the variation of temperature. The thermal conductivity of sandstone is 1.05 W/m/°C (Winkler 1994, 50). However, other properties of the sandstone studied were not mentioned here and it seems irrational to apply this number to every type of sandstone, especially sandstone used in Khmer construction in Thailand. The thermal conductivity of laterite, especially the one used in Thailand, has never been studied. The study of the effects of thermal variation on such materials in Thailand is solely based on observations site-by-site without any systematic calculation.

Variations in climate and temperature are the main cause of several material weathering phenomena, particularly those involved with water and humidity (Winkler 1994, 51-52; Feilden 1992, 94-99). Some phenomena occur alone while others are accompanied by additional environmental agents. For instance, expansion and contraction of materials occurs as a lone phenomenon, while cycles of wet-dry weathering, frost damage, salt crystallisation and biological growth are the results of climatic variation influencing other decay agents. The direct effects of variations in climate and temperature will be discussed with the effects of the other environmental decay agents below.

Water

Water is one of the most harmful agents of material decay. Not only does water itself cause materials to decay, but it is also the main component of other agents and increases the severity of other agents' effects. (The details of decay caused by water and by water associated with other decay agents will be discussed below.) Water comes from several sources and can enter materials in various forms. Rainfall, water vapour, groundwater, sea spray, waterfall, ice, fog, rivers and oceans are some examples of the sources of water in the world (Na Pompetch 1983, 1; Wikipedia 2005c). The forms of water that can be transported into porous materials include water as rain hitting the surface directly, as groundwater transported by capillary action, as water vapour transported by diffusion, condensation or deposition of aerosols (Feilden 1982, 99).

1) **Sources of water**

In general, one of the most significant water sources is water vapour in the troposphere at a height of sixteen to eighteen kilometres above the ground (in the equator zone) (Na Pompetch 1983, 3). Generally, the air contains about 13,000 cubic kilometres of water vapour (Wikipedia 2005a), and we are surrounded by water in the form of vapour all the time (anon in Clouds R. Us.com webpage, nd). However, the actual amount of water vapour in the air depends on how hot and dry the area is (ibid). (It is worth noting that water vapour is also produced by trees and organisms through photosynthesis and transpiration (Na Pompetch 1983, 3).)

Such invisible water vapour in the air is called humidity (Bry-Air, nd). Since the amount of water that can be contained in the air depends upon the temperature of the air (ambient temperature) and the pressure of the air, at a constant pressure, the warmer the air the more water vapour it can retain (ibid; American

Geophysical Union 2000). In addition, if the air at a certain temperature has absorbed all the moisture it can hold at that temperature, it is saturated (ibid).

The amount of water vapour present in the air or the degree of water vapour saturation is evaluated in terms of 'relative humidity' or 'saturation ratio'. Hence, relative humidity is the actual water content in the percentage of that of a saturated volume (Bry-Air, nd). In other words, relative humidity (%RH) is the ratio of the actual vapour pressure to the saturation vapour pressure at the air temperature, expressed as a percentage (American Geophysical Union 2000). For example, when the air is 50% saturated, or 50%RH, it contains only a half of the amount of water that it can potentially contain at the same temperature and pressure. At this state, or any state that the relative humidity is less than 100%, surface water can evaporate leading to a higher %RH of the air. As the relative humidity approaches 100%, the air can take in less and less moisture and at 100% relative humidity, that air cannot hold more water (Bry-Air, nd) and surface water then stops its evaporation, and, until either the relative humidity of the air reduces below 100% or the air temperature rises, surface water evaporates again.

Rainfall is the precipitation of the water vapour in the atmosphere. Based on the same principle—if air is saturated with water vapour at a given temperature, a drop in the temperature will lead to condensation of water in the form of droplets and the temperature at which moisture condenses out is the dew point temperature (Bry-Air, nd), when the air in one area contains a certain amount of cloud (a mass of steam or water vapour in the atmosphere), precipitation will occur in the form of rainfall, hail and snow—or only as rainfall in tropical areas (Na Pompetch 1983, 5). Rainfall may then form different types of water resources such as rivers and lakes, it may penetrate the ground as groundwater, it could evaporate as water vapour, or condense as dew and moisture. When moisture is suspended in the air as clouds, precipitation occurs again, so forming a repetitive cycle. The type, rate and amount of precipitation in any area depend on its climate and topography as well as temperature and gravity. Such factors, particularly temperature, also control the form of water existing in the environment at any particular moment.

Groundwater is another source of water. It is water flowing within aquifers below the water table. (The top of the upper unconfined aquifer is called the water table or phreatic surface, where water pressure is equal to atmospheric pressure.) Within aquifers, the water flows through the pore spaces in unconsolidated sediments and the fractures of rocks (Wikipedia 2005b). It is estimated that the global volume of groundwater is 13,000,000 km^3, fifty times that of surface freshwater (Wikipedia 2005a; Wikipedia 2005b). Groundwater is recharged from, and eventually flows to, the surface naturally; natural discharge often occurs at springs and seeps and can form oases or swamps. Groundwater can be a long-term 'reservoir' of the natural water cycle, with residence times from days to millennia, as opposed to short-term water reservoirs like the atmosphere and fresh surface water. Typically groundwater is thought of as liquid water flowing through shallow aquifers, but technically it can also include soil moisture, permafrost (frozen soil), immobile water in very low permeability bedrock, and deep geothermal or oil formation water (Wikipedia 2005b).

Groundwater is naturally refilled by surface water from precipitation, streams, and rivers when this recharge reaches the water table (Wikipedia 2005b). In order to consider the amount of existing groundwater, the rainfall (RF) and the potential of evapotranspiration (PE) in one area at one time must be taken into account (Wongsawad and Joolwong 1988, 21-45). If the ratio of RF to PE is greater than one, the groundwater exists in the area. In contrast, when the ratio is less than one, it can be concluded either that no rainwater has been absorbed into the ground or that the rate of evapotranspiration is exceedingly high hence a little amount of groundwater remaining.

The main sources of water as an environmental decay agent migrating to building materials in Thailand are rainfall, groundwater and moisture in the air (Poshyananda 1997, 88). In a tropical climate such as in Thailand, not only do heavy rains occur for many months of the year, but water is also retained in the air as moisture for long periods during wet or rainy seasons. This causes materials to weather and decay at a higher rate in wet seasons than during dry seasons and the details of the effect is discussed below.

The source of groundwater in the Northeast and East of Thailand is from rainwater that falls and penetrates sedimentary rocks in the Korat Plateau, i.e. sandstone and shale, which cover more than 80 percent of the plateau area (Wongsawad and Joolwong 1988, 21-45). The topography of the Northeast is a cultivated plateau and only little forest remains; therefore, rainwater cannot be retained in surface soils for a long period, but drains rapidly to the rivers or penetrates deeply to the rock strata and soils. Consequently, in dry seasons, water cannot be found in the surface soils. Most of the groundwater in this region is fresh. However, the freshness of the water depends upon the depth—the deeper the location, the saltier the groundwater (Yuwaniyom 1988b, 100-113). In Roi Ed Province, fresh groundwater is found at a depth of less than sixty metres (Wongsawad and Joolwong 1988, 21-38). In the Nakhon Ratchasima Province, fresh groundwater is shallow and salts can be found at about one hundred metres beneath the surface. Because of its deep location, salty groundwater in this region causes little harm to building materials when compared to salts in the soils transported to materials by water uptake.

2) Effects of water

Water itself can be harmful to any stone or other porous materials once it enters the porous network by absorption or adsorption. Depending on the porosity of stone, water can move in and out of the stone pore network in several ways and in various forms—direct attack of rain; diffusion and condensation of water vapour; transportation of liquid water by capillary action; evaporation of liquid water; and so on.

The simplest way of naturally introducing water to stone buildings is by rain. Water reaches a masonry surface when the rain hits the surface directly (Feilden 1982, 99). Water then moves to large pores, voids, cavity or cracks and remains there until it can evaporate completely. However, when it has not yet evaporated, it becomes another source of water to be transported into stone's micro pores by capillary action. In addition, if the surface of the masonry has soluble efflorescence or other kinds of environmental decay agents, such as aerosols and bird excrement, the remaining water also dissolves such agents and transports them into the pores causing more severe effects on the material.

Water vapour is also harmful to porous materials such as stone (Feilden 1982, 99; Winkler 1994, 142). It is introduced to stone surface by diffusion and condensation. Diffusion depends on the relative humidity and temperature of the atmosphere. This means that the diffusion of water vapour will occur when a dry porous material is placed in a humid atmosphere. The moisture in the air will rapidly diffuse into the material until it reaches equilibrium or will condense as drops depositing on the material surface.

Condensation occurs when the masonry surface is colder than the dewpoint of the surrounding air in the form of water droplets forming on the surface of masonry (Feilden 1982, 99). The water on the surface may clean dirt or gaseous pollutant on the surface and become acidic or saline solution; and then such solution is transported to the stone pores by capillary action or form crusts of salts and dirt depositing on the surface (ibid). Calcium sulphate crust on marble is an example; however, the effect of salts is discussed in detail below. Since condensation occurs on cold surface, materials with higher density and thermal conductivity are more affected by it than those with lower one (ibid). Aerosols, such as the liquid droplets formed around sodium chloride crystals, are also attracted to cold surface where they affect the surface in the similar way to those of condensation, but they do not need the air temperature to drop below the dewpoint before depositing on the surface (Feilden 1982, 99-100).

The most common and effective method of water transportation to stone is by capillary action. It is a phenomenon that liquid, especially water, rises in the capillary to a height with its surface tension (Nelkon and Parker 1970, 131). Pores in stone are also capillaries that attract water into it, and their capillary action depends on its structure and diameter. The height of capillary rise depends on the size of the pore and can be calculated with the formula: $h = 2s/Rd$, where h is the height of capillary rise, s is a constant (about 0.074 g/cm), d is the density of water and R is the radius of the pore (Winkler 1994, 146). When s and d are constants, the height of capillary rise is inversely proportional to the radius of the pore—the smaller the pore, the higher the capillary rise. Therefore, porous materials that have smaller pores are more affected by water, and salts transported by water, than the ones having larger pores.

Groundwater is another source of water that migrates into foundations and walls by capillary action and causes decay to materials (Goudie and Viles 1997, 82). In suitable topographic situations, it is a main source that either introduces or mobilises salts into pores and cracks in materials (ibid, 79 and 82). Contaminated with soluble salts in soils, groundwater creates more severe effects on materials than pure water alone. Generally, the deeper the soil, the greater the concentration of sodium chloride (Yuwaniyom 1988a, 75-79). (The effects of salts will be discussed in Salt Section.) Groundwater at one and a half to two kilometres below ground level is always brine (Na Pompetch 1983, 56), and the presence of high groundwater levels has been one of the main agents causing salt weathering of engineering structures (Goudie and Viles 1997, 82). However, in some tropical countries with plateaux, if compared to the effects caused by climate variation, groundwater has only a minor influence on soil because water remains in the soil only during rainy seasons and rapidly evaporates during dry seasons (Wongsawad and Joolwong 1988, 21-45). With a steep area, rainwater flows into rivers very rapidly resulting in a little amount of rainwater remaining in the soil (ibid). In addition, the low relative humidity in such areas creates a very high rate of the evaporation of surface water. Therefore, the level of groundwater in such an area is relatively low resulting in the low level of capillary fringe and, possibly, the low limit of capillary fringe. (The limit of capillary fringe is the position of the upper surface of the capillary fringe (Goudie and Viles 1997, 84). Cooke et al state that the line where the limit of capillary fringe intersects the ground surface is very important because it marks the boundary of the building area which is susceptible to the effects of the capillarity of groundwater and salts dissolved in such groundwater to the pores of materials (Cooke et al 1982, 169-170).)

The following deterioration problems are some examples of the effects of water:

Dampness in Stone

Dampness in stone occurs when stone retains water or moisture inside its pores for a prolonged period. Sandstone and laterite—like all porous materials—have a pore network of different sizes and shapes (Folk 1968, 7). Water can easily evaporate in the pores near the surface; however, water evaporation is more difficult in deeper or very small pores and water is consequently trapped in them. Additionally, in large pores, water molecules can pass into the vapour phase more quickly than in the small pores where the attractive forces between the pore wall and water molecule is stronger than the large pores. The attractive forces can interfere with the evaporation rate (Amoroso and Fassina 1983, 14). (The evaporation of water takes place where a saturated material is exposed to a flow of air that has a lower relative humidity and a higher temperature. This means that the rate of evaporation varies in line with an increase in temperature, a decrease in relative humidity, and particularly an increase in airflow velocity (Massari et al 1993, 28). The rate of evaporation can increase by about five times when the stone is exposed to a mild breeze, and by about three times when it is exposed to the sun (ibid).)

Water trapped inside stone can cause several problems. Not only can water dissolve soluble salts and allow them to penetrate the stone causing more problems, but the water itself is also harmful, especially when it changes phase creating pressure inside the pores. The details of this mechanism will be discussed below. When the stone is in a wet state, clay in stone absorbs water, and then swells. Consequently, the stone becomes softer and tends to delaminate, in the case of sedimentary rocks. In addition, under suitable conditions, water creates the appropriate environment for biological growth on stone, which will also be discussed in detail below.

Wet-Dry Cycles

In tropical climates, annual precipitation is extreme. When rain falls, stone absorbs water into its pores by capillary action vertically and horizontally, resulting in wet stone. With solar radiation and wind, the water in wet stone starts evaporating. These fluctuations from day to day and even within a day contribute to wet-dry cycling in stone, causing the stone to dilate and contract due to the change of moisture content within it: the stone expands during the wetting state and contracts during the drying state. Nevertheless, these phenomena happen only when the water is salt-free. When the water is contaminated with salts, such as sodium chloride (NaCl), the stone reacts in opposite ways—contracting during the wetting state producing a smaller grain-to-grain distance, and expanding during the drying state (Snethlage and Wendler 1997, 7-24). The result is that the premature deterioration and displacement of grains contribute to the loosening of the grain structure, and consequently, the friability of the stone (see Appendix IV for the definition of friability).

The types of damage depend on the zone of the maximum water content. Normally, if salt is present, the greatest salt deposition occurs in the same area as the zone of maximum water content, which is parallel to the surface. If this zone is located on the surface, efflorescence is observed, but if the zone is below the surface, cryptoflorescence and crumbling occurs. If it is about 1-2 mm beneath the surface, the stone will also be damaged with a thin scaling. The deeper the zone of the maximum water content, the thicker the scaling. Flaking and delamination will take place as a transition between crumbling and scaling zones. In case of sedimentary rocks, if delamination occurs parallel to the stone's bedding plane, it weakens the boundary of each bed leading to detachment and loss (Snethlage and Wendler 1997, 7-24 and see the definition of the deterioration problems in Appendix IV).

3) Soil and Soil Subsidence

Soil is the upper layer of earth in which plants grow, usually formed from weathered rock changed by chemical, physical and biological processes and typically consisting of a mixture of organic remains, clay and rock particles (Clark 2003, 386; Soanes and Stevenson (eds.) 2004). Gravel and sand are the main components of non-cohesive soils and silt; clay and water are essential components of cohesive soils. According to the United State Department of Agriculture, soil textures can be classified based on their particle sizes into groups as follows: 1) clay is composed of soil particles smaller than 0.002 millimetre; 2) silt comprises particles ranging from 0.002 to 0.05 millimetre; 3) very fine sand comprises particles ranging from 0.05 to 0.10 millimetre; 4) fine sand consists of particles ranging from 0.10 to 0.25 millimetre; 5) medium sand consists of particles ranging from 0.25 to 0.50 millimetre; 6) coarse sand comprises particles ranging from 0.50 to 1.00 millimetre; and 7) very coarse sand consists of particles ranging from 1.00 to 2.00 millimetre (Bunyawat 1972, 51-74). If soils comprise particles greater than 2.00 millimetres, they can be considered gravels. The amount of water present and its alterations indicate the load-bearing capacity and shear resistance of soils. Since water fills in the gaps, pores and voids of soil, the volume of soil is altered when the quantity of water changes. When water in soil increases, the effects from the increase of soil volume are not as significant as the reduction of shear resistance of soils. In contrast, the reduction of water leads to the reduction of soil volume resulting in the deformation and subsidence of the soil. Partial loss of water, however, increases the shear resistance because of the increase of pressure and friction between grains.

Generally, soil subsidence is related to three main phenomena—a flow of soil, a reduction of pore volume, and a reduction of grain volume (Croci 2000, 117)—and water plays an important role in such alterations. Loss of water results in soil subsidence leading to the deformation of structure upon the ground. However, other agents also cause soil to subside. Weight of structure, additional loads or construction, and change of use are the most important factors causing soil to subside. Constructions change the equilibrium stage of soil, distributing loads partly to soil grains and partly to water in soil pores. The result is that water initially supports the loads and then it flows out slowly until a new equilibrium is reached. Consequently, soil subsides gradually under the pressure created by the weight of constructions and foundations and may cause damage to the structure. Because of the pressure from foundations that acts on soils, the weight of additional superstructure or loads causes increased pressure to the ground leading to further subsidence of the soil. Such subsidence is normally non-uniform resulting in an uneven structural support and causes severe damage to the structure. For masonry constructions, subsidence of soils can lead to micro damage such as cracks and tilting on building material blocks or to macro damage such as the loss of structural balance.

Landslide is the other form of soil subsidence caused by the alteration of surroundings. Soil, especially cohesive soil, tends to flow and fills in an area because of its clayish characteristic. Grains are maintained as stable by their shear resistance; therefore, when some parts of the area are extracted, its equilibrium stage is disturbed and the soil may consequently move. Soil movement will occur when horizontal forces are greater than the shear resistance of the soil —friction of the grains. Thus, landslides happen in the area where the surrounding topography is altered by quarries, caves or excavation. This includes nearby embankment after building construction, which causes horizontal stresses leading to horizontal displacement and vertical settlement of the soil, unless sufficient retaining walls are built to prevent this phenomenon. When accompanied by the alteration in stress distribution as discussed previously, creeping may occur. If water is also present, the shear resistance of the soil will decrease significantly, resulting in siphonage phenomena in which the soil fails to keep in shape—the loss of its plastic limit (Croci 2000, 120). Moreover, vibrations created by earthquakes or sudden loading cause saturated loose sands to behave as a liquid—called the liquefaction phenomenon—and this consequently results in a critical soil settlement (Croci 2000, 119).

The variation of water present in soils causes several forms of soil subsidence. Because of the permeability of soil, water can migrate from its voids resulting in the lowering of the water table, the reduction of void volume, and, consequently, the compaction, consolidation, deformation, and subsidence of soil. The greater the permeability of soil, the higher the rate of water outflow. When the water table is rising by capillary action which may possibly be caused by the blocking of an ancient drain or the leakage of sewage, soil expands and the shear strength decreases leading to sudden settlements, tilting, or landslides which increase the pressure on retaining walls or foundations. The seasonal variation of water induces leaching of small particles in the soil during the wet seasons and causes irreversible soil settlement during dry seasons. Moreover, when water evaporates, it dries out the surface soil and so the top strata shrink.

To summarise, soil subsidence is one of the environmental agents that cause materials to decay. However, its effect is mainly on physical damage such as cracks rather than on chemical or mineralogical deterioration. Its effect is therefore dependent on the strength of the materials. To carry out a study of an individual laterite block and its decay mechanism, it is necessary to investigate how a laterite block can withstand shear stresses created by an uneven support due to non-uniform soil subsidence. As tested in Chapter III, laterite can bear only a little shear loads and it is possibly not to be used as structural members to withstand shear stresses.

As well as soil subsidence that causes materials to suffer damage physically, the contamination of salts in soil is another decay agent causing materials to decay. Salts in soil are very harmful to materials. Saline soil is defined by the electrical conductivity of more than two milliohms/centimetre (siemens $x10^{-1}$/ metre) at 25°C. In the Northeast of Thailand, the main salt is sodium chloride (Yuwaniyom 1988a, 75-90). Saline soil can be observed with efflorescence depositing on the fields or with the occurrence of deserted areas where no vegetation is able to grow, except plants that can grow well in saline areas. The level of salty groundwater and the concentration of salts in soil also vary according to the seasons (ibid). In rainy seasons, salts are leached to the bottom and during dry seasons, when water evaporates rapidly, salts become deposited on the soil surface.

Salts in the soils of Northeast Thailand are derived mainly from saline rocks in the area; the decomposition of sandstone and shale near the soil surface which have salts as the main components; or from salty groundwater (Wongsomsak 1986, 133-153; Sinanuwong et al 1974, 105-120). Saline rocks found in Northeast Thailand are composed of anhydrite and potash (Sattayarak et al 1988, 46-79). However, Yuwaniyom states that these rocks are too deep so that salts in such rocks cannot be transported to the surface soil and so groundwater and the weathering of sandstone and shale in the area are only the sources of salts in the soils (1988a, 75-79). Humans sometimes increase the diffusion of salts to the land by salt farming, constructing reservoirs on salty soils, abandoning land, or by irrigation of their farms' land with brackish water (ibid.).

The saltiness of soils in Northeastern Thailand is divided into five classes—heavily salt-affected lowland, moderately salt-affected lowland, slightly salt-affected land, elevated ground composed of saline rocks, and non-saline areas (Vichaidist 1983, 80). Generally, the types of vegetation growing in the land can also imply the concentration of contaminating salts in soils.

Heavily salt-affected lowland contains a large amount of salts in the soils (more than 50%). Efflorescence is always found on the soil surface and salt crystals contaminate at several levels of the soils. In dry seasons, brine is found at the depth of one to one and a half metres, while in rainy seasons it can be found at fifty centimetres beneath the surface (Vichaidist 1988, 80-83). The land is usually barren because plants and trees cannot grow on such salty soils.

Vichaidist (1988), in the later article, divides the first class into two. The first class contains more than 50% of efflorescence in the soils while the second contains about 10-50% on which some vegetation can grow, but not very well. In dry seasons, brine is found two metres beneath the ground of the second class while in rainy seasons it can be found at a depth of eighty centimetres to one metre. Moderately salt-affected lowland is always in alluvial valleys where efflorescence can be found in some areas (about 1-10% (ibid.)). Brine may be found more than two metres beneath the ground. The soils are sandy so only those areas at a depth of two metres or more are saline. Since the soils near the surface are not noticeably saline, rice and trees of the *Dipterocarps* family are able to survive. Salts are barely detectable in slightly salt-affected lands (less than 1% efflorescence deposits on the soil surface), except in reservoirs, ponds, or recent alluvial valleys where the soils are saline. Since brine or brackish water is at more than two metres beneath the surface in such land, plants and trees can grow fairly well. In elevated ground composed of saline rocks, no efflorescence is found. However, in areas where the parent rock is sandstone or shale (salt bearing rocks in the Mesozoic Era), salts in the rocks become dissolved and are transported to lower land.

In conclusion, soils are the main source of salts capable of contaminating building materials, especially when the buildings are located in the countryside and there is no pollution. In the Northeast of Thailand, the most common salt in the soil is sodium chloride (or halite), so-called ‘rock salt’. This begins as a component of rocks and thereafter, becomes dissolved and transported to the soil surface by water. When water evaporates, sodium chloride crystallises and deposits on the soil surface as efflorescence. Such efflorescence is later dissolved by rainwater and the solution penetrates the soil resulting in saline soil. Finally, groundwater transports the salt as a sodium chloride solution to materials positioned upon the ground by capillary action. The effects of salt on materials are discussed below.

4) Salts

Salts are one of the most harmful agents able to cause materials to decay. The process of salt crystallisation depends on several components. These include the particular materials involved, water, salts or polluting compounds present in the soil, water and atmosphere, contributions from microorganisms, and the variations in climate and temperature that are accompanied by surface wind.

Water is the major solvent for the transportation of soluble salts into materials. However, it must be noted that water plays a major role in the deterioration of stone caused by soluble salts; salts would not be harmful to stone without the presence of water. The decay patterns caused by the presence of salts depend on the properties and types of the salts, their concentration, the condition of the stone, and the environment that can affect salt solutions.

Products of water-soluble chlorides, sulphates, nitrates and nitrites are commonly found as efflorescence on the surface or cryptoflorescence in the pores of materials. Under certain conditions, water-insoluble calcium carbonate can also deposit on the surface of materials as an incrustation (Teutonico 1988, 58). Chlorides, particularly sodium chloride (NaCl) and calcium chloride ($CaCl_2$), are found as the original composition of materials, transported from soils to materials by capillary action, or as aerosols of sodium chloride crystal spread from sea spray (Schaffer 2004, 60-66; Feilden 1982, 99). Thereafter, rainwater dissolves such salts and transports the solutions into material pores by capillary action. When the climate and temperature change, water evaporates leaving the salts crystallised in the pores or bringing the salts back to the surface before evaporating and leaving the salts as efflorescence. In the case that chlorides are part of the chemical composition of materials, when water migrates into material pores, it dissolves these salts from the materials. In a similar way, salts crystallise if water from the salt solutions evaporates. As previously discussed, in Northeastern and Eastern Thailand, chlorides usually come from ground containing saline soil.

Sulphates are usually found in atmospheric pollution resulting from the transformation of sulphurs in hydrocarbon to sulphur dioxide in the air during the burning process. When sulphur dioxide reacts with oxygen in the air, it becomes sulphur trioxide or sulphuric anhydride (SO_3), which then reacts with water resulting in a sulphuric acid product. Moreover, sulphuric acid can also be neutralised by basic substances such as ammonia (NH_3) to form ammonia sulphate ($[NH_4]_2\ SO_4$) or by calcium carbonate present in the air to form calcium sulphate or sodium sulphate (gypsum) (Teutonico 1988, 59). Other sources of sulphates include agricultural soil, seawater, pre-existing chemical components of materials or restoration agents, and microorganisms. Although these sources produce fewer sulphates than pollution, they are the main sources of a few sulphates which are found in sandstone, and probably laterite, in Khmer buildings in Thailand that is located in regions with no industry.

Nitrites and nitrates are produced by the decomposition of nitrogen-containing matter such as sewage and animal remains. Nitrites tend to become oxidised to nitrates so that they are rarely found in masonry (Borrelli 1999, 7). Therefore, this thesis focuses only on nitrates. Other sources of nitrates are agricultural land, photochemical smog in polluted areas with long periods of sunshine and microbiological organisms, which transform nitrogen compounds into nitrites and nitrates in their metabolism (Borrelli 1999, 7). As with sulphates in building stone in the northeast and east of Thailand, nitrates in such stone come from microorganisms rather than pollution.

Carbonates are usually found in the forms of calcium or magnesium compounds, which are the major components of carbonate rocks, such as limestone (Amoroso 1983, 9-51). However, because of their low solubility, calcium or magnesium carbonates are hardly considered as soluble salts in building materials. The solubility of carbonates dissolved to bicarbonates may increase in a condition containing a high concentration of carbon dioxide. However, with the interaction of carbonates and other compounds or soluble salts, the carbonate compound products may deposit on materials as efflorescence, sodium carbonate for instance. The chemical reaction of sodium carbonate may create the same effects as those of sodium sulphate (Arnold 1976 cited by Amoroso 1983, 9-51) and when it reacts with magnesium sulphate, sodium sulphate and calcium carbonate are the resulting products (Winkler 1994, 159). Moreover, when calcium carbonate again reacts with sulphur dioxide and moisture in the air, gypsum is also formed.

Here is the list of decay problems in stone caused by the effect of such salts:

Crystallization of soluble salts

As previously discussed, the transportation of soluble salts into materials such as stone relies on water. That means water dissolves salts from various sources, for example from the atmosphere and the soil, and then salt solutions penetrate the stone. Sometimes, only the presence of water dissolves the salts that already exist in the stone's natural components or contaminations. With the process of water evaporation, which occurs after the process of re-migration of the solution to the surface by capillary action, the concentration of the salt solution increases. Consequently, crystallization takes place during the state between saturation and supersaturation of the salt solution, but not during the state of unsaturation (Winkler 1973b, 119). Salts start crystallising first at the surface of a stone when the water has already evaporated and the stone is dry. Efflorescence, therefore, deposits when the stone is exposed to low relative humidity with a high rate of water evaporation. Locations where salts crystallise thus depend on the solubility of salts and the rate of water evaporation, as well as the moisture supply from the stone's interior and the rate of surface ventilation (Amoroso and Fassina 1983, 29). Cryptoflorescence, on the other hand, can often deposit within the pores, especially the large pores between dry and wet areas, when water evaporation takes place below the stone's surface. This leads to the decay of the stone because of the pressure exerted on the pore walls by crystal growth. Mixtures of salts are often more harmful than single salts. The surface will disaggregate, the thin surface layer crumble, and the bed plane be blistered or exfoliated (Torraca 1981). However, there is a claim that this kind of pressure is not always harmful to the stone. This is because the solid salts that crystallise through water evaporation from the solution occupy less volume than the original solution, and will not create any harmful pressure to the pores (Charola 2000, 327-343). The rate of decay caused by salt crystallization—in cases where it is harmful—depends on not only the types of salts and the frequency of crystallization cycles, but also on the durability of the stone's pores (Ashurst and Dimes 1990, 155). Porosity and size of pores in the stone are also relevant. Larger pores or less porous stones can survive salt crystallization attack better than the smaller pores or the more porous stone. When the pore size is smaller than five microns, the pore structure is extremely susceptible to damage by salt growth (Bell 1992, 875-885).

Another pressure produced by salt crystallization is hydration pressure. This occurs as an increase in volume when salts try to adjust themselves to another hydration state (Amoroso and Fassina 1983, 45). The adjustment occurs when relative humidity increases resulting in an increase of absorbed water in the stone. This phenomenon, therefore, depends on the change in atmospheric temperature and humidity. Generally, low temperature and high humidity contribute to the highest pressure (Winkler 1973a). Moreover, the degree of effect varies in different kinds of salts, and is associated with their hydration pressures and the rate of hydration. Sodium sulphate is one of the most effective deteriorating salts. Hydration of sodium sulphate thernardite to mirabilite is more rapid than that of the other salts. The hydration-dehydration process of sodium sulphate can be repeated several times a day—creating a rapid pressure change that affects the stone more severely than the effects caused by the pressure exerted from the hydration process alone (Winkler 1973b, 125). The rapid change happens because the hydration process of this salt is not dependent on water absorption by a solid crystal, but on the dissolution of salt crystals and re-precipitation from the solution (Charola 2000, 327-343).

Differential Thermal Expansion of Salts

The differences of the rate of thermal expansion of soluble salts compared with that of the other substances in stone can also cause the deterioration of the stone. When the temperature increases, the stone, including every substance, will expand—but in different ratios. For example, tests have shown that sodium chloride expands 0.5% while every mineral in granite expands less than 0.2% when the temperature is increased from 0°C to 60°C (Cooke and Smalley 1968, 1226-1227). Gypsum in sandstone expands 1.7 times of the expansion of sandstone and creates stresses that can peel off the surface of the stone (Ashurst and Dimes 1990, 158). Nevertheless, this effect is only a minor cause of the overall salt decay mechanisms (Charola 2000, 327-343).

In summary, the decay patterns caused by salts that can commonly be found are flaking and powdering of the stone. Generally, the concentration of salts will be higher in areas that have a higher moisture content—about 1-5 centimetres from the surface depending on the stone's porosity (Snethlage and Wendler 1997, 7-24), and these areas are more susceptible to deterioration. However, as previously discussed, if the volume of cryptoflorescence is larger than the pore or the hydration pressure occurs inside the pore producing stress that exceeds the limit of its resistance, the stone will be gradually broken. Consequently, the stone becomes more porous causing it to be more susceptible to further damage caused by water and salts. (Amoroso and Fassina 1983, 46)

5) Air pollution

Pure air is composed of 78.09% nitrogen, 20.94% oxygen, and 0.97% carbon dioxide and other gases by volume. When the composition and ratio changes, such as when there is contamination with dust, smog, sulphur dioxide and radiations, the air becomes polluted. Therefore, air pollution is an atmosphere containing excessive impurities for a sufficiently long time to harm humans, animals, vegetation and materials.

Atmospheric pollution is the product of human urban activities, industrial and commercial activities, heating and traffic, amongst other things. Pollutants include particulates, grit, and dust emitted from chimneys; smoke or fine solids; and gases, such as SO_2, SO_3, NO_x (oxides of nitrogen), O_3, Cl_2, and organic oxidants that are released from aerosols. Aerosols are liquid or solid particles suspended in the air, liquid droplets formed around sodium chloride crystals, for instance (Feilden 1982, 99). Amongst these, aerosols, especially those ranging from 10^{-2} to 10^{-6} metres in diameter, are the most harmful decay agents affecting materials of urban architecture (Winkler 1994, 114).

Being contaminated with some gases, such as oxides of sulphur (sulphur dioxide and sulphur trioxide) and oxides of nitrogen (nitric oxide and nitrogen dioxide), aerosols in the atmosphere are acidic and become acid precursors in the air. The sources of such gases in Thailand are both natural and man-made. Natural sources include fire and organic decomposition. However, most of the gases come from human activities, especially from fossil fuels, garbage burning, and automobile engines. Oxides of sulphur are the products of the combustion of sulphur-containing fuels, petroleum refineries, and copper, lead or zinc smelting.

Oxides of nitrogen come from the same industrial processes as oxides of sulphur. Nitrogen reacts with oxygen in the air during the burning process and becomes nitric oxide. If nitric oxide reacts with ozone in the air, nitrogen dioxide and oxygen are the resulting products. The higher the burning temperature, the more the oxides of nitrogen produced. In addition, oxides of nitrogen are produced from industries such as fertilizer production and explosive and potassium nitrate industries.

From the records of the Thai Pollution Control Department, in 1998 there were about 0.884 and 0.904 million tonnes of sulphur dioxides and nitrogen dioxides respectively in the atmosphere of Thailand (PCD 2004). However, Thai Pollution Control Department recorded that, despite having 2,397, 557, and 739 factories in the Nakhon Ratchasima, Roi Ed and Prachinburi Provinces respectively (the Sra Keaw Province used to be the eastern border of the Prachinburi Province and has recently been separated to be a new individual province; therefore, there has as yet been no record of factories in the Sra Keaw Province), the amount of pollution in these provinces is fairly low (below the Ambient Air Standards values). This is because most of the factories are industrial plants, such as rice mills, and these use very little amounts of fuel. Since Khmer architecture in Thailand is mainly located in villages in these regions with only agricultural activities, air pollution has been only a tiny contributory factor in the decay of laterite and sandstone in these areas; therefore, in this thesis, the effects of salts from pollution will not be focussed upon.

6) Vegetation and microorganisms

Microorganisms and vegetation, particularly trees, are among the most harmful agents causing materials to decay. The root penetration of large trees not only affects materials, but also damages the overall structure, while microorganic deposits create acids and salts from their metabolic process that cause the gradual decay of materials.

In tropical areas such as Thailand, there are two types of forest—evergreen and deciduous (Tongsawang et al 1988, 137). Evergreen forest is where the plants and trees retain their green leaves throughout the year, and can be divided into four categories—1) tropical evergreen forest, 2) coniferous forest, 3) peat swamp, and 4) beach forest (Rujirakul 1980, 173). Tropical evergreen forest is usually located in the areas influenced by seasonal monsoons. This first group may be further subdivided into tropical rain forest, dry evergreen forest and hill evergreen forest (Tongsawang et al 1988, 137-139). (Tropical rain forest in Thailand can be found in the South and the East.) Commonly, the topographical location of this forest group is on plains or on low-level plains (less than six hundred metres above the sea level). Dry evergreen forest is found in the upper part of Southern Thailand, the West, and in most parts of the Northeastern region. The topography of dry evergreen forest is at one hundred to eight hundred metres above sea level, while hill evergreen forest can be found on the mountains (higher than eight hundred metres above sea level). The second group of evergreen forest is coniferous forest including trees in the Pinaceae Family, such as *Pinus merkusii Jungh & De Vries* and *Pinus kesiya Royle.* ex Gordon (ibid). Peat swamp is the third group, which covers the coastal areas in the South and the East. The last group, beach forest, is also found along the coasts where it grows well in alkaline soil, gravels or sandy soil, and rock.

Deciduous forest comprises trees whose leaves fall during dry seasons (ibid). It is usually found in areas at fifty to eight hundred metres above sea level. Such areas in Thailand are found in the North, the central part and the Northeast as well as in the upper part of the South. Trees in the Dipterocarpaceae Family are the main forest group of the Northeast, a high level plain (fifty to one thousand metres above the sea level) with shallow lateritic soil layers. The final forest group is found where grass fields grow in destroyed forest areas whose soils are acidic and unsuitable for any other plants.

The trees that usually grow in Khmer complexes located in the Northeast of Thailand include *Shorea obtuse* Wall. (Burma Sal), *Hopea odorata* Roxb. (Iron wood) and *Dipterocarpus alatus* Roxb. of the Dipterocarpaceae Family, and *Ficus religiosa* L. (Bo Tree), and *Streblus asper* Lour. (Siamese Rough Bush) of the Moraceae Family (Pichard 1972, 17; Aranyanark 1992, 23-33; Rujirakul 1980, 174). Their seeds were carried to the area by birds and wind so that these trees grew and spread near monuments. The penetration of their roots and branches over the precious architecture in the years that followed, resulted in broken masonry blocks and, consequently, the deformation and collapse of the monuments. (In addition, the excrement of birds contains not only plant seeds, but also acids and bacteria and will be discussed below.)

Trees and higher plants affect monuments both physically and chemically (Winkler 1994, 225-227). Physically, as previously mentioned, their roots penetrate materials and monuments. Particularly, they tend to wedge along cracks and joints creating both axial and radial pressure, which results in the widening of cracks and the breaking of material blocks. Such cracks also enhance the accumulation of moisture. Moreover, tree roots cause blockages and ground dampness because they often find their way into rainwater drains. They may excessively withdraw groundwater leading to ground shrinkage. Because of ground movement, foundations move or partially lose their load-bearing support capacity, and then masonry blocks start to crack. In terms of chemical effects, the dissociation of calcite and silicates by chelation is the main problem. (Chelation is the uptake of metal ions into a void space of an organic ring structure (Winkler 1994, 225).) Plant root tips emit cathode hydrogen ions, which readily exchange their cations with negatively charged ions of metal minerals, such as silica and calcium, within materials and soil (Keller 1957, 30-

31). However, if one compares the physical and chemical decay mechanisms of materials, the former create more rapid and severe damage and represent a main material decay agent in Thailand.

Microorganisms and biological growth often found on ancient masonry in the tropics include bacteria, actinomycetes, fungi, algae, lichens, moss, ferns, selaginella, and liverworts (Aranyanark 2000, 2). Building materials in tropical countries suffer from biodeterioration much more than in temperate climates (Agrawal 1995, 14-34). This is because the hot and humid environment provides the ideal conditions for biological growth. When the ambient humidity is more than 65% and sunlight is sufficient, they grow rapidly (Feilden 1982, 132). In Thailand, bacteria, algae, moss, and, particularly, lichens usually deposit on brick, ancient sandstone and sometimes on laterite and cause the materials to decay. Biological growth like lichens, mosses, liverworts and higher vegetation may be observed and identified in the field and in the laboratory through visual analysis. In contrast, microorganisms (e.g. bacteria, fungi and algae) are not easily identified with only optical observation. They need to be studied by isolation and characterization of the active microbial agents, re-creation of the geomicrobial process and characterization of active microbial agents.

The effects of microorganisms and biological growth depend on their types. The most effective biological growth to have caused deterioration in Khmer monuments in Thailand is lichens (Aranyanark 1992, 23-33). Lichens are the product of fungi and algae growing together in a state of mutualism. The types of lichens found in Khmer monuments in Thailand which are built of sandstone and laterite, are crustose, foliose, and squamulose (Aranyanark 2000, 7). These often form on the surface of material, especially in the rough areas. (In such areas, algae and mosses also grow well.) They like to grow on sandstone and laterite because such materials are porous and usually damp.

Lichens affect materials both physically and chemically (Kumar and Kumar 1999, 22-23; Aranyanark 2003, 6-7). Physically, the rhizoid of lichens penetrates and crumbles materials, while some types of lichens with no rhizoid produce slime to stick to the materials. In addition, the thallus of lichens can disaggregate the grains of materials. When the ambient relative humidity changes, lichens on materials become wet or dry alternately resulting in the expansion and contraction of lichens. Such cycles create compression and tension stresses within the material. Thereafter, the material beneath the thallus of lichens has been burrowed into and disaggregated. With their metabolism, lichens affect materials chemically by producing organic acids such as carbonic, malic, saxalic, glycolic, succinic, oxalic, usnic, ascorbic, lecanoric, psoromic, lepraric, and stictic acids. Lichen acids also cause chelation, and of those, oxalic acid has been found to be the most aggressive. This produces several complex soluble salts which are washed away when water is present. Consequently, the materials lose some of their main chemical components and their cementing material. Their chemical compositions are also altered. For instance, if feldspars exist, the materials can be converted into clay minerals (Intasopa and Maranet 2000, 4).

Bacteria that are harmful to ancient materials in Thailand include *Bacillus cereus, Bacillus sp., Bacillus megaterium, Nitrosomonas europeau, Nitrosococcus nitrosus, Nitrobacter winogradsky, Pseudomas syringae, Ps. aureofaciens, Ps. alcaligenes, Ps. fluorescens, Ps. aeruginosa, Micrococcus varians, M. luteus, and M. roseus* (Aranyanark 1992, 23-33). They produce acidic matter, either organic or inorganic (Kumar and Kumar 1999, 14-16). Formic, acetic, glycolic, citric, gluconic acids are examples of the former while nitric and sulphuric acids are members of the latter group. Some bacteria also produce other chelator or ligand radicals, such as CN^-, NH_3^-, NO_2^-, which react with cathode compounds and become complex salts leading to further decay problems for the materials.

Fungi found harmful to Thai ancient materials are in the *Aspergillus, Penicillium, and Mycelia sterilia* groups (Aranyanark 1992, 23-33). Since fungi, unlike vegetation, have no chlorophyll, they survive by decomposing organic matter. The products from their metabolism include citric, gluconic and fumaric acids. The fungi in the *Trichoderma, Penicillium, Mucor, and Fusarium* group can also produce other acids, such as oxalic and malic acids (Kumar and Kumar 1999, 17; Aranyanark 1992, 23-33). As mentioned above, acids are harmful to materials. Moreover, fungi, especially the ones in the *Mycelia sterilia* group, produce pigments that discolour material surfaces.

Algae can be found in every Thai ancient monument (Aranyanark 1992, 23-33). Unlike fungi, algae have chlorophyll, and need moisture and sunlight to survive (called 'aerial algae'). In a dry environment, aerial algae can also grow on the monuments by absorbing water from the materials of the monument. Blue-green, green and yellow brown algae are the most frequently found (Aranyanark 2003, 6). Among these, yellow brown algae, especially several types of diatom, like to grow on damp monuments and consume silica compounds in building materials that have sand as a component such as sandstone. Therefore, they are the most harmful algae that attack Khmer monuments in Thailand (ibid).

Algae cause materials to deteriorate directly and indirectly (Kumar and Kumar 1999, 18-20). Directly, they produce organic acids including glycolic, formic, acetic, citric, carbonic, uronic, and ketonic acids, which react with material components such as silica, aluminium, iron, manganese, magnesium, calcium, potassium and sodium resulting in salt products. Since algae stick to the material surface tightly with the slime they create, when dried, some of algae scales off taking small pieces of the material with them. However, the rate and degree of scaling is dependent on environmental factors and the properties of the target materials (ibid). The indirect effect of algae is to introduce further decay problems to materials. When the surface is burrowed and it has lost some of its components, the material is more susceptible to weathering and decay. If the impacted surface contains holes, it may collect other decay agents, such as dust, soil and animal excrement. Since algae absorb moisture, the materials beneath them are always wet providing a suitable condition for other biological and microorganic growth. Moreover, algae, as well as mosses, create humus on which larger plants can grow. The growth of algae also clogs material pores leading to a lower permeability of the material and a slower rate of water evaporation and drying.

In summary, microorganisms and biological growth affect building materials either physically or chemically, especially at the surface. Physically, damage will be the result of the mechanical actions of these organisms. The biological growth will burrow beneath the surface and disaggregate the mineral grains from their cement. The deposition of biological growth on the surface can also clog the pores of materials, lower the evaporation rate and lead to a longer retention of moisture inside the stone (Snethlage and Wendler 1997, 7-24). Chemically, the microorganisms release acids and/or complex agents that cause the material to deteriorate. These agents include: organic acids such as formic acid, acetic acid, glycolic acid, citric acid; inorganic acids such as nitric acid and sulphuric acid; and other chemical chelator or ligand radicals that can react with cathode radicals and become several complex salts such as CN^-, NH_3, etc. (Jones and Wilson 1985, 99-104).

7) Human and animal interventions

Theft is an activity most harmful to Khmer architecture. The main purpose of thieves is to look for ancient treasures and archaeological artefacts. Without consideration, carved lintels, stone blocks and metal clamps are stolen, masonry is removed and foundations are dug causing materials to crack or break and causing general deformation of the construction. Despite being harmful, theft only affects stone physically and mechanically without any alteration of the chemical properties of stone.

Inappropriate conservation approaches of humans are another cause of decay, causing material to deteriorate physically and chemically. Using incompatible new material to support or stabilise ancient structures may cause further problems. For example, replacing laterite foundations with Portland cement reinforced concrete foundations is not only done without consideration of ancient materials and construction techniques, but it also introduces salts, especially soluble sulphates, to adjacent materials (Perkins 1997, 16). Broken ancient masonry blocks are replaced with newly quarried laterite blocks that have different stress resistances from those of the ancient ones leading to uneven load supports of the structure. Consequently, the blocks crack because of overstresses created by such uneven supports.

Humans, without realising the consequences, sometimes change the use of buildings or alter the environmental surroundings, resulting in material decay and structural damage. Inappropriate reuse of monuments results in changing loads on the structure, introducing other decay agents, and directly causing material to decay. Overuse of groundwater is an example of environmental alteration by humans. As previously discussed, when the water table is lowered, the surcharge of subsoil is altered, leading to a decrease in load-bearing capacity. Consequently, the superstructure moves unevenly resulting in the cracking and breaking of materials. Industrial and urban activities are other examples. Air pollution, another decay agent as discussed above, is the result. Moreover, vibrations created by human movement, automobiles, or industrial machines affect both the construction and building materials.

Graffiti are another form of human and animal impact. It may be in the form of scratching, drawing or handwriting, painting, chiselling, hammering, nailing, and so on. Deep graffiti, especially that done by sharp tools, act like minor cracks which enhance other decay agents to damage materials. In addition to humans, animals also make marks on surfaces. The scratching or boring of wild animals physically affects materials just as human graffiti does. In contrast, their excrement affects materials both physically and chemically (Feilden 1982, 151). They cause the material to have a dirty appearance and introduce other decay agents, such as bacteria, acids and plant seeds, to materials causing other decay problems. For instance, birds and bats damage materials with their roosting and nesting (ibid). The accumulation of their droppings and nesting materials forms compost, which can be digested by bacteria. As previously discussed, the digestion releases acids harmful to calcareous materials. The compost contains salts that may crystallise in the pores and cause further decay in this way.

4.2 Summary

Decay in building materials is related to several agents in the environment, both natural and human. The environmental agents include water (the most important), climate and temperature variation, air, soil and its subsidence, vegetation, the terrain where buildings are located, animal and human interventions and salts. The agents and their effects on stone are summarised below:

1) Variation of temperature between day and night causes unequal expansions leading to stresses developing in the material which lead to cracks on the material.

2) Water, being one of the most harmful decay agents, comes from several sources and can enter materials in various forms such as diffusion and condensation of water vapour and transportation of liquid water by capillary action.

3) The main sources of water migrating to building materials in Thailand are rainfall, groundwater and moisture in the air.

4) Water trapped inside stone dissolves soluble salts and transports them to the stone; creates pressure inside the pores when it changes phases; and causes stone to dilate and contract due to the change of moisture content within the pores through wet and dry cycling.

5) Soil subsidence mainly causes physical decay such as cracks rather than chemical or mineralogical deterioration.

6) Soil subsidence is caused by its flow; the reduction of its pore and grain volumes; the reduction and variation of its water content; and the alteration of surroundings.

7) Salts are among the most harmful agents causing materials to decay, and water is the major solvent transporting them into materials.

8) Crystals of water-soluble chlorides, sulphates, nitrates and nitrites are the most commonly found as efflorescence on the surface or cryptoflorescence in the pores of materials after water evaporates.

9) Salt crystallization exerts hydrostatic and hydration pressures to surrounding stone compositions causing the surface to disaggregate, the thin surface layer to crumble and the bed plane to blister or exfoliate.

10) The differences of thermal expansion of soluble salts compared with that of the substances in stone can also cause the deterioration of the stone such as flaking and powdering.

11) Soils are the main source of salts contaminating building materials, especially when the buildings are located in the countryside where there is no pollution. The most commonly found salt in the soil in the northeast of Thailand is sodium chloride.

12) Air pollution is one of the most harmful decay agents affecting materials of urban architecture.

13) Since Khmer architecture in Thailand is mainly located in villages with only agricultural activity, air pollution has been only a tiny contributory factor in the decay of laterite and sandstone in these areas.

14) Microorganisms and vegetation, particularly trees, are among the most harmful agents causing materials to decay and, especially, damage.

15) The root penetration of large trees affects materials and damages the overall structure, while microorganisms stain the surface and create acids and salts that cause the gradual decay of materials by their metabolic process.

16) The most effective biological growth to have caused deterioration in Khmer monuments in Thailand is large trees and lichens.

17) Human activity is the most harmful decay agent; it includes theft of materials, inappropriate conservation approaches and change of use of buildings. All can result in material or structural damage.

The main environmental decay agents that have been affected the stone used in Khmer architecture in Thailand is summarised in Table 4.1 below:

Table 4.1: Summary of the main decay agents affecting on Khmer monuments in Thailand

Decay agent	Source	Effect
Water	Rainfall, groundwater, moisture in the air	Dissolving and transporting salts, causing dilation and contraction of stone, exerting pressure within stone's pores
Soil subsidence	Flow of soil, alteration of soil's water content, alteration of the surroundings	Crack and structural damage
Salts	Soils	Efflorescence on stone and cryptoflorescence in its pores, powdering, flaking, disaggregating, crumbling, exfoliating and blistering of stone
Large trees and lichens	Natural existing, bird excrement	Crack and structural damage, stains on stone's surface, some chemical deterioration and providing of suitable conditions for themselves and other decay agents
Human activities	Theft, inappropriate conservation approaches, alteration of building uses, alteration of the surroundings	Material and structural damage

However, the discussion above is based only on existing records for stone, especially sandstone, which was used in Khmer construction, while the decay mechanisms of laterite is still unknown and still needs to be studied. Therefore, in the next chapter there will be a pilot testing programme to study the effects of some environmental decay agents on laterite through laboratory experiments.

CHAPTER V

EFFECTS OF SOME ENVIRONMENTAL DECAY AGENTS ON LATERITE

In the previous chapter, the decay mechanisms of a building material caused by the atmosphere and other environmental decay agents, both natural and manmade, were reviewed and discussed. However, since laterite is a material that has yet to be studied in terms of the alterations that occur after environmental exposure, in this chapter, the analysis of laterite decay mechanisms will be investigated using laboratory experiments as a pilot study. The results of these experiments will then be analysed and compared to selected records for sandstone. In addition, the efficacy and necessity of these tests will be evaluated.

Again, it is to be noted that this research is continued from the study for my Master's thesis (Watsantachad 2001); therefore, the test methods here are mainly based on my previous study.

5.1 Selection of the tests

In order to select the tests to be carried out as a simulation programme for investigation the effects of environmental decay agents in this chapter, the literature was reviewed simultaneously with the literature review in Chapter III. (See Table 3.1 on page 105) The study of weathering (decay) resistance capacity is the test applied most frequently to stone. 68.2% of the reviewed research on decay mechanisms applied artificial weathering conditions to investigate the effects of the weathering agents on the studied materials. Within the body of material reviewed, 61.5% of the research identified and discussed salts while 53.8% studied the effects of material deterioration. When all the reviewed articles are considered, half of the articles tested the weathering resistance of materials, 26.7% focused on the identification of salt content and 23.3% studied the condition of material deterioration (see Table 3.1 in Chapter III and the list of literature in Appendix II). For testing resistance to decay, researchers usually simulated the effects of two major environmental decay agents: 1) salts (using a salt crystallization test) and 2) water (using freeze-thaw cycles and wet-dry cycles). Table 3.1 shows that 53.3%, 33.3% and 26.7% of the articles applying weathering tests tried salt crystallization, freeze-thaw cycles and wet-dry cycles, respectively. However, as previously discussed, since the temperature in the provinces where Khmer architecture is located has never been below zero, stone and laterite used in Khmer architecture in Thailand are never affected by freeze-thaw repetition. Therefore, the characterization of freeze-thaw resistance of laterite is omitted in this thesis.

In terms of advanced methods using high-technology instruments, X-ray Diffraction analysis, Fourier Transform Infrared Microspectroscopy (FTIR) or other methods, such as Atomic Absorption Spectroscopy (AAS) or Ion Chromatography (IC) were frequently applied to identify salt contents in stone. Scanning electron microscopy and drilling resistance analysis were usually applied to observe and assess the degree of deterioration. Moisture content could be measured in the drilled holes of the stone using a moisture sensor or microwaves.

In order to determine the methods and tools to be applied to simulate the effects of the selected environmental decay agents and to characterise the decay resistance of laterite, a brief summary of tests is displayed in Table 5.1. However, similar to the choice of tests for characterising laterite properties in Chapter III, not only were recommendations by other researchers and organizations considered, but the availability of tools and the limitation of sample collection were also taken into account. For instance, although X-ray Diffraction analysis is highly effective in the identification of salts in stone, it was costly and unaffordable at the time of the test being carried out. Furthermore, one of the purposes of carrying out the tests is to compare the properties of laterite with those of the sandstone used in Khmer architecture in Thailand which was tested by the author in 2001 (Watsantachad 2001, 43-46). The reason for this is to determine the degree to which laterite performs and weathers like stone, since this comparison might provide clues as to how it might be conserved. Therefore, where possible, the same standard tests applied to test such sandstone were selected for testing the selected laterite. The testing programme to be conducted in this chapter is therefore summarised in Table 5.2.

Table 5.1: Summary of tests for characterization the decay mechanisms of laterite

Properties	Tested area	Applied test	Advantage	Disadvantage
Resistance to decay	Stone sample	Salt crystallization test	- Simple and cheap - Useful to indicate salt resistance	- Sodium sulphate solution is harmful. Care needs to be taken during the test
	Stone sample	Wet-dry cycling	- Able to determine the effects on individual pieces of rock for wet-dry erosion - Able to evaluate the durability of stone	- Unable to provide an absolute value; thus, the test cannot be used as the sole basis for the determination of stone durability
	Stone sample	Accelerated weathering test	- Useful to simulate natural weathering by wet and dry cycle - Able to indicate the UV-radiation resistance of stone	- Expensive - UV-radiation is harmful
Soluble salts	Stone sample	X-ray diffraction	- Used to identify the efflorescence of salts over the stone surface	-Unable to identify invisible salts in stone, especially after cleaning and while the stone has not been dried
	Ground stone sample	Qualitative salt analysis test	- Simple - The rough quantification of salts can be furthered with Salt-Test analytical testing strips	- Unable to indicate accurate amount or concentration of salts

Table 5.2: Summary of tests to be applied for characterising the decay mechanisms of laterite

Property to be tested	Test/method to be applied	Required sample
Weathering resistance	Ex.15-Teutonico: Salt crystallization test	Five 2x2-inch cube (about 5x5-centimetre)
	ASTM D-5313: Wet-dry cycling	Five 2x2-inch cube (about 5x5-centimetre)
Soluble salts	Ex.16-Teutonico: Qualitative salt analysis test	Randomly selected sample

5.2 Sample preparation

The samples to be subjected to the tests in this chapter were drawn from the same laterites which were subjected to the tests described in Chapter III—laterite samples collected from four different sites (three ancient sites and one freshly quarried). (See the process of sample preparation in Diagram 3.1 in Chapter III on page 118) All laterite samples were cut into shapes according to the requirement of each standard test, and their porosities were calculated. The details of samples required in each test are discussed below.

5.3 Testing programme

5.3.1 Effects of water

Method

1) **Wet-dry cycle test**

Changes in stone moisture content during wet and dry states cause stone to expand and contract, and consequently, lead to stone friability (see Appendix IV for the definition). Therefore, the wet-dry cycle test determines the effects on the stone for erosion control of wetting and drying action, as well as the resistance of the stone to deterioration.

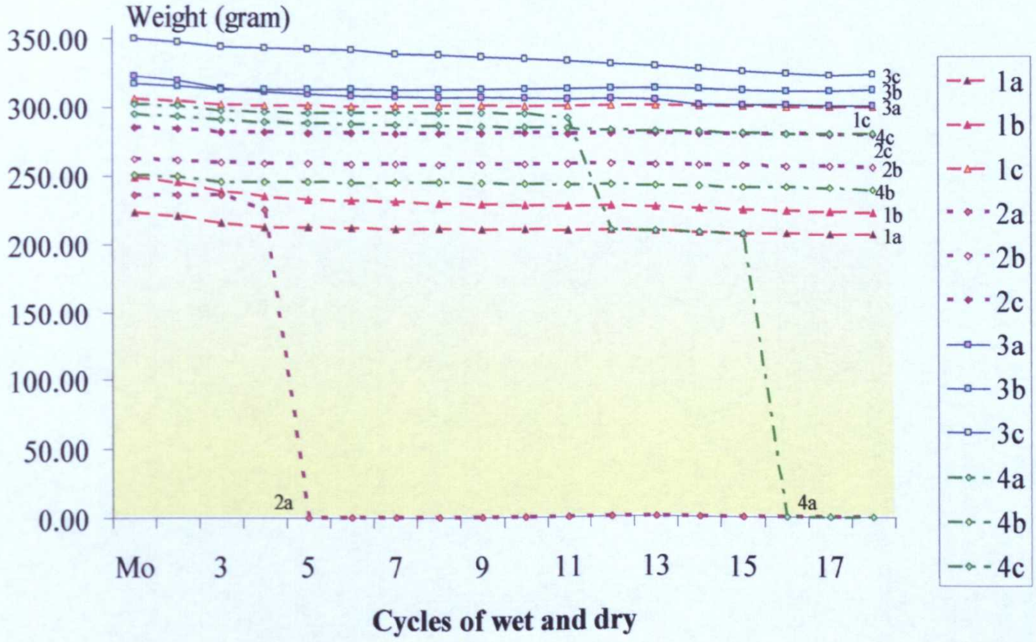
The adopted test followed ASTM D-5313. Because of the limitation of samples, only three laterite cubes (2"x2"x2" or about 5x5x5 centimetre) of each sample set were tested. They were first dried in the oven at 60°C for 24 hours. After being removed from the oven and cooled in a desiccator, the cubes were weighed, and then were immersed in a container of de-ionised water for 24 hours (the same procedure as the water absorption by total immersion test). They were weighed again after 24 hours of immersion, and re-dried in the oven at 60°C for 24 hours. The cycle was repeated until evidence of macroscopic deterioration of the tested cubes was observed.

Results (See Appendix V for the raw data)

Table 5.3: Laterite damage after wet-dry cycle test

Sample 1		Sample 2		Sample 3		Sample 4	
a	remained intact after 18 cycles	a	broke after 4 cycles	a	remained intact after 18 cycles	a	broke after 15 cycles
b	remained intact after 18 cycles	b	remained intact after 18 cycles	b	remained intact after 18 cycles	b	remained intact after 18 cycles
c	remained intact after 18 cycles	c	remained intact after 18 cycles	c	remained intact after 18 cycles	c	remained intact after 18 cycles

Chart 5.1: Laterite sample weights and wet-dry cycles



Conclusion

Table 5.4: Percentage total weight loss of laterite after wet-dry cycles

Sample		Mo (g)	Md (g)	%TL
1	a	223.45	206.40	7.63
	b	249.35	222.00	10.97
	c	306.90	299.00	2.57
2	a	235.90	0.00	100.00
	b	262.55	255.00	2.88
	c	285.55	279.00	2.29
3	a	322.65	300.40	6.90
	b	316.85	311.20	1.78
	c	349.75	323.00	7.65
4	a	302.45	0.00	100.00
	b	250.70	238.70	4.79
	c	294.95	279.50	5.24
Mean of %TL=				21.06
Mean of %TL(excl broken) =				5.27
Number of samples=				12
Number of broken=				2
% of broken=				16.67

Mo = Original dried weight
Md = Final dried weight
TL = Total weight loss

The repetition of wet and dry conditions caused only 16.67% of the laterite samples to break before the end of the test (eighteen cycles of wet and dry) resulting in the greatest average weight loss of 21.06%. It can be concluded that the repetition of wet and dry conditions is possibly not the main environmental agent that causes laterite to decay or damage—as many as 83.33% of samples remained intact after eighteen cycles of wet and dry conditions.

5.3.2 Effects of salts

Method

1) **Salt crystallization test**

As already explained, when stone is contaminated with a solution of salts, crystallization will occur once the water, as the solvent, is evaporated. This process will produce pressures by non-accommodative crystal growth in the pores of stone, and will lead to disruption (Winkler 1973b, 119; Price 1996). Therefore, the salt crystallization test serves to evaluate the durability of the stone as to whether or not it can resist pressure exerted by the crystallization of salts, and this test is one of the oldest and most aggressive artificial aging tests that can also be used to evaluate the effectiveness of stone consolidation. The test is based on Experiment 15 in *A Laboratory Manual for Architectural Conservators* (Teutonico 1988, 57). As previously stated, this research is continued from the earlier study; therefore, based on such research, the test suggested by Teutonico is used rather than the more recent one suggested by Borrelli.

The salt solution recommended for testing is a 14% solution of sodium sulphate decahydrate ($Na_2SO_4 . 10 H_2O$), called “Mirabilite”. Three ancient laterite cubes and fresh one (2”x2”x2” or about 5x5x5 centimetres) were tested. Before being tested, all samples were dried in the oven at 60°C for 24 hours, and then cooled in a desiccator. They were weighed before immersion in the salt solution for 24 hours, and then were dried again in the oven for 24 hours. The cycle was repeated until evidence of macroscopic deterioration of the laterite cubes was observed.

2) Qualitative analysis of water-soluble salts

Stone may naturally contain water-soluble salts as mineral constituents, such as halite. However, salts often migrate into stone pores after the stone has been set in place (Winkler 1973b, 111). These salts may come from the ground, through exposure to air pollution or sea spray, or from some construction materials attached to the stone. Salt formation, through dissolution and crystallization in the pores, can cause several problems to the stone by producing disruptive pressures while crystallizing, or creating differential thermal expansion between themselves and their host—the stone.

The main soluble salts that are normally present in stone as deterioration products are sulphates, chlorides, nitrites and nitrates (Teutonico 1988, 58). By measuring and identifying which of these are present, the data obtained can be used as clues to study and predict the decay mechanism and type of deterioration that have occurred in the weathered stone. The qualitative analysis of water-soluble salt content is based on Experiment 16 in *A Laboratory Manual for Architectural Conservators* (Teutonico 1988, 58).

Result

Table 5.5: Laterite damage after salt crystallization test

Sample 1		**Sample 2**		**Sample 3**		**Sample 4**	
a	broke after 6 cycles	a	broke after 9 cycles	a	broke after 6 cycles	a	broke after 4 cycles
b	broke during 6th cycle	b	broke during 8th cycle	b	broke after 6 cycles	b	broke after 5 cycles
c	broke during 6th cycle	c	broke during 8th cycle	c	broke after 6 cycles	c	broke after 4 cycles

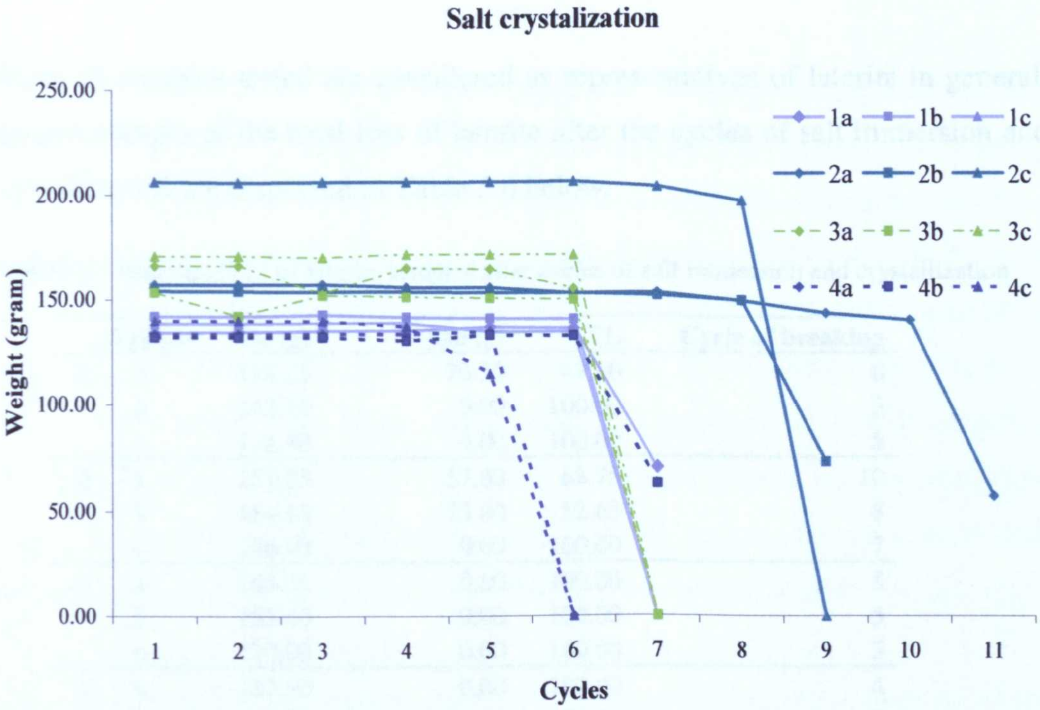
Regarding the analysis of salt contents (see the sample preparation in Diagram 3.1 in Chapter III on page 118), all sets of laterite samples were ground and mixed with deionised water in a tube in order to dissolve any soluble salts. The solutions obtained from this mixture were divided into tubes and tested. From the qualitative analysis of soluble salts in the laterite samples, only chlorides were observed in the solutions from Sample 1, 2 and 3. With the test reagents, the chemical reaction was as follows:

Drops of diluted nitric acid (HNO_3 -2N concentration) and silver nitrate solution ($AgNO_3$ –0.1N concentration) were added to the solution in the tubes. Precipitation of silver chloride (AgCl) produced a whitish-blue gelatinous precipitate, and indicated the presence of chloride ions in the solution.

$$Cl^- + AgNO_3 \longrightarrow AgCl + NO_3^-$$

However, the result obtained from strips for chloride concentration measurement indicated that the amount of chloride contaminating the laterite samples was as little as the lowest measurable concentration, i.e. 0-500 mg/l.

Chart 5.2: Cycles of salt crystallization and weight loss of laterite samples (three cubes per each sample)



The test shows that laterite samples were susceptible to salt crystallization. Chart 5.2 above show in which cycles of salt crystallization the tested laterite samples were broken. Two of Sample 1 were in a completely crumbly and broken state (their last dried weight were considered as zero) and the other was split at the end of the sixth cycle. All of the sample 3 were in a completely crumbly and broken state during the sixth salt immersion as well. Similarly, two of Sample 4 were crumbled and broken during the fifth cycle of salt immersion while the other was split at the end of the sixth cycle. Sample 2 was more resistant to salt crystallization than the others—one was totally broken and crumbly, one was split at the end of the eighth cycle, and the other was damaged at the end of the tenth cycle.

Conclusion

When all samples tested are considered as representatives of laterite in general, the percentages of the total loss of laterite after the cycles of salt immersion and crystallization are displayed in Table 5.6 below:

Table 5.6: Total loss (TL) of laterite samples after cycles of salt immersion and crystallization

Sample		Mo (g)	Md (g)	%TL	Cycle of breaking
1	a	134.15	70.30	47.60	6
	b	142.15	0.00	100.00	5
	c	138.50	0.00	100.00	5
2	a	157.25	57.00	63.75	10
	b	154.10	73.00	52.63	8
	c	206.40	0.00	100.00	7
3	a	166.35	0.00	100.00	5
	b	153.40	0.00	100.00	5
	c	170.90	0.00	100.00	5
4	a	133.50	0.00	100.00	4
	b	132.10	62.80	52.46	6
	c	139.90	0.00	100.00	4
			Mean of %TL=	84.70	
			Mean of %TL(excl broken) =	54.11	
			Number of samples=	12	
			Number of broken=	8	
			% of broken=	66.67	

Mo = Original dried weight, Md = Final dried weight and TL =Total weight loss)

The calculation shows that laterites lost 84.70% of their original weight after ten cycles of salt immersion and crystallization. 16.67% of laterite (two of twelve samples) were totally broken at the end of the fourth cycle; 41.67% (five of twelve samples) were in a complete crumbly and broken state at the end of the fifth cycle; and 41.67% were completely broken after the fifth cycle. In terms of the condition of laterite after being decayed by sodium sulphate, 66.67% of laterite were in a complete crumbly and broken while 33.33% were only split. Obviously, all samples were physically damaged; therefore, it can be concluded that laterite is susceptible to the effects of sodium sulphate crystallization. However, in reality, laterite buildings located in remote areas may survive the effects of salt crystallization, especially sodium sulphate, because, according to the salt qualitative analysis, such salts are not present in laterite.

It is possible that the chloride in the samples from the ancient sites derived from soils as previously discussed. Noticeably, Samples 1, 2 and 3 containing chloride were collected from the ground and had been buried in the soils for a period. Thus, it is possible that the salts found in the samples were from the soils that buried them. Being newly quarried, Sample 4 contained no salts, or so little, that they were untraceable. This data confirms that salts in laterite were from the environment rather than being the original composition of laterite samples. However, the amount of chloride contaminating in the laterite was very little and can possibly be considered to be nil, and so it can be concluded that environmental salts are not involved in the deterioration of laterite.

One of the possible reasons why salts are not present in laterite is because of the size of its pores. Laterite is composed of such large pores and voids that capillary action cannot happen; therefore, environmental salt solutions may not be transported into the body of the laterite.

5.4 Conclusion

According to the observations of several laterite-building sites in Thailand and the conclusion of the qualitative analysis of salt contents, efflorescence and subflorescence was rarely encountered, but analysis of the salt content of the samples showed that chloride, possibly sodium chloride, was the predominant salt. However, if sodium sulphate had been present instead of sodium chloride, the effect would have been more severe, as seen from the result of the test described above. Sodium sulphate is the most harmful salt that attacks stone—according to Weber and Zinsmeister, sodium chloride affects stone much less harmfully than sodium sulphate (1991, 43). The molecular volume of sodium sulphate decahydrate ($Na_2SO_4.10H_20$) is 220, while that of sodium chloride is 28. Under test conditions it can be seen that this difference will produce a much greater effect if sodium sulphate is used, rather than sodium chloride.

However, the purpose of the salts crystallisation test is to give an indication of the level of vulnerability of a material, compared to another, and is intended to simulate in a short period of time, what in reality takes place over a long period of time. It is not specifically to test the resistance of a set of samples to sodium sulphate crystallisation, nor will it provide any evidence of the relative vulnerability of a set of samples to different types of salts. As previously explained, laterite was generally used together with sandstone in Khmer architecture, even in cases of laterite buildings where sandstone was used as structural members such as lintels. Therefore, in this thesis, the comparison of the tested laterite and sandstone results is the most important comparison.

The comparison of the decay mechanisms of sandstone and laterite is displayed in Table 5.7.

Table 5.7: Comparison of the decay machanisms of laterite and sandstone

Property		Sandstone		Laterite 1		Laterite 2		Laterite 3		Laterite 4	
	Anionic salt contents	- Chloride - Nitrate		- Chloride		- Chloride		- Chloride		- nil	
Decay mechanism	Wet-dry	a	broke after 2 cycles	D/a	remained intact after 18 cycles	D/a	Broke after 4 cycles	D/a	remained intact after 18 cycles	D/a	broke after 15 cycles
		b	broke after 4 cycles	D/b	remained intact after 18 cycles	D/b	remained intact after 18 cycles	D/b	remained intact after 18 cycles	D/b	remained intact after 18 cycles
		c	remained intact after 5 cycles	D/c	remained intact after 18 cycles	D/c	remained intact after 18 cycles	D/c	remained intact after 18 cycles	D/c	remained intact after 18 cycles
	Salt	U1	broke after 4 cycles	F/a	broke after 6 cycles	F/a	Broke after 9 cycles	F/a	broke after 6 cycles	F/a	broke after 4 cycles
		U2	broke during 7th cycle	F/b	broke during 6th cycle	F/b	Broke during 8th cycle	F/b	broke after 6 cycles	F/b	broke after 5 cycles
		U3	broke during 7th cycle	F/c	broke during 6th cycle	F/c	Broke during 8th cycle	F/c	broke after 6 cycles	F/c	broke after 4 cycles

Note: The capital and small letters in the table are the labels of the tested samples.

When compared with sandstone used in the same sites, laterite is not very much decayed by their environmental salts. In the tests, when laterite was attacked by sodium sulphate, it was decayed less severely than sandstone tested in my earlier research (Watsantachad 2001, 106-107). This might be because laterite samples were mostly composed of pores larger than five microns which are not supposed to be susceptible to salt crystallization (Bell 1992, 878), while the pores of sandstone samples were smaller and more susceptible to salt attacks. Noticeably, sandstone was mostly damaged with the split along its bedding planes while laterite was crumbled overall, eventually being completely broken. Therefore, the chemical constituents and physical structure of the materials might have been involved in the degree and rate of salt decay. The tested sandstone was ferruginous. Its bedding plane was mainly composed of quartz cemented with ferric oxide while between its beddings was clay and iron oxide cementing (Watsantachad 2001, 53). Iron oxides and clay cement are easily susceptible to chemical degradation, resulting in the disaggregating of grains and exfoliation of stone according to its bed plane splitting (Aranyanark 2000, 1). Therefore, the bedding planes of sandstone are the most susceptible area to wet-dry cycles and salt attacks. In contrast, having observable vesicular structure, laterite should not have been susceptible to salt attack and wet-dry repetition. However, it may be possible that the material, likely to be clay or kaolin (Sinsakul nd.), filling in the pores of laterite was responsible for the damage occurring during the tests. Clay is susceptible to salt attacks and wet-dry cycles, and it might have swollen and exerted pressure within the large pores of the laterite samples leading to the breakage of the laterites.

The standard tests for porous material performed in this chapter were applicable to investigate the decay mechanism of laterite. However, they only simulated the decay mechanisms under laboratory conditions; the environment of the tests was not the real environment that affects laterite buildings in Thailand, and the environmental agents causing laterite to decay in reality are not only water and salts. Hence, in order to study the decay mechanisms of laterite used in Thailand thoroughly and learn whether or not such decay affects the mechanical strength of laterite, deterioration assessments of laterite buildings also need to be conducted. These assessments, which enhance the knowledge of the decay mechanisms that actually happen to Khmer laterite buildings in Thailand, will be carried out and discussed in the next chapter.

CHAPTER VI

DETERIORATION ASSESSMENTS OF LATERITE FAÇADES

In the previous chapter, laterite performance and decay mechanisms were studied and tested, but only under simulation conditions in the laboratory. Questions of environmental factors were raised but left unanswered. They can only be considered through field observations of standing structures, and in order to understand weathering processes, the deterioration rates of walls that face in different directions must be observed and compared. Such a study will enhance our understanding of the real weathering processes of laterite and the effects of actual environmental factors.

The purpose of the following assessment of deterioration in façades is to survey and record the current condition of the stonework and estimate decay and damage caused by environmental weathering agents or structural impacts, as well as to observe and record any previous conservation treatments and alterations. Such assessment not only is a mandatory task prior to further conservation treatments or stabilization, but also yields supporting information to conservators when investigating causes of alteration and deciding an appropriate conservation approach.

This chapter will concentrate on two types of façade deterioration—macro and micro, based on whether or not their physical effects can be observed by eye. Theoretically, macro alterations should be related to physical changes in the structure as a whole, while micro alterations are rather the results of chemical or mechanical decay mechanisms. Nevertheless, a few cases contradict this theory; for instance, biological growth and animal excrement attack stone not only physically but also chemically resulting in both macro and micro alterations. In this thesis, macro deterioration assessment will therefore be focussed on either natural weathering evidence on façades visible by eye including cracks, flaking, spalling, detachment, disintegration, and microorganic deposits; or any damage caused by man or animals. At the same time, the purpose of micro assessment is rather to investigate the changes in laterite properties occurring within the structure, invisible to the eye, including change in mineral and chemical composition, porosity and compressive strength.

For this purpose, in this chapter, a Khmer laterite monument has been selected as a case study. I begin by explaining the criteria for selecting a site to be studied and then environmental and general current conditions of the site are discussed. Afterwards, the deterioration assessment section will begin with the assessment of macro alteration based on photographic records and manual survey of the current condition of the walls of the selected monument, and end with a graphically computerised analysis using AutoCAD. The micro alteration assessment is carried out on laterite samples collected from different locations in each façade and three laboratory tests, proved in Chapter III as the applicable tests for characterising laterite, are applied. These tests are adapted from ASTM and other standard tests for stone properties. Sampling methods and testing aims and procedures are discussed followed by the results of each test. Thereafter, the data obtained from the tests are analysed using EXCEL and SPSS computer programmes. Finally, comparisons amongst the changes taking place on each side of the façade are discussed and the correlations between the environment in different positions of the walls and the deterioration of laterite properties are calculated and conclusions drawn.

It is worth noting that this chapter is focussed only on the assessment of laterite deterioration in relation to its location, while the causes of such deterioration and the correlations of such deterioration with other laterite properties will be studied and discussed in detail in the next chapter.

6.1. Case Study

6.1.1 Selection of a case study

As previously discussed, Khmer monuments in Thailand are mostly situated in the northeastern region; hence, the search for a representative example of laterite architecture was concentrated in this region. Thus, the suitability of the location to the aims of the study is the first criterion for selecting a site.

The accessibility of the site was an important criterion. Since many sites have been abandoned to the forest and are inaccessible, an excavated site (by definition, therefore, accessible to archaeological teams) was sought. This gave the added advantage of the existence of site documentation. Since all heritage monuments in Thailand are cared for by the Department of Fine Arts, gaining their permission was also a requirement for access.

The selection was also based on other criteria: the site, particularly the walls, must be mainly built of laterite; the walls must survive to an acceptable height and their condition must be recordable; most importantly, there must be some observable evidence of weathering problems on the walls.

Nakhon Ratchasima province in the northeast of Thailand was the centre of the western Khmer Empire's state. It therefore has abundant Khmer architecture including the major Phimai Complex and several hospitals and pilgrimage rest houses along the Imperial Road running directly from Angkor to Phimai. Furthermore, since, in the present day, it is the nearest province to the northeast of Bangkok, most of the Khmer monuments located in Nakhon Ratchasima have also been excavated resulting in their accessibility.

The Ban Prasat complex was selected for following reasons: it has been recently excavated but not yet restored; it is accessed easily and safely; it is officially accessible with the permission of the Department of Fine Arts; and it demonstrates observable deterioration problems.

The Ban Prasat complex is located in the District of Meung Prasat in the City of Nonsoong in the Province of Nakhon Ratchasima at the 15°11'46'' north latitude and the 102° 18' 04'' east longitude. Built in the eleventh to thirteenth century, it is one of the ancient Khmer monuments in Thailand that are between seven hundred and a thousand years old. Its surroundings are agricultural fields with a small creek one and a half kilometres away to the north. The pool in the site was dug at the time the monument was built. The information of the site in detail could be found in FAD's *The Summary of the archaeological excavation project at the Ban Prasat Complex* (2003).

The Ban Prasat complex is a pilgrimage rest house composed of a main sanctuary at its centre and a library called in Thai '*Banalaya*', located in the southeast enclosed by a boundary wall with an entrance gateway in the east and a pool located outside the wall in the northeast. (See Figure 6.1 on page 258 and Map 6.1 on page 259) All buildings in the complex were built of laterite between the eleventh and the thirteenth century (FDA 2003, 1). Of the surviving buildings only two fulfil the criteria of walls surviving to a recordable height: the library and the gateway have over seven courses of remaining masonry, and are higher than one metre. By contrast, the main sanctuary and the boundary wall remain to only four courses of masonry, on average or less than one metre high. However, a comparison between the library and the entrance gateway shows that the former has not been conserved or stabilized even temporarily and its walls display a higher level of weathering problems than those of the latter. Since it fulfils all the criteria listed above, the library, *Banalaya*, is thus selected to be the case study of this chapter (see Figure 6.1 at the end of the chapter).

6.1.2. Historical, environmental and general current conditions of the case study

It is necessary to document the historical and environmental conditions of an ancient site before a discussion about appropriate conservation approaches/treatments to the building can be made. The scientific investigation which will be carried out in the following section on the historical and environmental conditions, including all completed or uncompleted additions and interventions, also yields information about the site that helps conservators to understand how the building has reached its current condition and, thereafter, how to deal with it. In this section, the location and its surroundings, the date of construction, and the conditions of the site before excavation will be discussed.

Before the excavation in 2003, the monuments in the complex were covered with grasses, vines and trees of the tropical rain forest such as tamarind trees (*Tamarindus indica*) and persimmon trees (*genus Disopyros*). Buried under local soils, whose types have not yet been identified, one third of the monuments were placed on a mound at a slightly higher level than the ground level of the fields. Apart from remaining laterite walls and bases, occasional sandstone blocks and bricks were found, and there was evidence of theft from the treasury. According to local elderly people, some laterite blocks were removed for constructing nearby temples and roads.

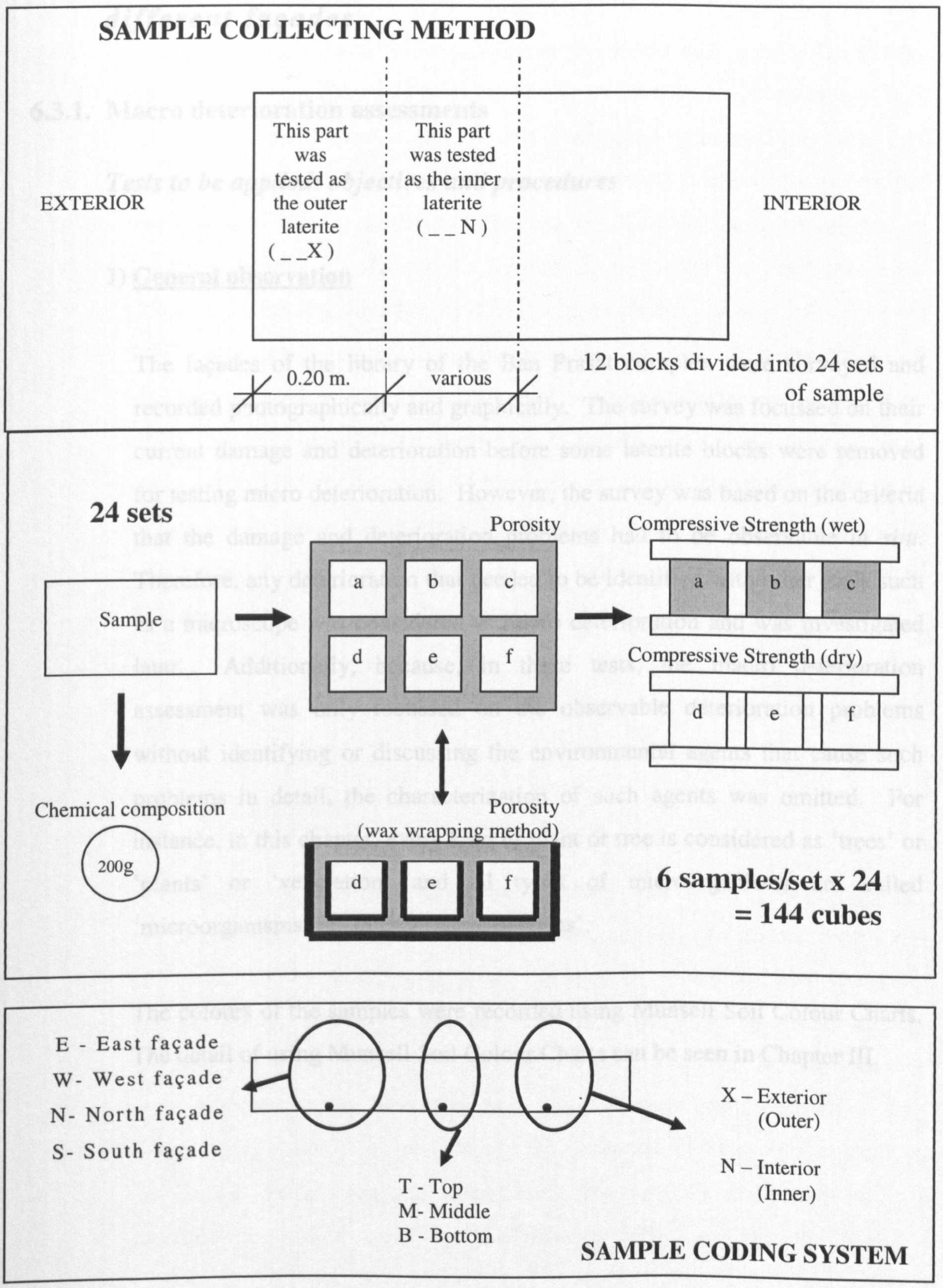
Most of the remains of the library of the Ban Prasat Complex are laterite walls enclosing a rectangular 5.5x6.5-metre floor facing the entrance to the west with an east-west orientation (see Figure 6.1). Before excavation, the height of the walls was one metre and thirty centimetres above the ground with one metre of soil fill on the interior floor. At the southwest corner (as seen in Map 6.1) is a tree with a trunk measuring sixty centimetres in diameter, whose roots have penetrated the walls and pushed some masonry blocks away from their original places. There is another tree with a thirty-centimetre diameter near the south wall whose roots have also penetrated the wall noticeably. Microorganisms are observable on the wall. However, salt efflorescence is hardly found. There are some ferruginous sandstone structures such as elements of the roof and the doorjamb at ground level. The walls are leaning inward but have not yet collapsed. The general condition is fairly critical. Nevertheless, in order to assess the current condition of the site thoroughly, especially to make a comparative assessment of the deterioration problems of the walls on different sides of the building, photographic and optical condition surveys and a laboratory-based materials analysis were carried out, and they are the subject of this chapter.

6.2. Sampling Method

As previously discussed, the aims of this chapter are to assess weathering and deterioration problems on the façades of a selected laterite monument; and to compare and analyse which façade and what locations on the façades are the most susceptible to the environmental weathering agents. Therefore, laterite samples were collected from the walls of the Banalaya (library) of the Ban Prasat Complex. Initially it was intended that laterite blocks from two locations of each façade were to be collected—one location was to represent blocks where three sides were facing the air and the other three facing adjacent laterite blocks, and the other location to represent blocks where two sides faced to the air, one side faced the ground and the other three faced other laterite. However, since it was known that the walls now exposed had, until 2003 when excavated, been buried to a depth of about a metre for several hundred years, blocks from three not two different locations were collected. Eventually, on each façade, one block from the top, one from the middle just above the soil level before excavation, and another block from above the current ground level, but which had previously been buried under the soil and exposed to the air recently, were collected. In total, twelve blocks were collected from the monument with the express consent and co-operation of the Department of Fine Arts and Dr Peter Gouldsborough. The positions from where samples were collected are displayed in Drawings 6.1 on page 260. Each block was then divided into two parts—outer laterite being from the surface of the blocks up to twenty centimetres deep horizontally; and inner laterite being from the point of twenty centimetres from the surface inward up to the core of the blocks (see Diagram 6.1 on page 226). This was so as to fulfil the other aim of this chapter, which is to assess the change/deterioration effects of environment on laterite by comparing the properties of two parts of laterite that had been exposed to the environment with that which had not. Hence, there were twenty-four sets of laterite samples ready to be tested. Each set was labelled with a three-letter code where the first letter indicates in which façade it originated, the second indicates the position of the block, and the last indicates either the inner or outer part of each block.

As shown in Chapter III, chemical composition, porosity and compressive strength tests could yield a useful set of data of laterite micro properties. Therefore, only these tests were selected to investigate this new group of laterite samples. In order to identify the chemical composition of each sample set, two hundred grams of each were sent to the Department of Mineral Resources to carry out chemical identification tests. For the porosity and compressive strength tests, each set of samples was cut into cubes in the size of 2" x 2" (about 5x5 centimetres) according to the ASTM standard. Three samples of each set were required for the porosity test. However, to carry out the measurement of the porosity of large pores, three further samples were needed. In total, one hundred and forty-four cubes were prepared for the tests. For the compressive strength test, the samples tested in the porosity test could be reused. In each set of samples, three samples were tested when dry while the other three samples were tested when wet (see Diagram 6.1). In addition, the colour of each set of samples was recorded using Munsell Soil Colour Charts.

Diagram 6.1: Sample collection method



6.3. Assessment of variability in deterioration rates in different façades

6.3.1. Macro deterioration assessments

Tests to be applied: objectives and procedures

1) General observation

The façades of the library of the Ban Prasat complex were surveyed and recorded photographically and graphically. The survey was focussed on their current damage and deterioration before some laterite blocks were removed for testing micro deterioration. However, the survey was based on the criteria that the damage and deterioration problems had to be observable *in situ*. Therefore, any deterioration that needed to be identified with other tools such as a microscope was considered as micro deterioration and was investigated later. Additionally, because, in these tests, the macro deterioration assessment was only focussed on the observable deterioration problems without identifying or discussing the environmental agents that cause such problems in detail, the characterization of such agents was omitted. For instance, in this chapter, every kind of plant or tree is considered as 'trees' or 'plants' or 'vegetation' and all types of microorganisms are called 'microorganisms' or 'microorganic deposits'.

The colours of the samples were recorded using Munsell Soil Colour Charts. The detail of using Munsell Soil Colour Charts can be seen in Chapter III.

2) Photographic and computerised deterioration assessments

The photographs taken at the façades were inserted into AutoCAD as raster images, and base drawings of the elevations of the library were drawn from the images. Evidence for damage and deterioration recorded graphically on paper was digitised over the base drawings. In order to investigate whether environment affects laterite façades, the digitised deterioration extents on each façade were calculated and a comparison was made between the façades. Finally, the relationships between the assessed deterioration and the location of laterite were concluded. In addition, the data obtained from the assessments will also be useful to analyse whether the macro deterioration affects the strength and other properties of laterite in the next chapter. It is to be noted that the results obtained from these macro deterioration assessments are only summarised but not concluded and discussed in this chapter, but the discussion, including analyses of their correlations with other properties of laterite, will follow in the next chapter.

Results

1) General observation

Every façade showed some evidence of damage and deterioration. Although all large plants had been cut since the excavation was carried out, their roots still remained and small young plants had recently rooted in the soil between laterite blocks. Major cracks had occurred, resulting in outwardly leaning façades, and minor cracks appeared in some laterite blocks. Microorganisms were observed on the blocks, especially in the upper parts of each façade. There was no trace of observable salt efflorescence. Hence, only vegetation, cracks and microorganisms were taken into account and recorded, and thereafter digitised in AutoCAD (see Drawings 6.2-6.5 on pages 261-264).

According to Munsell Soil Charts, all samples taken from the façades were strong brown with the hue of 7.5YR in various colour values and chroma ranging from 4/6 to 5/8 (the smaller the number, the darker the colour). Details of the colour of each sample are displayed in the table below.

Table 6.1: Colour of laterite samples based on Munsell Soil Chart

Sample	1(WTX)	2(WTN)	3(WMX)	4(WMN)	5(WBX)	6(WBN)	7(NMX)	8(NMN)
Hue	7.5YR	7.5YR	7.5YR	7.5YR	7.5YR	7.5YR	7.5YR	7.5YR
Value	5	5	5	5	5	5	4	4
Chroma	6	6	8	8	6	6	6	6
Colour	Strong brown	Strong brown	Strong brown	Strong brown	Strong brown	Strong brown	Strong brown	Strong Brown

Sample	9(NTX)	10(NTN)	11(NBX)	12(NBN)	13(ETX)	14(ETN)	15(EMX)	16(EMN)
Hue	7.5YR	7.5YR	7.5YR	7.5YR	7.5YR	7.5YR	7.5YR	7.5YR
Value	4.5	4.5	5	5	4.5	4	5	5
Chroma	6	6	7	7	6	6	8	8
Colour	Strong brown	Strong brown	Strong brown	Strong brown	Strong brown	Strong brown	Strong brown	Strong brown

Sample	17(EBX)	18(EBN)	19(STX)	20(STN)	21(SMX)	22(SMN)	23(SBX)	24(SBN)
Hue	7.5YR	7.5YR	7.5YR	7.5YR	7.5YR	7.5YR	7.5YR	7.5YR
Value	4.5	4.5	5	5	5	5	5	5
Chroma	6	6	6	7	6	6	7	7
Colour	Strong brown	Strong brown	Strong brown	Strong brown	Strong brown	Strong brown	Strong brown	Strong brown

2) Photographic and computerised deterioration assessments

After all photographs had been inserted as a background layer under the AutoCAD drawings of the façades and microorganic deposits had been digitised onto the drawings as seen in Drawings 6.2-6.5, the areas of laterite blocks and microorganic deposits on each façade were calculated using the AutoCAD area calculation command. Thereafter, the percentage of microorganic deposits of each façade was calculated proportionally to the total drawing area of the laterite blocks of each façade. The calculations and analyses show that microorganisms covering laterite of the north façade covered as much as 32.90% of the total laterite area on the façade. On the south, the east and the west façades, microorganisms covered 26.91%, 23.66% and 12.25% of their laterite areas respectively. Hence, it may be concluded that the north façade had been affected by microorganisms in the highest degree followed by the south and the east façades, and the west façade had been colonised by microorganic deposits the least. Noticeably, all microorganisms deposited on only the laterite blocks which had been exposed to the air for a period of time, as seen in the drawings as the blocks above ground level before excavation. The reason for this phenomenon will be discussed in detail in Chapter VII.

Regarding microorganisms on each sample block individually, since only the external face was surveyed, only the outer part of each block was taken into consideration. The calculations of percentage of microorganisms on each block are shown in the table below:

Table 6.2: Percentages of microorganic deposits on individual laterite blocks

Sample	**West**	**%**	**North**	**%**	**East**	**%**	**South**	**%**
Top	**1(WTX)**	92.31	**7(NMX)**	12.20	**13(ETX)**	100.00	**19(STX)**	100.00
Middle	**3(WMX)**	7.56	**9(NTX)**	78.12	**15(EMX)**	82.16	**21(SMX)**	73.61
Bottom	**5(WBX)**	0.00	**11(NBX)**	0.00	**17(EBX)**	0.00	**23(SBX)**	0.00

Since the selection of the collected blocks was based on the criterion of being in different positions—on the top, next to the ground before excavation, and above the ground after excavation and recently exposed to the air—and based on the ease of being removed without any consideration of the microorganisms covering them, they are unlikely to represent the most critical microorganic effects on laterite in a variety of locations. Therefore, the comparison of the percentage of microorganisms on individual blocks from various locations is unlikely to prove significant. However, this data may later be useful to analyse whether or not microorganisms affects other laterite properties. This analysis will be discussed in the next chapter.

Plants can be shown to grow on the façades unevenly. In considering which façade provided the best conditions for plant growth and therefore was colonised by plants the most, the number of plants is more important than their area coverage which merely reflects their age—the older, the larger—and the type of plant. Thus, unlike studying microorganic deposits, it is not useful to calculate the percentage of the area covered. Rather, the comparison between the number of plants growing on each façade and the area of each façade is studied (see Drawings 6.2-6.5).

There were twenty-six plants on the west façade as well as on the south façade. Seventeen plants grew on the east façade and eleven plants on the north façade. Although the west and the south façades were colonised by the same number of plants, because the west façade is smaller than the south façade, the west façade was more affected by the plants than the south one. According to the calculations of the plant density, the east façade had 1.57 plants/m^2, the north façade had 1.70 plants/m^2, the south façade had 2.60 plants/m^2 and the west façade had 4.52 plants/m^2. Hence, the west façade had the highest density of plant colonization, followed in order of density by the south, the north and the east.

Dead tree roots could be seen in every façade (see Drawings 6.2-6.5). The south and the east façades had greater numbers of roots but such roots were small. In contrast, there was only one remaining tree root on the west façade but its diameter was as large as 0.40 metre. Therefore, out of the total façade area, the area of the root on the east façade was the greatest, 2.27%, while the roots on the south and the east façades covered only 0.18% and 0.19% of their façade areas. The area of the only remaining tree root on the north façade was as small as 0.009% which could be disregarded. However, these data will be used for analysing the correlations between the area coverage of tree root and other macro deterioration and other laterite properties in Chapter VII.

Cracks occurred in every façade but in different degrees, and seemed to occur on the north and south façades the most and on the east façade the least (see

Drawings 6.2-6.5). Qualitatively, minor cracks appeared within the blocks of every façade, whereas major cracks damaged the façades structurally causing gaps between laterite blocks only on the north and the south façades. Quantitatively, according to the calculation of crack areas compared with the façade areas, the north façade was damaged by cracks the most as much as 1.67% followed by the south façade, 1.31%, and the east façade, 0.73%, and the west façade was damaged the least as little as 0.26%. Whether cracks are related to other deterioration problems, especially tree root penetration, will be analysed in the next chapter.

Summary

Amongst all samples collected from the site (see Table 6.1), Sample 7, 8 and 14—the first two collected from the middle of the north façade and the other from the top of the east façade—were the darkest brown with the Munsell value/chroma of colour of 4/6. Sample 9 and 10 from the top of the north façade, Sample 13 from the top of the east façade, and Sample 17 and 18 from the bottom of the east façade with the value/chroma of 4.5/6 were slightly more yellow than the first group. The others were more yellow while Sample 3 and 4 from the middle of the west façade, and Sample 15 and 16 from the middle of the east façade, being 7.5YR 5/8, were the lightest. This data is to be used for analysing as to whether the colour of the laterite samples relates to other laterite properties in Chapter VII.

According to the calculations, the north façade was affected by microorganisms and cracks the most, while the west façade had the highest number of plant growth but the lowest cracks and microorganic deposits. In order to compare the macro deterioration problems of every façade and study whether or not there is any correlation among them, the table and chart below are drawn:

Table 6.3: Comparison of deterioration problems on façades

	West	South	East	North
Microorganisms (% coverage)	12.25	26.91	23.66	32.90
Plants (live/m^2)	4.52	2.60	1.57	1.70
Cracks (% coverage)	0.26	1.31	0.73	1.67
Roots (% coverage)	2.27	0.18	0.19	0.01

Chart 6.1: Deterioration problems on each façade

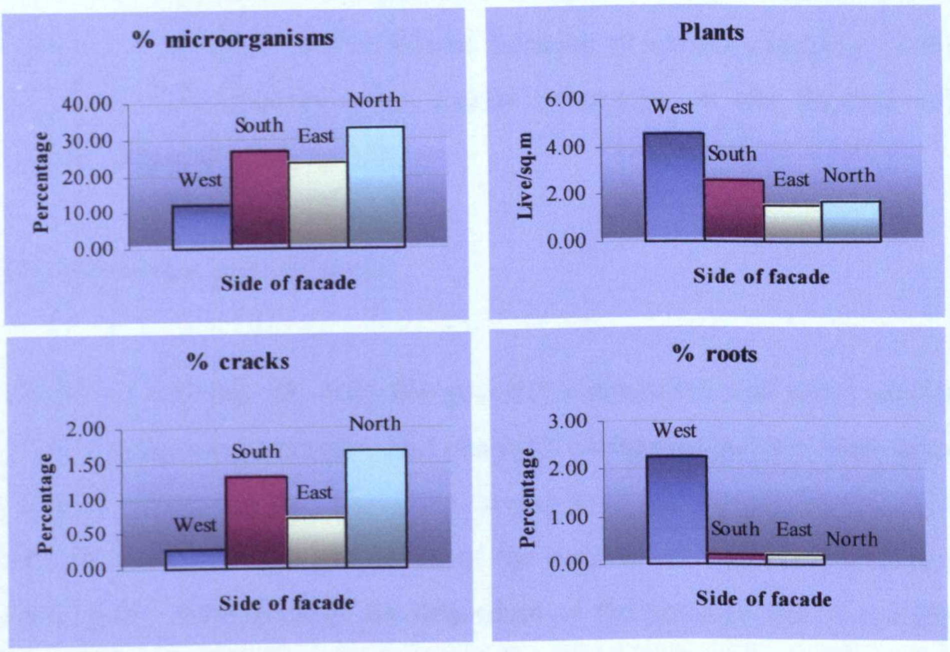


Table 6.3 and Chart 6.1 show that, when compared among these four problems, all façades were adversely affected by microorganisms in the highest degree. The north façade was colonised by micro bio-organism the most but little affected by plants. On the other hand, the west façade was affected by microorganisms the least but by plant growth the most. The percentages of microorganisms on the south and the east façades were similar, and the percentages of plant growth on the east and the north façades were almost identical. Therefore, it may be concluded that the degrees of susceptibilities to microorganisms of the south and of the east façades are the same. In addition, the susceptibilities to plant growth of the east and of the north façades are also noticeably the same. The reason why these phenomena occurred will be

analysed and discussed in the next chapter, as will the inverse relationship between microorganisms and plant growth.

The occurrence of crack damage on the façades did not correspond to the occurrence of the percentages of root penetration. Thus, root penetration is not the only cause of cracks to laterite façades; there might also have been other agents of damage such as soil subsidence, superstructure overload or even the movements of adjacent laterite blocks because of earlier cracking. Like the other deterioration problems, the causes of cracks on the façades will be discussed in detail in Chapter VII.

6.3.2. Micro alteration assessments

As shown in Chapter III, only the porosity calculation and water absorption capacity, compressive strength, and chemical composition tests were effective and yielded useful results. Therefore, in this field study, only these tests were selected to investigate the properties of the deteriorated laterite collected from the case study. Nevertheless, the procedure of the porosity test was altered in order to offer the measurement of large pores which it was not possible to measure with the standard tests in Chapter III.

Tests to be applied: objectives and procedures

1) Chemical composition quantitative analysis (Wet chemical analysis)

In order to investigate the main chemical composition of laterite samples collected from the study site, two hundred grams of each were sent to the Department of Mineral Resources in Thailand. The main chemical compounds, including silicon dioxide, aluminium dioxide and ferric oxide were focussed upon while some minor minerals such as potassium oxide and manganese oxide were traced, where possible. These compounds are possibly the main chemical compositions in laterite, according to the summary of the literature review in Chapter II. The procedure of the test can be seen in Chapter III.

Result

Chart 6.2: The comparison of the main chemical compounds in the laterite samples (sample codes given in Table 6.4 below)

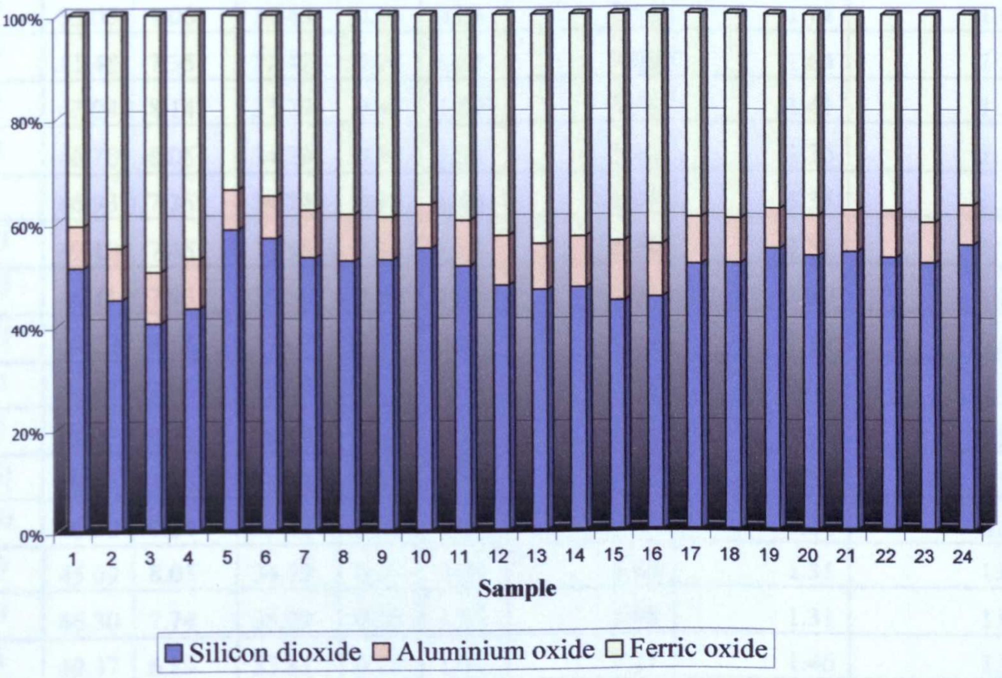
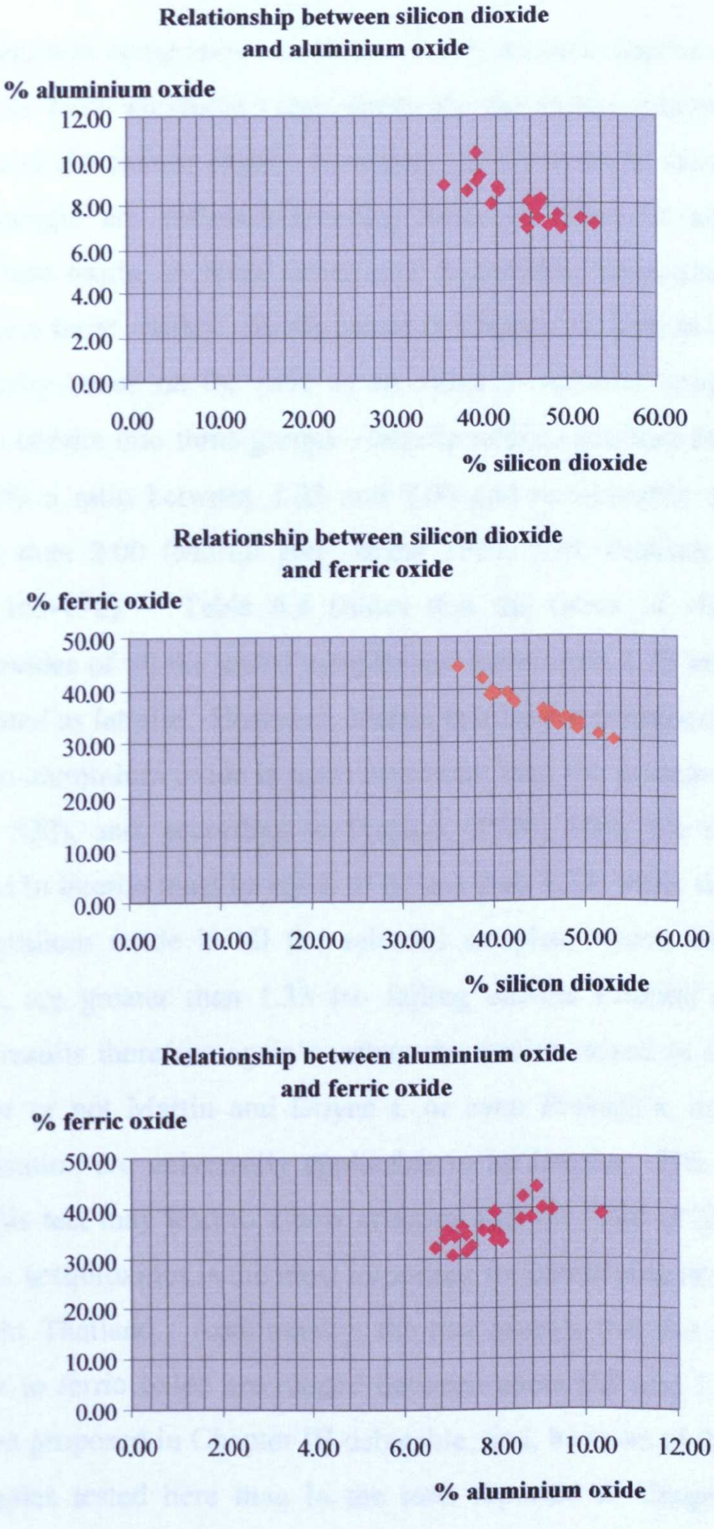


Table 6.4: Chemical compositions of laterite samples (see Set 1 in Appendix VI)

Sample	Chemical Compound (%)					**Ratio**		
	SiO_2	Al_2O_3	Fe_2O_3	K_2O	MnO	$SiO_2:Al_2O_3$	$SiO_2:Fe_2O_3$	SiO_2: sesquioxides
1 (WTX)	45.38	7.26	36.04	0.17	1.75	6.25	1.26	1.05
2 (WTN)	39.77	9.02	39.78	0.20	1.30	4.41	1.00	0.81
3 (WMX)	36.02	8.89	44.17	0.11	0.20	4.05	0.82	0.68
4 (WMN)	38.66	8.59	42.10	0.12	0.22	4.50	0.92	0.76
5 (WBX)	53.05	7.06	30.43	0.16	0.88	7.51	1.74	1.42
6 (WBN)	51.48	7.35	31.42	0.16	1.02	7.00	1.64	1.33
7 (NMX)	47.04	8.14	33.29	0.36	1.80	5.78	1.41	1.14
8 (NMN)	46.70	8.05	34.29	0.33	1.39	5.80	1.36	1.10
9 (NTX)	46.93	7.35	34.74	0.14	1.40	6.39	1.35	1.11
10 (NTN)	49.10	7.45	32.56	0.14	1.64	6.59	1.51	1.23
11 (NBX)	46.11	7.93	35.50	0.30	1.06	5.81	1.30	1.06
12 (NBN)	42.22	8.58	37.69	0.33	1.62	4.92	1.12	0.91
13 (ETX)	41.47	7.96	39.20	0.14	1.29	5.21	1.06	0.88
14 (ETN)	42.07	8.77	38.10	0.19	1.31	4.80	1.10	0.90
15 (EMX)	39.63	10.33	38.94	0.31	0.71	3.84	1.02	0.80
16 (EMN)	40.20	9.24	39.48	0.21	1.08	4.35	1.02	0.83
17 (EBX)	45.69	8.05	34.79	0.17	2.09	5.68	1.31	1.07
18 (EBN)	46.30	7.74	35.29	0.15	1.57	5.98	1.31	1.08
19 (STX)	49.37	6.89	33.81	0.12	1.01	7.17	1.46	1.21
20 (STN)	47.90	6.96	34.87	0.13	1.25	6.88	1.37	1.15
21 (SMX)	48.83	7.11	34.15	0.14	1.27	6.87	1.43	1.18
22 (SMN)	46.91	7.96	33.62	0.16	2.10	5.89	1.40	1.13
23 (SBX)	45.61	6.93	35.31	0.15	2.52	6.58	1.29	1.08
24 (SBN)	48.75	6.68	32.25	0.17	2.96	7.30	1.51	1.25

Chart 6.3: The relationships between silicon dioxide and aluminium oxide and ferric oxide in the laterite samples


Relationship between silicon dioxide and aluminium oxide

Relationship between silicon dioxide and ferric oxide

Relationship between aluminium oxide and ferric oxide

Conclusion

The chemical composition analysis of the selected laterite samples reveals that their main chemical components are the same—silicon dioxide, ferric oxide and aluminium oxide. However, the amounts of those compounds in each sample are different creating different ratios in each of silica to aluminium oxide, to ferric oxide and to metallic sesquioxides (aluminium oxide and ferric oxide). As discussed in Chapter II, laterite can be classified chemically based on the ratio of its silica to metallic sesquioxides, which divides laterite into three groups—laterite with a ratio less than 1.33, lateritic soil with a ratio between 1.33 and 2.00 and non-lateritic soil with a ratio greater than 2.00 (Martin and Doyne 1927, 530; Prakash and Basavanna 1969, 165-175). Table 6.4 shows that the ratios of silicon dioxide to sesquioxides of all the tested samples are lower than 1.33 and may therefore be defined as laterite. However, Martin and Doyne proposed that the ratio of silica to aluminium oxide is more important than the presence of ferric oxide (1927, 530), and, according to Prakash (1970, 166), the ratio of silica to alumina in laterite must be equal to or less than 1.33, while the ratios of silica to aluminium oxide in all the selected samples, which were undoubtedly laterite, are greater than 1.33 (so falling outside Prakash's classification). These results therefore again confirm the doubts raised in Chapter III as to whether or not Martin and Doyne's, or even Prakash's, criteria of laterite classification are universally applicable to all laterite. The results obtained from this test may lead to a new criterion that the ratio of silicon dioxide to metallic sesquioxides is the most important for classifying laterite specifically found in Thailand. Additionally, the test reveals that the ratios of silicon dioxide to ferric oxide are ranged between about 0.8 and 1.7 and make the criterion proposed in Chapter III debatable, and, because of the larger number of samples tested here than in the tests reported in Chapter III, this new proposal is possibly more applicable to classify Thai laterite.

In addition, the percentages of aluminium oxide in the laterite samples are almost all less than 10 (only one out of twenty four samples that comprises 10.33%). Therefore, it may be concluded that all laterite samples are not bauxitic, but they are siliceous-ferruginous laterite.

Whether or not the façades had deteriorated at different rates may be estimated by assessing the alteration in the chemical composition of laterite collected from different locations. Theoretically, because laterite is so heterogeneous in origin, comparisons between different blocks are unlikely to be very informative. Thus, only a comparison of the inner and outer parts within the same blocks were considered. The chemical composition difference between the inner and outer parts within each is displayed in Table 6.5:

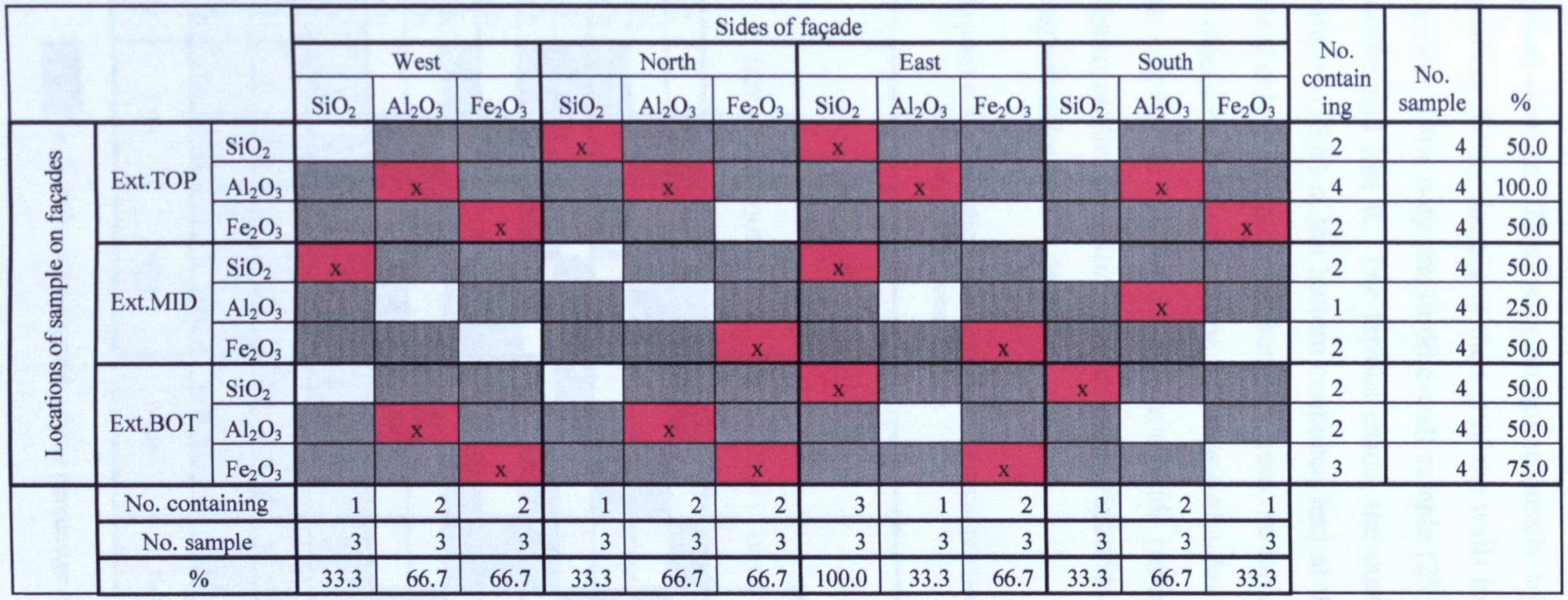
Table 6.5: The different of chemical compositions between inner and outer parts of each sample

Sample	% compound difference btw/ inner&outer		
	SiO_2	Al_2O_3	Fe_2O_3
1 (WTX)		-1.76	-3.74
2 (WTN)	-5.61		
3 (WMX)	-2.64		
4 (WMN)		-0.30	-2.07
5 (WBX)		-0.29	-0.99
6 (WBN)	-1.57		
7 (NMX)			-1.00
8 (NMN)	-0.34	-0.09	
9 (NTX)	-2.17	-0.10	
10 (NTN)			-2.18
11 (NBX)		-0.65	-2.19
12 (NBN)	-3.89		
13 (ETX)	-0.60	-0.81	
14 (ETN)			-1.10
15 (EMX)	-0.57		-0.54
16 (EMN)		-1.09	
17 (EBX)	-0.61		-0.50
18 (EBN)		-0.31	
19 (STX)		-0.07	-1.06
20 (STN)	-1.47		
21 (SMX)		-0.85	
22 (SMN)	-1.92		-0.53
23 (SBX)	-3.14		
24 (SBN)		-0.25	-3.06

Note: The negative values indicate the differences of percentage chemical compound which a particular sample contained less than the other sample from the same block.

In order to find out whether the alteration of chemical composition is related to the location of laterite blocks on the façades, the percentage of external samples whose the percentage of chemical composition is less than that of the core is calculated in relation to the location of the samples. The result is displayed in Diagram 6.2 below:

Diagram 6.2: The percentage of external samples that contain major chemical compounds in lower degree than the core of samples

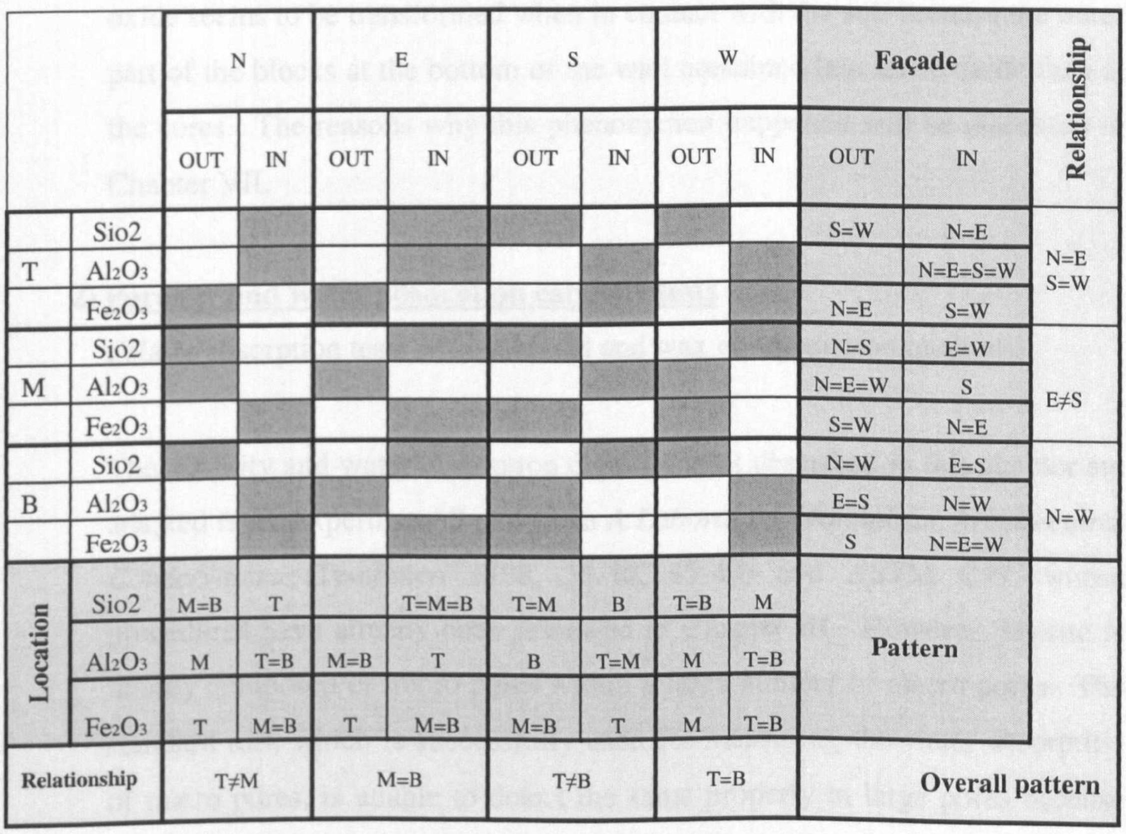


Locations of sample on façades			Sides of façade												No. containing	No. sample	%
			West			North			East			South					
			SiO_2	Al_2O_3	Fe_2O_3	SiO_2	Al_2O_3	Fe_2O_3	SiO_2	Al_2O_3	Fe_2O_3	SiO_2	Al_2O_3	Fe_2O_3			
	Ext.TOP	SiO_2		▨	▨	x	▨	▨	x	▨	▨		▨	▨	2	4	50.0
		Al_2O_3	▨	x	▨	▨	x	▨	▨	x	▨	▨	x	▨	4	4	100.0
		Fe_2O_3	▨	▨	x	▨	▨		▨	▨		▨	▨	x	2	4	50.0
	Ext.MID	SiO_2	x	▨	▨		▨	▨	x	▨	▨		▨	▨	2	4	50.0
		Al_2O_3	▨		▨	▨		▨	▨		▨	▨	x	▨	1	4	25.0
		Fe_2O_3	▨	▨		▨	▨	x	▨	▨	x	▨	▨		2	4	50.0
	Ext.BOT	SiO_2		▨	▨		▨	▨	x	▨	▨	x	▨	▨	2	4	50.0
		Al_2O_3	▨	x	▨	▨	x	▨	▨		▨	▨		▨	2	4	50.0
		Fe_2O_3	▨	▨	x	▨	▨	x	▨	▨	x	▨	▨		3	4	75.0
	No. containing		1	2	2	1	2	2	3	1	2	1	2	1			
	No. sample		3	3	3	3	3	3	3	3	3	3	3	3			
	%		33.3	66.7	66.7	33.3	66.7	66.7	100.0	33.3	66.7	33.3	66.7	33.3			

Note: No. containing = Number of sample that contained such compound
No. sample = Number of sample studied
% = The percentage of external samples containing such compounds in lower percentage than their internal part
🟥x x (in red boxes) = Indicator of the lower percentage of such chemical compounds composed in the external part of the sample
(Only red and white boxes are considered—red indicates the same as 'x' above, while white without x means in the opposite way)

As demonstrated in Diagram 6.2, fifty percent of samples from each position had lost some of their silicon dioxide; however, a comparison between façades shows that all samples from the east façade had lost some of their silicon dioxide. There was no quantitatively significant loss in any specific position. Every sample at the top of the walls had lost its aluminium dioxide partially while only one middle-wall sample (25%) and two samples from the bottom had lost it. For ferrous oxide, the outer parts of three out of four samples (75%) at the bottom contained less at the surface than at their core, while only fifty percent of samples from the top and the middle had lost some of their iron oxide over time. In terms of sides of walls, every sample from the east façade had lost its silicon dioxide partially. In order to analyse the pattern of the alteration in chemical compounds in every façade's block, the diagram below is created:

Diagram 6.3: The pattern of alteration in chemical composition in samples from different locations on different façades



		N		E		S		W		**Façade**		**Relationship**
		OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	
T	Sio2		▨		▨	▨		▨		S=W	N=E	N=E S=W
	Al_2O_3		▨		▨		▨		▨		N=E=S=W	
	Fe_2O_3	▨		▨			▨		▨	N=E	S=W	
M	Sio2	▨			▨	▨			▨	N=S	E=W	E≠S
	Al_2O_3	▨		▨			▨	▨		N=E=W	S	
	Fe_2O_3		▨		▨	▨		▨		S=W	N=E	
B	Sio2	▨			▨		▨	▨		N=W	E=S	N=W
	Al_2O_3		▨	▨		▨			▨	E=S	N=W	
	Fe_2O_3		▨		▨	▨			▨	S	N=E=W	
Location	Sio2	M=B	T		T=M=B	T=M	B	T=B	M	**Pattern**		
	Al_2O_3	M	T=B	M=B	T	B	T=M	M	T=B			
	Fe_2O_3	T	M=B	T	M=B	M=B	T	M	T=B			
Relationship		T≠M		M=B		T≠B		T=B		**Overall pattern**		

Note: ▨ = Sample containing the greater percentage of such compounds than the other

According to this analysis, on the west, north and south sides, the core of the blocks contained more silicon dioxide than the surface. Therefore, it is possible that on these sides, silicon dioxide had not been changed or leached out over time. In contrast, on the east side, the surface of laterite blocks in all positions had lost some of its silicon dioxide. In terms of aluminium dioxide, at the east side, the outer part of laterite block had lost aluminium dioxide the least, but lost some ferric oxide in the middle and at the bottom. At the south side, it seems that the percentages of silicon dioxide and ferric oxide had not decreased over time because at the outer edge of the blocks there was higher percentage than at the cores; or, to look at it another way, some other compounds might have been transformed or leached away leaving to the higher percentages of silicon dioxide and ferric oxide at the surface. At the top of each wall, laterite blocks had lost aluminium dioxide partially over time, but the loss hardly occurred in the middle of the wall (which was just above the ground before excavation). It may also be concluded that ferric oxide seems to be transformed when in contact with the soil because the outer part of the blocks at the bottom of the wall contained less ferric oxide than at the cores. The reasons why this phenomenon happened will be discussed in Chapter VII.

2) Porosity and water absorption capacity tests

(Water absorption tests with standard and wax encapsulation methods)

The porosity and water absorption capacity tests described in this chapter are adapted from Experiment 8 and 11 in *A Laboratory Manual for Architectural Conservators* (Teutonico 1988, 35-40, 45-49) and ASTM C97, whose procedures have already been reviewed in Chapter III. However, laterite is mainly composed of micro pores within a large number of macro pores. The standard test, which is successfully used for measuring the water absorption of micro pores, is unable to detect the same property in large pores because the water is not retained in such pores when the testing cube is taken out of the immersion tray. Therefore, when the tests were repeated, the large pores, which were unable to be measured with the standard tests, were measured by applying some adapted methods to the standard tests. To trap water in the large pores throughout the testing process, paraffin wax was then used to encapsulate three sides of the tested cubes. However, in order to reduce the period of saturation and to investigate the data differences between the original standard test and the adapted test, a set of laterite cubes was tested twice—firstly as naked cubes and then as encapsulated cubes. The original tested cubes were first immersed in water for a week or more until the micro pores were saturated and the data were recorded following the standard test's method. Thereafter, the cubes were taken out of the water and encapsulated with paraffin wax, and then re-immersed until their new saturations were reached. The second set of data was also recorded. The summary of the adapted test is as follows:

Aims

The purpose of this test is to suggest a method to effectively measure the porosity of a large-pore material such as laterite. However, whether or not this suggested method is effective and whether the measurement of the porosity of large pores is necessary also need to be evaluated by comparing the data obtained from this test with the data obtained through the standard porosity tests.

Preparation and procedure

The samples (Set A for the porosity calculation and Set B for the comparison of two testing methods) were dried for 48 hours at 60°(± 5°) C. or until the change of their weight in two consecutive days was less than 0.1% of the total mass.

Procedure

1. The mass of dry cool samples was determined (M_d) and recorded.
2. The weighed samples were placed in an immersion tank on glass beads and then deionised water was added until the samples were covered by two centimetres of water.
3. At predetermined time intervals as indicated below, each sample was removed, quickly blotted with a paper towel to remove excess water and then weighed. The result was recorded as M_n. The sample was then reimmersed.
4. Laterite samples were weighed after the first five, fifteen, and thirty minutes of immersion and then every hour for the first 3 hours.
5. All samples were then weighed at eight hours after the start of the test and then every twenty-four hours until the quantity of water absorbed in two successive weighing was not greater than 0.1% of the total mass.
6. When the relative equilibrium was reached, the samples were removed and their saturated weight (M_{max}) measured.
7. The samples were then placed in a beaker containing a known volume of water. According to Archimedes' Principle, the quantity of water displaced is equal to the apparent volume (V_a).
8. In order to measure the volume of large pores, five sides of Set B saturated samples (labelled as Sample d, e, and f) were encapsulated with paraffin wax and reimmersed until the quantity of water absorbed in two successive weighing was not greater than 0.1% of the total mass.
9. When the relative equilibrium was reached, the samples were removed and their saturated weight was measured (M_x+M_w).
10. The procedure in 7 was repeated, and the volume of saturated encapsulated samples (V_a+V_w) was measured.
11. The encapsulation wax was melted and its weight (M_w) and volume (V_w) were measured. The saturated weight (M_{x2}) and volume (V_{a2}) of the samples in paraffin wax encapsulation were calculated by subtracting the

weight and volume of the wax from the saturated encapsulated weight and volume.

12. All samples were dried at 60°(± 5°) C until the weight in two consecutive weighing was not greater than 0.1% of the total mass.
13. The dry weight (M_d) was recorded.

Finally, the percent porosity was calculated as instructed in ASTM 97. The results were recorded and displayed in the attached tables (Table 6.6 and 6.7, and see the raw data in Data Set 2 in Appendix VI).

Results

Table 6.6: The averages of the water absorption capacity (WAC) and the percentage porosity of laterite samples (measured through the ASTM method)

Sample	**WAC**			**% porosity**		
Set A (a/b/c)	**Average**	**Standard deviation**	**Number of cases**	**Average**	**Standard deviation**	**Number of cases**
1 (WTX)	8.73	0.54	3	18.60	0.28	3
2 (WTN)	9.56	1.46	3	20.40	3.22	3
3 (WMX)	11.13	1.07	3	22.03	1.74	3
4 (WMN)	10.68	0.83	3	22.90	1.22	3
5 (WBX)	8.76	0.81	3	19.95	1.95	3
6 (WBN)	9.17	0.66	3	19.85	1.42	3
7 (NMX)	8.30	0.15	3	18.76	0.40	3
8 (NMN)	8.32	0.32	3	18.18	0.60	3
9 (NTX)	9.77	1.11	3	21.47	1.86	3
10 (NTN)	11.00	0.25	3	23.33	0.71	3
11 (NBX)	7.36	0.20	3	16.79	0.59	3
12 (NBN)	7.55	0.05	3	17.27	0.12	3
13 (ETX)	8.78	0.32	3	21.66	0.93	3
14 (ETN)	9.00	0.42	3	19.46	1.55	3
15 (EMX)	10.18	0.45	3	22.15	0.59	3
16 (EMN)	9.52	2.98	3	19.76	7.38	3
17 (EBX)	9.98	0.37	3	21.23	0.87	3
18 (EBN)	9.19	0.16	3	20.73	1.12	3
19 (STX)	9.33	0.32	3	20.95	1.25	3
20 (STN)	8.67	0.25	3	20.51	0.17	3
21 (SMX)	10.23	0.18	3	20.15	2.45	3
22 (SMN)	10.43	0.95	3	21.12	0.77	3
23 (SBX)	11.86	0.62	3	23.89	1.37	3
24 (SBN)	10.87	0.32	3	21.58	0.33	3

Table 6.7: The comparison of the averages of water absorption capacity (WAC) and percentage porosity of laterite samples measured through ASTM method and the wax encapsulation method (see the number of cases and the standard deviation of the data in Data Set 4 in Appendix VI)

Sample	**ASTM method**		**Wax encapsulation method**		**%porosity difference**
Set B (d/e/f)	**WAC**	**% porosity**	**WAC**	**% porosity**	
1 (WTX)	9.05	18.46	13.95	26.21	7.75
2 (WTN)	10.81	21.39	16.71	29.35	7.97
3 (WMX)	11.83	22.40	18.02	31.12	8.72
4 (WMN)	10.69	22.67	17.85	33.71	11.03
5 (WBX)	9.74	20.53	15.54	29.79	9.27
6 (WBN)	8.65	17.28	12.78	22.99	5.72
7 (NMX)	8.82	18.28	12.18	22.70	4.42
8 (NMN)	9.30	17.67	13.99	25.54	7.87
9 (NTX)	10.06	21.21	22.62	42.85	21.64
10 (NTN)	10.32	23.28	20.57	38.58	15.29
11 (NBX)	7.85	15.38	11.00	22.00	6.62
12 (NBN)	8.13	17.63	13.46	26.72	9.10
13 (ETX)	9.16	20.98	16.20	32.43	11.45
14 (ETN)	9.46	21.06	14.93	30.13	9.07
15 (EMX)	10.22	19.79	13.37	24.71	4.93
16 (EMN)	12.98	25.47	15.30	28.76	3.29
17 (EBX)	10.82	22.35	16.84	31.60	9.24
18 (EBN)	10.11	20.73	17.91	32.49	11.77
19 (STX)	8.87	19.96	16.99	33.01	13.05
20 (STN)	9.75	20.54	15.78	30.24	9.70
21 (SMX)	10.52	17.82	14.20	18.73	0.91
22 (SMN)	9.84	22.01	20.71	38.07	16.07
23 (SBX)	10.32	21.69	17.45	32.78	11.09
24 (SBN)	10.12	18.23	18.30	31.07	12.84
Average	**9.89**	**20.28**	**16.13**	**29.82**	**9.53**

Conclusion

In terms of the efficiency of the recommended new method of measuring the percentage of porosity of a large-pored material such as laterite, wax encapsulation succeeded in retaining water and allowing the measurement of such water's weight and volume which had been considered as hidden values while applying the standard water absorption test. The results suggested that these hidden values were sometimes as high as 21.64% or could be as low as 0.91%. The average percent porosity difference amongst twenty-four samples was 9.53, that is the large pores of the laterite samples accounted for approximately ten percent additional porosity to that measured by the standard method (or approximately six percent additional water absorption capacity).

Since the large pores of the laterite samples accounted for only 9.53% additional porosity, when the averages of percentage porosity and water absorption capacity (WAC) measured through the standard test is 20.28 and 9.89, the overall percentage porosity of small and large pores will be 22.22 leading to the water absorption capacity of 10.51, or only a 0.62-WAC addition to the original WAC. This additional WAC is so little that it can possibly be omitted. Therefore, the measurement of large pores in laterite may be unnecessary. However, the porosity of large pores may correlate to the change of compressive strength of laterite; hence, whether or not the additional percentage porosity of large pores affects the strength of laterite needs to be studied and will be analysed and discussed in Chapter VII.

The purpose of this suggested test is only to evaluate whether or not the wax encapsulation method was efficient; therefore, it was conducted without being standardised to be comparable to other standard tests. In addition, it has never been applied to test other laterite or any porous materials. Thus, in order to compare the results with those obtained from other standardised tests easily and systematically, the percentage of porosity measured by the standard method is mainly used in the following analyses in this chapter.

According to the results gained from two sets of sample tested with the same method, they can be compared as displayed in the table below:

Table 6.8: The comparison of average percentage micro porosity (% pore) and water capacity (WAC) of different sets of laterite samples

Sample	Set B (ASTM method)		Set A (ASTM method)		WAC (ave)	% Pore (ave)	Difference			
	WAC	% pore	WAC	% pore			% WAC btw/ in&out	% pore btw/ in&out	% WAC btw/ Set A&B	% pore btw/ Set A & B
Average (ave)	9.89	20.28	9.52	20.53	9.70	20.41	0.56	1.49	0.76	1.22

Each sample had its own water absorption capacity and percentage porosity and this may confirm that laterite is heterogeneous when quarried from different locations or in different periods. Regarding the calculations, the difference of the averages of water absorption capacity between two sets of the laterite samples is only 0.76; and the difference of the averages of percentage porosity is only 1.22. The different averages of WAC and percentage porosity of the inner and outer parts of a sample are also as little as 0.56 and 1.49, respectively, and they may be ignored. Therefore, it may be concluded that most of the samples were homogeneous individually. However, some samples such as the ones from the middle of the east façade and from the bottom of the south façade were fairly heterogeneous, but this case rarely recurred, only one out of twelve samples or only 8.33%.

In terms of the comparison of percentage porosity amongst the samples, the interior of the samples collected from the middle of East façade displayed the greatest water absorption capacity and contained the highest percent porosity (by the standard method). Nevertheless, because each laterite block has its own individual property and is incomparable to others, the comparison of these two properties amongst different blocks is impracticable. Therefore, only the comparison of such properties within the same block but different positions was undertaken. The results are shown in Table 6.9 below:

Table 6.9: The comparison of average percentage micro porosity of the laterite samples taken from different positions

Set B (ASTM)	WT	WM	WB	NT	NM	NB	ET	EM	EB	ST	SM	SB
Outer	18.46	22.40	**20.53**	21.21	**18.28**	15.38	20.98	19.79	**22.35**	19.96	17.82	**21.69**
Inner	**21.39**	**22.67**	17.28	**23.28**	17.67	**17.63**	**21.06**	**25.47**	20.73	**20.54**	**22.01**	18.23
Set B (Wax)	WT	WM	WB	NT	NM	NB	ET	EM	EB	ST	SM	SB
Outer	26.21	31.12	**29.79**	**42.85**	22.70	22.00	**32.43**	24.71	31.60	**33.01**	18.73	**32.78**
Inner	**29.35**	**33.71**	22.99	38.58	**25.54**	**26.72**	30.13	**28.76**	**32.49**	30.24	**38.07**	31.07

Note: The **bold** number indicates the higher percentage when compared within the same block.

According to the results, within the same blocks, eight of twelve interior samples had a higher percent micro porosity than the exterior ones, or 66.67% of all samples (or, in the case of the percentage of both micro and macro pores within a sample, seven out of twelve or 58.33 % of all samples had higher percentage porosity at the interior than the exterior). It may be concluded that the percentage porosity of mature laterite used as façade walls tend to decrease when exposed to the environment for a period of time. The reason why this phenomenon occurred will be discussed in Chapter VII.

To confirm the assumption of the environmental effects above, further analysis needs to be carried out. The comparison of the results is displayed in the following table:

Table 6.10: The averages of percentage micro porosity of laterite samples in relation to their locations (Note: The **bold** number indicates the higher percentage when compared within the same block.)

Set B (ASTM)	**WT**	**WM**	**WB**
X	18.46	22.40	**20.53**
N	**21.39**	**22.67**	17.28
	NT	**NM**	**NB**
X	21.21	**18.28**	15.38
N	**23.28**	17.67	**17.63**
	ET	**EM**	**EB**
X	20.98	19.79	**22.35**
N	**21.06**	**25.47**	20.73
	ST	**SM**	**SB**
X	19.96	17.82	**21.69**
N	**20.54**	**22.01**	18.23

The samples from the west, east and south show the same pattern of micro-porosity, where the samples from the exterior of the wall had lower porosity than those from the interior. This is indicated by the numbers in bold. Unlike the other parts of samples, the outer part of the samples collected from the bottom of every façade, except the north, had higher percentage micro porosity than that of the interior. Preliminarily, because the history of the site states that the samples in the bottom had been buried under the soil for years and given the climate in Thailand where east, west and south walls directly face the sunlight daily, it may be concluded that sunlight may have been a predominant cause in the change of percentage of micro pores of laterite—the more the exposure to sunlight of laterite, the lower the micro percentage porosity. For the north façade's samples, the change of percentage porosity may have not been related to sunlight but to other environmental agents. How sunlight affects and whether or not other environmental decay agents affect the change of percentage micro porosity of ancient/mature laterite will be thoroughly studied and discussed in the following chapter.

3) Compressive strength test

The compressive strength test carried out in this chapter was based on the ASTM C170-87 test whose procedure was explained in the Chapter III. Six laterite cubes per sample were tested with three cubes (Set A: a, b, c in Data Set 3 in Appendix VI) demonstrating wet laterite under compression and the others (Set B: d, e, f in Data Set 3 in Appendix VI) demonstrating dry laterite under compression.

Results

Table 6.11: The average compressive strength of laterite samples (see the number of cases and the standard deviation of the data in Data Set 4 in Appendix VI)

Sample	Compressive Strength (psi)		% strength difference
	Wet	Dry	
1 (WTX)	-853.61	-2208.35	52.02
2 (WTN)	-825.26	-875.90	5.74
3 (WMX)	-684.58	-499.80	38.41
4 (WMN)	-673.28	-890.35	26.15
5 (WBX)	-1380.66	-1354.90	-1.05
6 (WBN)	-610.08	-2006.29	69.45
7 (NMX)	-649.28	-1169.76	45.04
8 (NMN)	-306.97	-639.38	51.90
9 (NTX)	-671.51	-948.03	45.48
10 (NTN)	-372.77	-773.37	52.22
11 (NBX)	-1786.84	-1846.04	0.67
12 (NBN)	-1544.57	-2892.86	47.72
13 (ETX)	-999.36	-2048.93	47.70
14 (ETN)	-1107.00	-1467.07	24.84
15 (EMX)	-248.10	-407.82	34.88
16 (EMN)	-149.00	-458.67	66.00
17 (EBX)	-492.72	-1085.55	62.56
18 (EBN)	-841.21	-1314.39	36.35
19 (STX)	-1024.08	-1971.97	48.64
20 (STN)	-1399.88	-1358.79	-10.21
21 (SMX)	-530.95	-910.45	39.79
22 (SMN)	-747.28	-1200.48	40.98
23 (SBX)	-561.52	-1444.64	60.90
24 (SBN)	-941.98	-954.00	-0.67

Conclusion

In terms of the compressive strength of laterite, as previously discussed in Chapter III, dry laterite performs better than wet laterite. However, in this test, some samples (three of twenty-four samples, or 12.5%) performed unexpectedly and in their wet state, they bore greater compression. Hence, it is not always that laterite loses its compressive strength when wet and we should look for other factors causing such change of compressive strength and these factors will be discussed in Chapter VII.

Whether or not the compressive strength of laterite is affected by environmental decay agents is one of the main purposes of the test in this chapter. Therefore, to investigate whether or not the locations in which laterite blocks were placed are related to the alteration of compressive strength, the following analysed data table is drawn:

Table 6.12: Analysis of the compressive strength of wet and dry laterites in relation to locations

	WTX	WTN	NTX	NTN	ETX	ETN	STX	STN
Wet	O		O			O		O
Dry	O		O		O		O	
	WMX	WMN	NMX	NMN	EMX	EMN	SMX	SMN
Wet	O		O		O			O
Dry		O	O			O		O
	WBX	WBN	NBX	NBN	EBX	EBN	SBX	SBN
Wet	O		O			O		O
Dry		O		O		O	O	

O = Higher compressive strength in a comparison between the inner and outer parts of a block

According to the table, there is no similar pattern of higher compressive strength in laterite from different locations. The laterite from the top of the west and the north façades, that from the top of the east and the south façades, that from the middle of the west and the east façades and from the bottom of the west and the north facades, and that from the middle of the south façade and from the bottom of the east facade performed as expected. However, the samples from the middle of the north façade performed inversely to the previous group (WT=NT, ET=ST, WM=EM=WB=NB, SM=EB≠NM). These correlations are not systematic and rational, and do not indicate any relevant environmental cause of changes in strength. Therefore, it is tentatively concluded that neither location of laterite nor environmental decay agents are related to a change in laterite compressive strength over time. What actually causes the change will be investigated more thoroughly in the next chapter.

6.4. *Summary*

In order to clarify the results of the assessments and analyses, the summary is listed as follows:

1) Macro deterioration in relation to the aspect of facades,
    a) the north façade was affected by microorganisms and cracks the most, but had very little root penetration;
    b) the west façade had the largest amount of plant growth and the largest area of tree root, but had the smallest area of cracks.

2) Chemical composition in relation to the location of the laterite samples,
    a) fifty percent of samples from every position had lost some of their silicon dioxide;
    b) every sample at the top of the walls had lost some of its aluminium dioxide while only one middle-wall sample (25%) and two samples from the bottom had lost it;
    c) three out of four samples (75%) at the bottom had lost some of their ferric oxide, while only fifty percent of samples from the top and the middle had lost some;
    d) all samples from the east façade had lost some of their silicon dioxide;
    e) 66.7% of the samples taken from the west, the north and the south had lost some of their aluminium oxide, while only 33.3% of the laterite blocks from the east façade had lost some;
    f) 66.7% of the laterite samples from the west, the north and the east had lost some of their ferric oxide, while only 33.3% of the laterite blocks from the south façade had lost some;
    g) silicon dioxide in laterite is possibly leached out when exposed to the east environment;

  h) aluminium oxide in laterite is likely to be transformed when exposed to the air directly (at least two sides of the block are exposed to the air);
  i) ferric oxide in laterite seems to be transformed when in contact with the soil.

3) The wax encapsulation method for measuring the percentage large pores in laterite succeeded in retaining water and allowing the measurement of such water's weight and volume.

4) Because the additional percentage porosity and hence the additional WAC measured by the wax encapsulation method is so little that it can possibly be omitted, the measurement of large pores in laterite may be unnecessary. The discussion of the correlation between the overall percentage porosity and the strength of laterite samples, to be discussed in the next chapter, will justify whether this conclusion is valid.

5) Because each sample had its own water absorption capacity and percentage porosity, it may be concluded that laterite is heterogeneous when quarried from different locations or in different periods.

6) It may be concluded that most of the laterite samples are homogeneous individually because the difference averages of WAC and percentage porosity of the inner and outer parts of a sample are so little that they can be discussed as insignificant.

7) It may be concluded that the percentage micro porosity of mature laterite used as façade walls tend to decrease when exposed to the environment for a period of time.

8) In terms of compressive strength, there is no similar pattern of higher compressive strength in laterite from different locations. The correlations

are not systematic and rational, and do not indicate any relevant environmental cause of the strength change.

9) It is not always that laterite loses its compressive strength when wet.

10) It is tentatively concluded that neither the location of laterite nor environmental decay agents affects change of laterite compressive strength over time.

This study therefore enhances our greater understanding of the nature of laterite in terms of its characteristics and properties and of the real weathering processes of laterite under the effects of various environmental decay agents. However, since this chapter is only focussed on the assessments of laterite deterioration in relation to its location without characterising the decay agents, what causes such deterioration to occur in laterite has yet to be investigated and discussed. In particular, what actually causes change in laterite strength needs to be investigated more thoroughly. These investigations will be carried out and discussed in the next chapter.

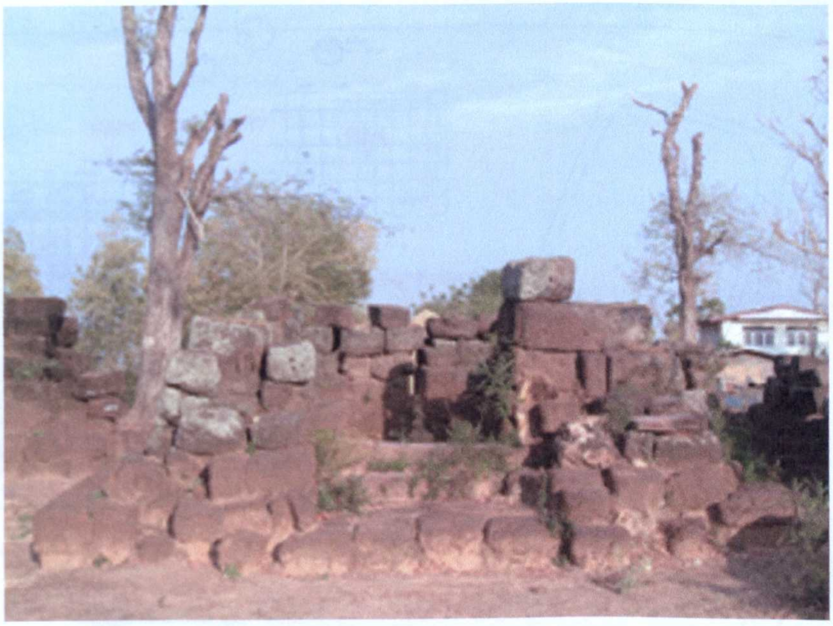
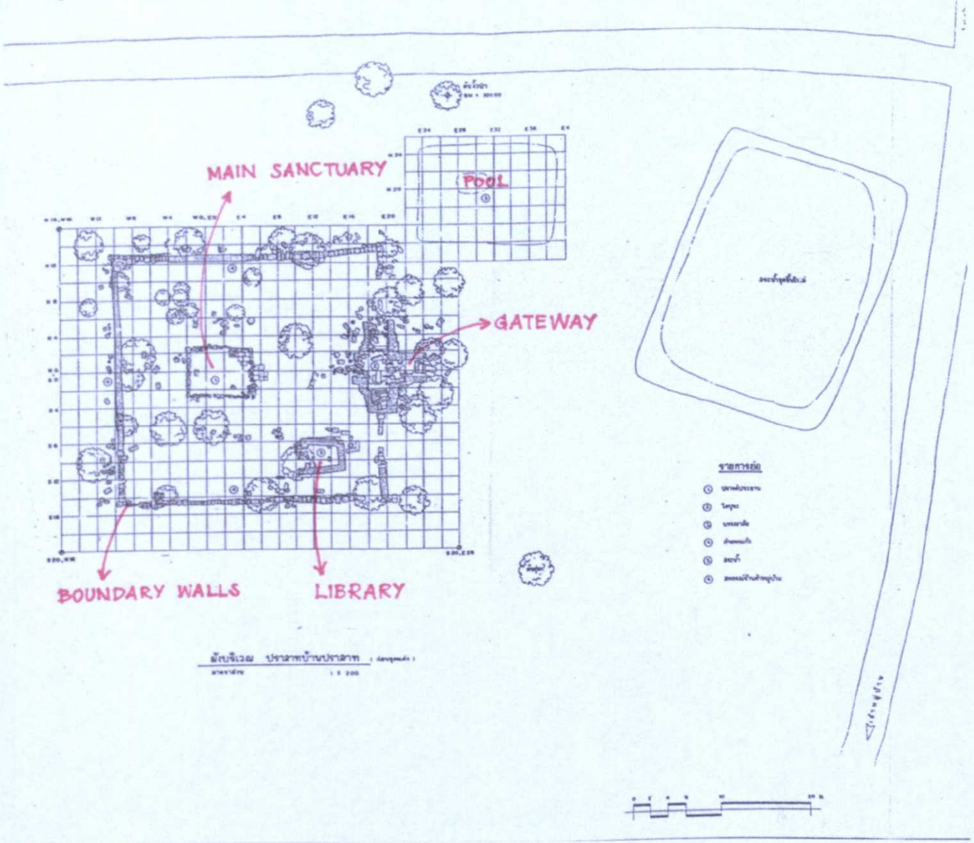
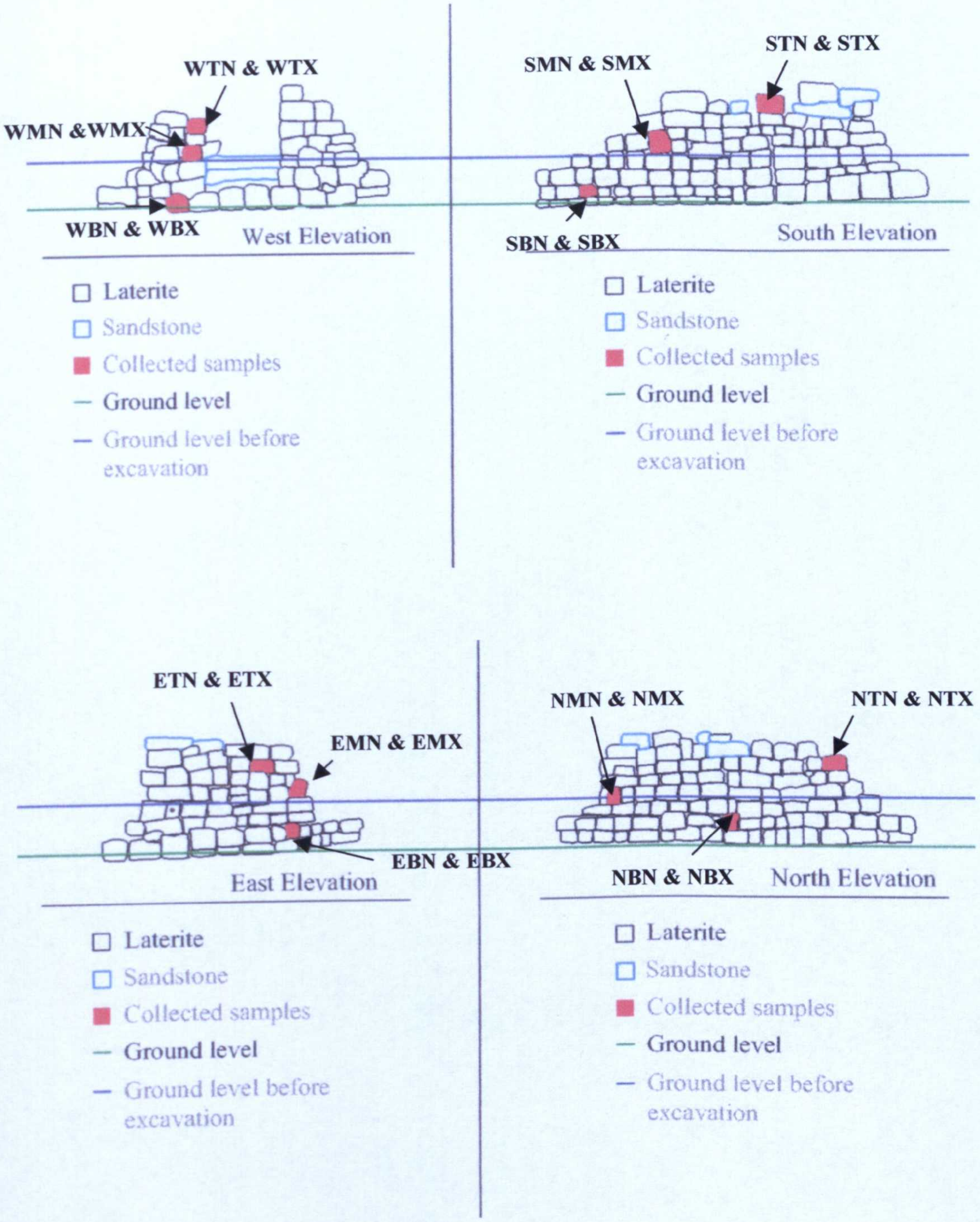


Figure 6.1:
Banalaya (library) of the Ban Prasat Complex
(in 2004)

Map 6.1: Site plan of the Ban Prasat Complex (FAD 2003)

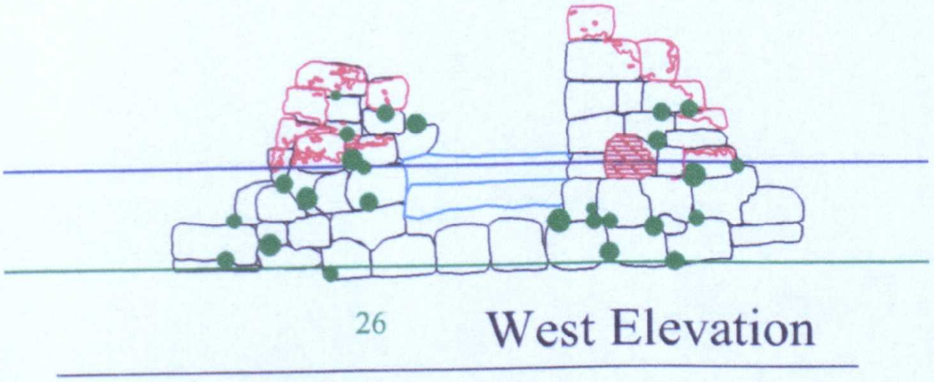


Drawing 6.1: Positions of collected samples



Drawing 6.2: Macro deterioration assessments on the west façade

Laterite area = 144205
Lichen area = 17660 = 12.25%



☐ Laterite

☐ Sandstone

— Ground level

— Ground level before excavation

☐ Lichens

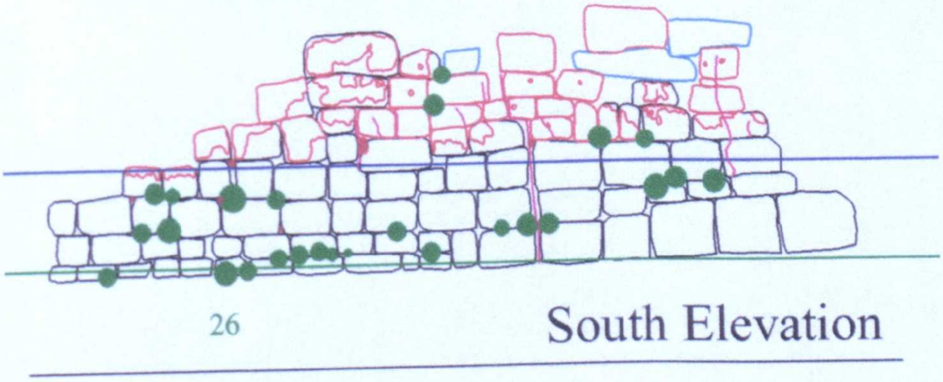
● Plants

■ Tree roots

— Cracks

Drawing 6.3: Macro deterioration assessments on the south façade

Laterite area = 241093
Lichen area = 64886 = 26.91%



☐ Laterite

☐ Sandstone

— Ground level

— Ground level before excavation

☐ Lichens

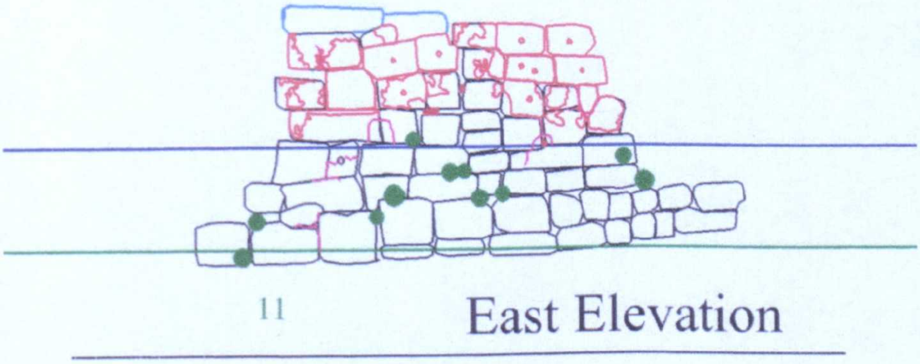
● Plants

■ Tree roots

— Cracks

Drawing 6.4: Macro deterioration assessments on the east façade

Laterite area = 145753
Lichen area = 34488 = 23.66%



☐ Laterite

☐ Sandstone

— Ground level

— Ground level before excavation

☐ Lichens

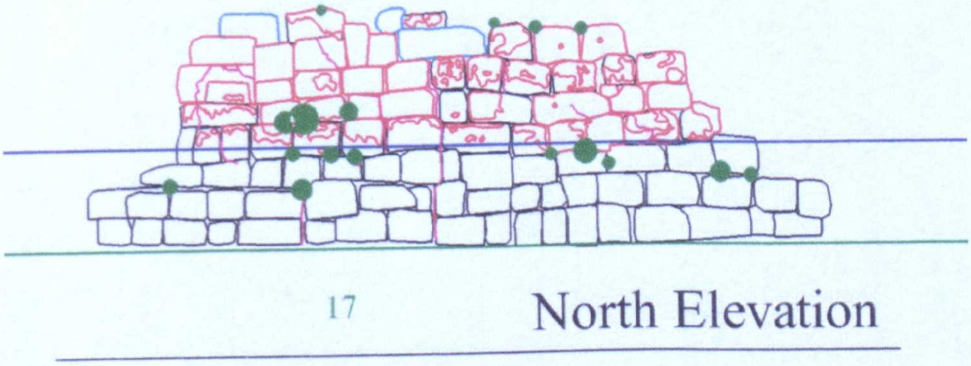
● Plants

■ Tree roots

— Cracks

Drawing 6.5: Macro deterioration assessments on the north façade

Laterite area = 212182
Lichen area = 69807 = 32.90%



☐ Laterite

☐ Sandstone

— Ground level

— Ground level before excavation

☐ Lichens

● Plants

■ Tree roots

— Cracks

CHAPTER VII

DISCUSSIONS

In Chapter VI, a laterite monument was selected and studied and its deterioration problems were assessed. However, because only the assessments of laterite deterioration in relation to its location were focussed upon, the analyses of the correlations–amongst the laterite properties, the environment and the deterioration—and the investigations of the causes of laterite deterioration—especially the causes of the alteration of laterite strength—are waiting to be conducted in order to complete the assessments. Therefore, one of the purposes of this chapter is to analyse these correlations and these deterioration causes. This will be done through analyses and discussions of the relationships amongst laterite properties and the environment. Knowledge gained from other literature will helpfully confirm the conclusion of each analysis.

The other purpose of this chapter is to discuss whether laterite is suitable as a building material. As previously discussed, the strength of a material is the most important property in its suitability for construction; hence, whether the strength of laterite depends on other properties or on its environment is the subject to be investigated here. The results obtained from the tests in Chapter VI are analysed, and the analyses can be helpfully justify the suitability of laterite for being used as a building material. Moreover, in order to apply an appropriate conservation approach to remaining Khmer architecture in Thailand which were either wholly or partially built of laterite, whether or not ancient laterite needs to be conserved is also another subject to be discussed.

7.1. Correlation analysis and discussions

The assessments and analyses in Chapter VI provided useful data and results for studying the effects of environmental deterioration agents on laterite in different locations. They will now be employed to analyse whether or not the properties of laterite, its deterioration and its locations correlate significantly. The significant relationship could be calculated statistically through a command in SPSS programme called 'Bivariate correlation' in the 'Analyze' tool. Whether Pearson's correlation significant value (*r*) or Spearman's rank correlation significant value (*rho*) is used depends on whether the two sets of data are normally distributed. If either one is not normally distributed, the Spearman's *rho* indicates whether they correlate with each other significantly. However, to analyse some data sets, such as percentages which constitute a closed number system in which all numbers are related, Pearson's *r* is not an appropriate method to use. These results need to be analysed using a non-parametric test method, and therefore Spearman's *rho* should rather be used. In addition, some data sets that are obtained from a small sample size (smaller than 30 samples) should be analysed using a non-parametric test method and Spearman's *rho* should also be used. Thereafter, such significant correlations can be indicated by their significant values higher than the critical significant value and by the linear regression of the correlations. If the correlation is significant, the linear regression can be calculated using the linear regression command in the EXCEL programme. Such linear regression can also be used by conservators for predicting the properties and decay mechanisms of any laterite.

7.1.1 Correlation amongst laterite properties

Correlation amongst main chemical composition

According to the results of the chemical composition investigation obtained in Chapter VI, the ratio of silicon dioxide to aluminium oxide and to ferric oxide of each sample and their correlations could be calculated as shown in Tables 7.1 below:

Table 7.1: Spearman's rank correlation significant values (*rho*) between the percentages of the main chemical composition in the tested laterite samples
(n = 24, critical *rho*= 0.409 (0.05) and 0.537 (0.01))

rho (n=24)	SiO_2	Al_2O_3	Fe_2O_3	SiO_2: Al_2O_3	SiO_2: Fe_2O_3	SiO_2: sesquioxides
SiO_2	**1.000**	**-0.762**	**-0.950**	**0.909**	**0.986**	**0.988**
Al_2O_3	**-0.762**	**1.000**	**0.664**	**-0.951**	**-0.727**	**-0.783**
Fe_2O_3	**-0.950**	**0.664**	**1.000**	**-0.827**	**-0.985**	**-0.966**
SiO_2: Al_2O_3	**0.909**	**-0.951**	**-0.827**	**1.000**	**0.882**	**0.922**
SiO_2: Fe_2O_3	**0.986**	**-0.727**	**-0.985**	**0.882**	**1.000**	**0.991**
SiO_2: sesquioxides	**0.988**	**-0.783**	**-0.966**	**0.922**	**0.991**	**1.000**

According to the rank correlation significant values (*rho*) in the tables, there are significant correlations between each main chemical composition. If the percentage of silicon dioxide increases, the percentage of aluminium oxide decreases as a negative correlation significance of 0.762**. (When the number of samples is twenty-four, the Spearman's critical *rho* is 0.409 in the two-tailed test of significance at the 0.05 level of significance and is 0.537 in the two-tailed test of significance at the 0.01 level of significance. * represents a significant correlation at the 0.05 level of significance and ** represents a significant correlation at the 0.01 level.) Similarly, the percentage of ferric oxide decreases when the percentage of silicon dioxide increases. In contrast, when the percentage of silicon dioxide increases, the ratio of silicon dioxide to aluminium oxide gets higher, as same as the correlation between silicon dioxide and ferric oxide; if the percentage of the former increases, the latter becomes higher. Furthermore, if the percentage of aluminium oxide increases, the percentage of ferric oxide increases. Since the percentage of aluminium oxide correlates with the percentage of ferric oxide positively, when the ratio of silicon dioxide to aluminium oxide gets higher, the ratio of silicon dioxide to ferric oxide also gets higher. (See Chart 6.3 on page 237 to see the relationships amongst them)

In terms of the greatest significant correlation, regarding the values of the correlation significance in the table, the percentage of silicon dioxide inversely correlates with that of iron oxide more significantly than that of aluminium oxide, resulting in a very predominant correlation between the percentage of silicon dioxide and its ratio to the percentage of ferric oxide. The more the laterite contains a large amount of silicon dioxide, the less the percentage of ferric oxide, leading to a higher ratio of these two compounds.

The significant correlations for the main chemical composition of laterite can be explained through the genesis of laterite. As reviewed in Chapter II, iron is primarily deposited in laterite as highly-hydrate ferric hydroxide. Such ferric hydroxide later reacts with primarily deposited tri-hydrate alumina to be gibbsite ($Al_2O_3.H_2O$) and ferric oxide (Fe_2O_3) composed in laterite (Campbell 1917, 67-77). In addition, hardening of laterite, through wet-dry cycles, is accompanied by the transformation of kaolinite to aluminium oxide and silicon dioxide. Thereafter, soluble silicon dioxide in laterite is leached away and only quartz grains remains (Alexander and Cady 1962, 10). These phenomena result in the greater amount of ferric oxide and aluminium oxide in laterite. The more they occur, the higher the percentage of the aluminium oxide and ferric oxide, hence the lower the percentage of silicon dioxide in the laterite and the lower the ratio of silica to these metallic sesquioxides. That might be why some scholars have used such a ratio (lower than 1.33) to differentiate laterite from lateritic soils and other non-lateritic materials (Martin and Doyne 1927, 530; Prakash and Basavanna 1970, 166). According to them, such a ratio could therefore indicate the maturity of laterite. As previously discussed in Chapter VI, the ratio of silicon dioxide to metallic sesquioxides is more suitable to be used for classifying laterite specifically found in Thailand than the ratio to aluminium oxide or to ferric oxide alone.

In summary, the main chemical compounds in the tested laterite correlate with each other significantly—either inversely or directly—and the ratio of silica to sesquioxides can indicate the maturity of laterite. However, whether or not each main chemical composition correlates with other properties (and knowing it can be useful for characterising the properties of laterite, especially for predicting the strength of laterite) needs further analyses and will be discussed below.

Correlations between colours and other micro properties

The correlations between colours and other laterite micro properties are discussed next. The tables below display the values of correlation significant among them. Since the value and chroma of the colour of the tested samples are non-normally distributed, only Spearman's rank correlation significant values are taken into account.

Table 7.2: Rank correlation significant values (*rho*) between laterite colour (value and chroma) and other properties
n = 24, critical *r*= 0.409 (0.05) and 0.537 (0.01)

***rho* (n=24)**	SiO_2	Al_2O_3	Fe_2O_3	Dry strength	Wet strength	*Value*	*Chroma*
Value	-0.057	-0.183	0.133	0.041	0.194	1.000	
Chroma	**-0.534**	0.341	**0.491**	-0.343	-0.164	0.386	1.000

Table 7.2 shows that the chroma of the samples correlates with their silicon dioxide and ferric oxide significantly. It shows a significant negative correlation with the percentage of silicon dioxide (significant value is -0.534*, while the critical significant value is 0.409 in the two-tailed test of significance at the 0.05 level of significance and equals to 0.537 in the two-tailed test of significance at the 0.01 level of significance); and significantly correlates with the percentages of ferric oxide (correlation significant value is 0.491*). Since chroma of a colour indicates the purity and intensity of such colour, that means the percentage of silicon dioxide and ferric oxide in laterite only affects the purity or intensity of laterite colours but does not affect their degree of lightness and darkness or 'value' in Munsell Soil Colour Charts (the detail of how to measure the colour of laterite was previously discussed in Chapter III). The lower the content of silicon dioxide, the more intense the colour. In contrast, the higher the percentage of ferric oxide, the more intense the colour of laterite. However,

this conclusion may be applicable only in the case where the laterite colour is brown (7.5YR: yellow-red in Munsell Soil Colour Chart).

However, because there is no significant correlation between the colour and the strength of laterite, it may be concluded especially in this case that iron oxide, which commonly gives laterites colours, is not a good tool for the estimation of the strength of laterite. Although the purer colour of laterite composed of higher amount of ferric oxide usually indicates its greater maturity and hence hardness, this should not suggest to users that such laterite is capable of bearing loads any better than the less mature one.

Correlations between compressive strength and other properties

It was tentatively concluded in the previous chapter that neither locations of laterite on façades nor environmental decay agents result in changes to the compressive strength of laterite over time. Hence, we need to understand what does affect the change of compressive strength in laterite. Since compressive strength is generally related to the macro or micro structure of a material, its porosity, density and chemical/mineral composition should also be taken into account. The results of all the tests in Chapter VI—the chemical composition, the percentage of porosity and the compressive strength— are now compared and displayed in the tables below:

Table 7.3: Comparison of the chemical composition and compressive strength of the tested laterite

Sample	Chemical Compound (%)			Strength (average)	
	SiO_2	Al_2O_3	Fe_2O_3	Dry Comp(psi)	Wet Comp(psi)
1 (WTX)	45.38	7.26	36.04	-2208.35	-853.61
2 (WTN)	39.77	9.02	39.78	-875.90	-825.26
3 (WMX)	36.02	8.89	44.17	-499.80	-684.58
4 (WMN)	38.66	8.59	42.10	-890.35	-673.28
5 (WBX)	53.05	7.06	30.43	-1354.90	-1380.66
6 (WBN)	51.48	7.35	31.42	-2006.29	-610.08
7 (NMX)	47.04	8.14	33.29	-1169.76	-649.28
8 (NMN)	46.70	8.05	34.29	-639.38	-306.97
9 (NTX)	46.93	7.35	34.74	-948.03	-671.51
10 (NTN)	49.10	7.45	32.56	-773.37	-372.77
11 (NBX)	46.11	7.93	35.50	-1846.04	-1786.84
12 (NBN)	42.22	8.58	37.69	-2892.86	-1544.57
13 (ETX)	41.47	7.96	39.20	-2048.93	-999.36
14 (ETN)	42.07	8.77	38.10	-1467.07	-1107.00
15 (EMX)	39.63	10.33	38.94	-407.82	-248.10
16 (EMN)	40.20	9.24	39.48	-458.67	-149.00
17 (EBX)	45.69	8.05	34.79	-1085.55	-492.72
18 (EBN)	46.30	7.74	35.29	-1314.39	-841.21
19 (STX)	49.37	6.89	33.81	-1971.97	-1024.08
20 (STN)	47.90	6.96	34.87	-1358.79	-1399.88
21 (SMX)	48.83	7.11	34.15	-910.45	-530.95
22 (SMN)	46.91	7.96	33.62	-1200.48	-747.28
23 (SBX)	45.61	6.93	35.31	-1444.64	-561.52
24 (SBN)	48.75	6.68	32.25	-954.00	-941.98

Table 7.4: Rank correlation significant values (*rho*) amongst laterite chemical composition and compressive strengths

n= 24, critical *rho*= 0.409 (0.05) and 0.537 (0.01)

***rho* (n=24)**	SiO_2	Al_2O_3	Fe_2O_3
Dry Comp(psi)	0.269	**-0.432**	-0.185
Wet Comp(psi)	0.092	-0.276	0.028

In calculating the correlations between chemical composition and compressive strength properties, as seen in Tables 7.4, there is a negative correlation significance of 0.432* between the percentage of aluminium oxide and dry compressive strength. However, there is no significant correlation between compressive strength (in any condition) and the other chemical compounds as the correlation significant values are all lower than the critical significant value of 0.409 in the two-tailed test of significance at the 0.05 level of significance and of 0.537 in the two-tailed test of significance at the 0.01 level when twenty-four samples were tested. Therefore, it may be concluded that the compressive strength of a dry laterite only depends on the percentage of aluminium oxide it contains. The more the percentage of aluminium oxide, the lower the strength. The analysis of the percentage of aluminium oxide in a laterite may be helpful to predict its compressive strength.

It is to be noted that this conclusion is contrary the conclusion in Chapter III, stating of the significant correlation between percentage ferric oxide and compressive strength. However, the conclusion in this chapter is obtained from testing a larger number of laterite samples; this new conclusion, therefore, should be more statistically correct.

Table 7.5: Comparison of laterite compressive strength (average data) in wet and dry conditions and the percentage porosity

Sample	Wet condition		Dry condition		
	% micro porosity	Compressive Strength.(psi)	% overall porosity	% micro porosity	Compressive Strength (psi)
1 (WTX)	18.60	-853.61	26.21	18.46	-2208.35
2 (WTN)	20.40	-825.26	29.35	21.39	-875.90
3 (WMX)	22.03	-684.58	31.12	22.40	-499.80
4 (WMN)	22.90	-673.28	33.71	22.67	-890.35
5 (WBX)	19.95	-1380.66	29.79	20.53	-1354.90
6 (WBN)	19.85	-610.08	22.99	17.28	-2006.29
7 (NMX)	18.76	-649.28	22.70	18.28	-1169.76
8 (NMN)	18.18	-306.97	25.54	17.67	-639.38
9 (NTX)	21.47	-671.51	42.85	21.21	-948.03
10 (NTN)	23.33	-372.77	38.58	23.28	-773.37
11 (NBX)	16.79	-1786.84	22.00	15.38	-1846.04
12 (NBN)	17.27	-1544.57	26.72	17.63	-2892.86
13 (ETX)	21.66	-999.36	32.43	20.98	-2048.93
14 (ETN)	19.46	-1107.00	30.13	21.06	-1467.07
15 (EMX)	22.15	-248.10	24.71	19.79	-407.82
16 (EMN)	19.76	-149.00	28.76	25.47	-458.67
17 (EBX)	21.23	-492.72	31.60	22.35	-1085.55
18 (EBN)	20.73	-841.21	32.49	20.73	-1314.39
19 (STX)	20.95	-1024.08	33.01	19.96	-1971.97
20 (STN)	20.51	-1399.88	30.24	20.54	-1358.79
21 (SMX)	20.15	-530.95	18.73	17.82	-910.45
22 (SMN)	21.12	-747.28	38.07	22.01	-1200.48
23 (SBX)	23.89	-561.52	32.78	21.69	-1444.64
24 (SBN)	21.58	-941.98	31.07	18.23	-954.00

Table 7.6: Rank correlation significant values (*rho*) between the micro percentage porosity and compressive strength in both conditions

n= 24 critical *rho*= 0.409 (0.05) and 0.537 (0.01)

Rank correlation significant values (*rho*)

	%porosity	*Strength (wet)*
%porosity	**1.000**	
Strength (wet)	-0.332	**1.000**

r (n=24) df = 24-2 = 22, critical *r*= 0.404 (0.05) and 0.515 (0.01)

Correlation significance values (*r*)

	%porosity	*Strength (dry)*
%porosity	**1.000**	
Strength (dry)	**-0.429**	**1.000**

Table 7.7: Rank correlation significant values (*rho*) between compressive strengths of laterite in wet and dry conditions

n= 24 critical *rho*= 0.409 (0.05) and 0.537 (0.01)

	Strength (dry)	*Strength (wet)*
Strength (dry)	**1.000**	
Strength (wet)	**0.675**	**1.000**

In terms of correlation between percentage micro porosity and the compressive strength of laterite, when the twenty-four sets of samples are considered as a group, the compressive strength of laterite in a dry condition correlates inversely with the porosity. It seems that the lower the percentage micro porosity, the greater the compressive strength in the dry condition. The correlation between the compressive strength of wet laterite and of dry laterite is relatively significant (as seen in Table 7.7, the correlation significant value is 0.675** while the critical significant values are only 0.404 in the two-tailed test of significance at the level of significance of 0.05; and 0.515 in the two-tailed test of significance at the level of significance of 0.01). It indicates that the greater the compressive strength of wet laterite, the greater the compressive strength of dry laterite.

In terms of the correlation between the percentage of both large and small pores and the strength, regarding the test in Chapter VI, only the samples tested for their compressive strength when dry were measured for their micro and macro percent porosity. The comparison between their average overall porosity and compressive strength is also shown in Table 7.5 above.

Table 7.8: Rank correlation significant values (*rho*) between the overall percentage porosity and compressive strength in dry condition

n= 24 critical *rho*= 0.409 (0.05) and 0.537 (0.01)

Rank correlation significant values (*rho*)

	%porosity	*Dry comp.*
%porosity	**1.000**	
Dry comp.	-0.018	**1.000**

According to Table 7.8, there is no significant correlation between the percentage of overall pores and the compressive strength of dry laterite. The overall percentage porosity of a laterite does not indicate the strength, especially when it is dry. That means it is not necessary to measure the overall percentage porosity of a laterite in order to estimate its compressive strength because a low percentage of micro and macro pores in a laterite, especially the macro ones, does not guarantee its high compressive strength.

In summary, the compressive strength of dry laterite is inversely related to the porosity of micro pores. The higher percentage porosity indicates the lower density of a laterite resulting in its more vesicular structure which, basically, is ineffective for bearing loads. However, how such vesicular structure forms to be a laterite should also be taken into consideration—for instance, in the fields of architecture and civil engineering, a honeycomb structure is one of the strongest structural forms in terms of durability and load bearing capacity, despite its vesicular structure.

The correlation between the percentage micro porosity and compressive strength was however not so greatly significant that a low percentage of pores always implies high compressive strength. Therefore, there must be other factors affecting the compressive strength of laterite and its alterations over time. As previously discussed, pore structure is one of them. Some laterite blocks that comprise a large number of micro pores resulting in high percentage porosity might have stronger pore structure leading them to bear greater compressive loads than others having lower percentage porosity but being formed with a weaker pore structure. Some researchers suggest classifying pore structure of laterite into two types—pisolitic and cellular/slag-like—which can be considered the easiest way to classify pore structure of laterite blocks used in building construction (Marbut and Manifold 1926, 414-442; Pendleton 1941, 177-202; Pendleton and Shanasuvana 1946, 423-440). From the observation of the laterite structure with the naked eye, most of the samples that had high compressive strength were densely slag-like/composed of only a very few large pores (greater than 0.5 centimetre in diameter), or were mainly composed of pisolitic nodules smaller than five millimetres in diameter. Thus, it may be suggested that laterite that is visually higher slag-like or densely cellular tend to perform greater compressive strength. Simultaneously, those which are dense usually have a lower overall percentage porosity as well.

7.1.2. Correlation of laterite properties and its locations

The assessment in Chapter VI suggested that the percentages of micro porosity of laterites which had been exposed to the air, especially those of the blocks placed on the top of walls, were all lower, and, except in the north side, so were those of the blocks in the middle. The porosity of the blocks in the bottom however performed inversely— the blocks in every side had higher percentage porosity in the outer part than in the core. As discussed in Chapter VI, sunlight might decrease the porosity. Therefore, how sunlight affects the porosity of laterite is discussed here.

Laterites are hardened by the process of laterization which is the combination of the leaching out of silica and other soluble matters and the precipitation of iron oxides from ferrous to ferric compounds through wet-dry cycles. Rain and sunlight are therefore predominantly involving factors. Rainwater leaches away soluble minerals which may remain in laterite and reacts chemically with remaining ferrous hydroxide to become ferric oxide. Thereafter, sunlight dries out the remaining solutions leading to the precipitation of ferric oxide around laterite grains, mainly quartz. Consequently, the precipitation of ferric oxide cements the laterite grains and partially closes micro pores resulting in lower percentages of porosity of the laterites. However, this conclusion contradicts findings of earlier scholars presented in the literature review in Chapter II, suggesting that after laterization, laterite becomes more porous.

There are three possible reasons for explaining this contradiction. Firstly, this study demonstrates the fallacy of earlier positions. Secondly, this new conclusion may be applicable only to the percentage of micro pores, while large pores and voids remain, as a result of the leaching out of fine-grained constituents during the process of laterization, leading to the higher percentage of macro porosity as discussed in Chapter II. The last possible reason is that the decrease of percentage porosity in the tested laterite samples might be related to sunlight. However, if we suppose this to be the case, sunlight might not cause the laterite to continue laterising, but rather affect laterite in an unknown way and decrease its porosity.

However, it would be irrational to accept one of the reasons above as a correct answer without further discussion. Other contexts including the type of laterite have to be taken into consideration. Earlier literature reviewed in Chapter II discusses the laterization of parent rocks, but in this research, only ancient mature laterite which had already passed the process of laterization was tested. Therefore, it is possible that both conclusions are correct. When parent rocks laterise and eventually become mature laterite, the percentage porosity of the final product is higher than that of the immature one. Thereafter, if the mature laterite continues laterising, the percentage porosity will decrease.

Whether or not the new proposed conclusion can be applied to both macro and micro porosity is studied next. Table 7.9 compares changes in the porosity pattern of laterite samples.

Table 7.9: The comparison of the percentage porosity of laterite samples in relation to their location (the highlight indicates the part that has a lower percentage porosity in each block)

	Set B (Wax method)	**WT**	**WM**	**WB**	**Set B** (ASTM)	**WT**	**WM**	**WB**
WEST	X	26.21	31.12	29.79	X	18.46	22.40	20.53
	N	29.35	33.71	22.99	N	21.39	22.67	17.28
NORTH		**NT**	**NM**	**NB**		**NT**	**NM**	**NB**
	X	42.85	22.70	22.00	X	21.21	18.28	15.38
	N	38.58	25.54	26.72	N	23.28	17.67	17.63
EAST		**ET**	**EM**	**EB**		**ET**	**EM**	**EB**
	X	32.43	24.71	31.60	X	20.98	19.79	22.35
	N	30.13	28.76	32.49	N	21.06	25.47	20.73
SOUTH		**ST**	**SM**	**SB**		**ST**	**SM**	**SB**
	X	33.01	18.73	32.78	X	19.96	17.82	21.69
	N	30.24	38.07	31.07	N	20.54	22.01	18.23

From the table, only the micro porosity, measured with the ASTM method, changed systematically, while there is no pattern of the change of the overall percentage porosity, measured by the wax encapsulation method. The systematic change of micro porosity is undoubtedly caused by sunlight because only the samples facing strong sunlight—the west, the east and the south—were affected. Therefore, the discussion in this paragraph confirms that sunlight is the main agent that decreases the percentage of micro porosity of laterite. However, whether or not sunlight causes the continuous laterization to ancient laterite is still in doubt and needs a further study.

Regardless of the precise mechanism by which it affects laterite, sunlight certainly decreases the number of micro pores in laterite. According to the significant inverse correlation between the percentage of micro pores and the compressive strength of laterite, it may be concluded that sunlight makes mature laterite stronger by decreasing its micro porosity. Unlike other porous materials, laterite surprisingly becomes stronger after the direct exposure to the sun, and, possibly, rain, in a tropical climate.

Nevertheless, if sunlight and rainfall alone had affected the porosity of laterite, the percentage porosity of the samples at the bottom should not have been changed regardless of whether or not they were from the outer or the inner part of the blocks. In fact, the calculation of the percentage difference of the percentage of micro porosity between the inner and outer parts confirms that although the samples from the bottom had been buried in the soils and not exposed to the sun for hundreds years, there was no significant difference from such changes of the samples above the burying soils. Hence, there must be other factors involved and they need to be further studied.

Unlike micro pores, the number of large pores of laterite from the bottom was decreased the most, while from the top only the external samples from the west façade had a lower percentage of porosity than the internal ones. At the bottom, only the samples from the north and the east façades had a smaller percentage of porosity in the outer part. Therefore, obviously, the change of macro pores of laterite was not related to sunlight or wet-dry cycles.

Since all the samples in the middle had a lower percentage of large pores in their outer sections, it might be possible that their original locations above the burying soil could be a factor. The pores at the outer part might have been filled with soils and debris from the soils. Since such soils had recently filled the site, their particle arrangements were so loose that the soil particles could move into the pores by wind or rain and stuck in the large pores so tightly that they could not be removed naturally. For example, to remove the remaining soil in large pores of the samples tested in Chapter III, a spatula and a needle along with water injecting were needed. In contrast, the original soils being as the foundation of monuments were more packed and dense so that they hardly moved, especially in the places where there was no fluctuation of ground water; and that is why there was no systematic change pattern of the macro porosities in the samples from the bottom.

7.1.3. Correlation amongst laterite properties and its deterioration problems

In order to study whether or not microorganisms correlate with other laterite properties, the percentage of these deposits on each collected sample was calculated compared with the total area of the sample face. This means that only the external part of each sample was considered. However, because all external parts of the samples, including the blocks that did not have microorganisms on, were considered, this might be an inaccurate calculation. Therefore, the calculations were done but the blocks without microorganism deposits (the ones buried in the soil before excavation) were taken out of consideration. The results were shown in the tables below:

Table 7.10: Rank correlation significant values (*rho*) between percentage of microorganisms and other laterite properties (only external blocks which had microorganisms on were considered)

n= 8 critical *rho*= 0.738 (0.05) and 0.881 (0.01)

r (n=8)	SiO_2	Al_2O_3	Fe_2O_3	$SiO_2:Al_2O_3$	$SiO_2:Fe_2O_3$	Dry strength	Wet strength	% micro organisms
% micro organisms	0.345	-0.317	- 0.300	0.393	0.272	0.560	0.285	1.000

Although it is possible that microorganisms affect the chemical composition of a material by producing biogenic acids and chelating agents, such as oxalic acid, which react with the metallic ions minerals of the material (Jones et al 1987, 129-134; Singh and Sinha 1993, 355-357), Table 7.10 shows that there is no significant correlation between microorganism colonization and the main minerals of the tested laterite. This is possibly because either the laterite samples had too small an amount of microorganisms so that the effect of chemical degradation is unnoticeable, or the main chemical minerals of the laterite samples were not susceptible to such acidic reaction and chelation as commonly occurs on other stone. However, microorganisms, especially lichens, are generally capable of attacking iron and silicate minerals in stone (Kumar and Kumar 1999, 22). Therefore, it seems that the first assumption—that the amount of microorganism deposits on the tested laterite is too small—is a more likely reason for the absence of significant correlation between microorganisms and the mineral composition of the laterite.

The biophysical degradation of stone by microorganisms, especially lichens, is caused primarily by the penetration of their thallus to its pores, pre-existing cracks and fissures, leading to the widening of such cracks or resulting in new cracks being created (Kumar and Kumar 1999, 22). When cracks occur, the strength of the stone reduces. In the case of this research, Table 7.10 shows that there is no significant correlation between the compressive strength of the tested laterite and microorganisms deposited on them. Hence, it may be concluded that microorganisms do not alter the strength of laterite. However, it is possible that the amount of microorganisms on the tested laterite is too small to create any severe effect on the laterite, and, indeed, the samples that were tested for their compressive strength rarely had microorganism deposits.

It is possible that microorganisms also alter the percentage porosity of the stone. Generally, microorganisms cause a stone surface to appear honeycombed with etch pits and its intergranular cementing materials are sometimes affected, resulting in the loosening of the mineral grains (Jones and Wilson 1985, 99-104). Therefore, whether or not microorganisms on the laterite samples affected their porosity is now investigated. Like the previous analysis, only the samples that had microorganism deposits were taken into account and analysed with the data of the percentage of both overall and micro porosity to calculate the correlation between these two sets of data. The tables below display such data:

Table 7.11: The percentage of overall pores compared with the percentage of microorganisms

Sample	WAC (Ave)	% porosity (Ave)	% porosity difference btw/ inner and outer	% micro organisms
1 (WTX)	13.95	26.21	10.70	92.31
3 (WMX)	18.02	31.12	7.68	7.56
7 (NMX)	12.18	22.7	11.12	12.2
9 (NTX)	23.19	42.85	-11.07	78.12
13 (ETX)	16.2	32.43	-7.63	100
15 (EMX)	13.37	24.71	14.08	82.16
19 (STX)	16.99	33.01	-9.16	100
21 (SMX)	14.2	18.73	50.80	73.61

Table 7.12: The percentage of micro pores compared with the percentage of microorganisms

Sample	%porosity (Ave)	WAC (Ave)	% porosity difference btw/ inner-outer	% micro organisms
1 (WTX)	18.53	8.89	13.70	92.31
3 (WMX)	22.22	11.48	1.19	7.56
7 (NMX)	18.52	8.56	-3.45	12.2
9 (NTX)	21.34	9.92	8.89	78.12
13 (ETX)	21.32	8.97	0.38	100
15 (EMX)	20.97	10.20	22.30	82.16
19 (STX)	20.46	9.10	2.82	100
21 (SMX)	18.99	10.38	19.04	73.61

Table 7.13: Rank correlation significant values (*rho*) between percentage porosity, the percentage difference of overall porosity (outer-inner) and the percentage of microbiological growth

n= 8 critical *rho*= 0.738 (0.05) and 0.881 (0.01)

	WAC (Ave)	%porosity (Ave)	% porosity difference btw/ inner-outer	% micro organisms
% micro organisms	0.036	0.443	-0.371	1.000

Table 7.14 Rank correlation significant values (*rho*) between percentage porosity, the percentage difference of micro porosity (outer-inner) and the percentage of microbiological growth

n= 8 critical rho= 0.738 (0.05) and 0.881 (0.01)

	WAC (Ave)	%porosity (Ave)	% porosity difference btw/ inner-outer	% micro organisms
% micro organisms	0.072	0.395	0.120	1.000

From Table 7.13 and 7.14, there is no significant correlation between the percentage of microorganism deposits on the samples and the percentage difference of either macro or micro porosity of their outer and inner parts. Therefore, it is possible to conclude that microorganisms are not instrumental in the porosity change of laterite. So, the identification of what, apart from sunlight and rain, actually caused the overall porosity of the samples on the top of the west façade and at the bottom of the north and the east façade to change requires additional information and more thorough investigation than can be carried out in this research programme and therefore still needs to be investigated in the future.

Plants, root penetrations and cracks affected the façades on a macro scale and the samples collected to be tested did not have these deterioration agents affecting them. Hence, it is impossible to calculate whether their effects correlate with laterite micro properties.

7.1.4. Correlation of laterite deterioration problems in relation to its locations

In terms of environmental/extrinsic deterioration agents and their effects, according to the analysis in Chapter VI, the north façade was the most affected by microorganisms and cracks, while the west façade had the highest numbers of plants. In order to study whether or not there is any significant correlation among the extrinsic deterioration agents, Table 7.15 below shows their correlations:

Table 7.15: Rank correlation significant values (*rho*) between macro deterioration problems

When n ≤ 5, critical *rho* = 1.000 (level of *rho* =0.05)

n=4	*Plants*	*Cracks*	*Roots*
Plants	1.000	-.400	.400
Cracks	-.400	1.000	-1.000**
Roots	.400	-1.000**	1.000

According to Table 7.15, the values of correlation significance among these three macro deterioration problems show that there is an absolute negative significant correlation between cracks and root penetration which does not correspond to the observation survey that some cracks were penetrated by roots. Therefore, the actual causes of cracks on the façades need to be further investigated and will be discussed below.

Regarding macro deterioration problems in Chapter VI, all façades of the selected site showed a high level of microorganic deposits. They deposit on the north façade the most and on the west façade the least. The south and the east façades were affected by microorganisms in nearly equal part—the south was slightly more affected. It is worth noting that microorganisms were deposited only on the laterite blocks which had been exposed to the air for a period of time. What causes microorganisms to grow in different degrees in different locations is discussed below.

Microorganisms, especially microbiological growth, need sunlight, air and moisture as well as mineral nutrients from their host to grow (Kumar and Kumar 1999). Sunlight is the most important requirement for photosynthesis; however, as the results in Chapter VI showed, they occurred most abundantly on the north façade and were at their most sparse on the west façade, so what really happened is unexpected. The west and south façades undoubtedly face the sun directly longer than the east façade; whereas the north façade was in shade for more than half the day; thus, the result should have shown that the west and south façades had been affected by microorganisms the most. From this unexpected result, it may be concluded that sunlight alone is not the main environmental factor for microorganism deterioration and it is not always laterite on the west façade that is the most susceptible to microorganisms.

Moisture may also play an important role in providing favourable conditions for microorganic deposits (Kumar and Kumar 1999, 4). Because the north façade does not face to the sun directly, the drying process of laterite blocks on this side would have taken longer than the other sides. Consequently, water/moisture remains in such blocks longer and possibly results in a suitable humid condition for certain types of microorganisms. For example, foliose lichens, *Parmellia* sp. in particular, prefer to grow on a damp surface on the north and south façades (Aranyanark 2003, 7). Algae colonization is also associated with places of high humidity and water retention (ibid, 5).

Different types of microorganisms have different preferred conditions (Kumar and Kumar 1999, 4). Some lichens prefer surfaces with low humidity, moderate light and mild ventilation while others grow well on surfaces exposed to other different environments and some prefer surfaces directly exposed to the sun, while some favour shady locations (Aranyanark 2003, 6-7). Therefore, not only the location on façades and environmental conditions, but also the type of microorganisms forms an important factor in establishing whether laterite will be colonised by them. Thus, microorganism identification needs to be studied by biologists or other microbiological experts site by site.

Plants colonise in gaps between laterite blocks once they begin to fill with soil. The macro deterioration assessment in Chapter VI showed that plants grew the best on the west façade and grew the least on the north and the east façades. The number of remaining dead tree roots could also indicate where an environment was suitable for trees. The south and the east façades had a greater number of dead tree roots than the west façade, whereas the north face had none. Considering root penetration alone, this possibly means that the south and the east façades provided the most favourable conditions for plants to grow while the north façade was likely to be unsuitable for plant growth. If both living plants and remaining dead tree roots are considered together, it may be concluded that plants grow best on the west, followed by the south, the east and the north façades respectively. This conclusion is unsurprisingly related to the natural fact that trees need sunlight for their photosynthesis; therefore, the west and the south laterite façades, facing to the sun during most of the day, are undoubtedly the most susceptible to plant growth.

Tree root penetration can exert pressures on laterite façades leading to cracks (Kumar and Kumar 1999, 25). The diameter of roots is more important than the number, and, according to the assessment in Chapter VI, the west façade had the largest area of root penetration. However, when the pattern of cracks on the façades is considered, the west façade had the fewest cracks. It might be because the root had penetrated the façade for such a long period that the façade had regained its equilibrium and the root became a part of structural system—comparable to the famous Ta Prohm Temple in Angkor where the trees could not be removed from the monument without causing its collapse (see Figure 7.1 on page 302). Moreover, major cracks causing structural damage occurred only on the north and the south façades where there was less evidence of tree root penetration, especially on the north façade. It may be concluded that tree roots alone did not cause major cracks, but there must also be some other factors involved. As regards the pattern of major cracks on the north and the south façades, in both locations they were wider at the top and narrower at the bottom splitting the façades outwards. According to Croci, this crack pattern indicates the soil movement under the foundation of the east and the west walls causing the walls to rotate outwards (2000, 124-126). However, there might have been other factors such as overloading of superstructure or the movement of soil or of its foundation; unfortunately, the information or evidence of roofing or soil subsidence of this monument is not provided so that further investigation of causes of its major cracks in this thesis is impracticable.

Minor cracks on every façade might have been caused by either small root penetration or uneven supports due to the movement of the blocks underneath. Like a ripple effect, when one crack occurs, especially a main structural one, it causes other blocks to move and thereafter, as all blocks are structural parts of a bearing wall, this leads to an uneven support for every block above, resulting in other cracks occurring. Subsequently, when cracks first occur on the upper courses, they cause uneven loads to the blocks beneath resulting in further cracks on such blocks. Noticeably, both major and minor cracks on monuments are not agents of environmental deterioration, but are the results of such agents' effects; therefore, cracks affect monuments regardless of the aspects of the façade. Cracks however may encourage other agents by providing suitable conditions for them. For instance, they provide gaps between blocks for trees to grow.

7.1.5. Summary

In order to clarify the results of the assessments and characterization of laterite carried out in Chapter VI, especially in terms of significant correlations, Table 7.18 was created and a summary is listed as follows:

Table 7.16: Significant correlations of the properties and deterioration of laterite

	SiO_2	Al_2O_3	Fe_2O_3	SiO_2: Al_2O_3	SiO_2: Fe_2O_3	Dry strength	Wet strength	Colour		% porosity	%micro organisms
								Value	Chroma		
SiO_2		(-)	(-)	(+)	(+)				(-)		
Al_2O_3	(-)		(+)	(-)	(-)	(-)					
Fe_2O_3	(-)	(+)		(-)	(-)				(+)		
SiO_2: Al_2O_3	(+)	(-)	(-)		(+)				(-)		
SiO_2: Fe_2O_3	(+)	(-)	(-)	(+)					(-)		
Dry strength		(-)					(+)			(-)	
Wet strength						(+)					
Value											n/a
Chroma	(-)		(+)	(-)	(-)						n/a
% porosity						(-)					
% micro organisms								n/a	n/a		

Note: (+)/(-) Indicators of significant correlations and (-) indicates an inverse correlation

1) There is a significant inverse correlation between the percentage of silicon dioxide and the percentage of aluminium oxide—the higher the percentage of silicon dioxide, the less the percentage of aluminium oxide.

2) There is also a significant inverse correlation between the percentage of silicon dioxide and the percentage of ferric oxide—the higher the percentage silicon dioxide, the less the percentage ferric oxide.

3) There are significant correlations between the percentage of silicon dioxide and the ratios of the percentage of silicon dioxide to the percentage of aluminium oxide and to the percentage of ferric oxide—the more the percentage of silicon dioxide, the higher the ratio of the percentage of silicon dioxide to sesquioxides, unsurprisingly.

4) The percentage of aluminium oxide significantly correlates with the percentage of ferric oxide—the more the aluminium oxide, the more the ferric oxide.

5) Therefore, the ratio of silicon dioxide to aluminium dioxide correlates significantly with the ratio of the percentage of silicon dioxide to the percentage of ferric oxide.

6) When laterite is brownish, there is a significant inverse correlation between the chroma of laterite and the percentage of silicon dioxide—the less the percentage of silicon dioxide, the more the intensity of laterite colour.

7) In contrast, chroma of laterite correlates positively strongly with the percentage of ferric oxide—the more the percentage of ferric oxide, the higher the intensity of laterite colour.

8) There is no significant correlation between the value of colour and the percentage of laterite chemical/mineral compositions. Therefore, it is not true that ferric oxide makes laterite darker (approaching black), but it makes the colour of laterite closer to rusty brown. The rustier the colour, the more the percentage of ferric oxide, hence the more mature the laterite.

9) There is no significant correlation between the colour of laterite and its compressive strength. Therefore, we cannot predict the strength of laterite by observing its colour.

10) There is also no significant correlation between silicon dioxide and ferric oxide contained in laterite and its compressive strength. However, there is an inverse significant correlation between the percentage of aluminium oxide and the strength of dry laterite. Therefore, if possible, the analysis of aluminium oxide should be conducted in order to predict the strength of a laterite.

11) There is a significant inverse correlation between the compressive strength of dry laterite and the percentage of its micro porosity. Knowing the percentage micro porosity of a laterite can therefore be helpful for its strength prediction.

12) In contrast, there is no significant correlation between the compressive strength of laterite and the percentage of overall porosity (large voids and micro pores). Therefore, it is unnecessary to measure percentage overall porosity in order to predict the strength of a laterite.

13) The compressive strengths of laterite in a dry and in a wet state correlate with each other significantly. In case an oven for drying samples is unavailable, testing the strength of a wet laterite can yield a result that can helpfully be used for estimating the ultimate strength of the laterite. (Statistic predictions of laterite strength will be discussed in detail in the section of a guideline for estimating the strength of laterite.)

14) There is no significant correlation between the percentage of microbiological growth and the change in laterite chemical composition, percentage porosity and compressive strength.

15) Statistically, all the significant correlations above are not the result of chance.

16) Interestingly, laterite becomes stronger when exposed to the environment especially to the direct sunlight. There is a significant relationship between the decrease of micro pores of laterite and the strong sunlight—the more direct the exposure to the sun, the lower the micro percentage porosity hence the higher the compressive strength.

7.2. Suitability of using laterite as a building material

Laterite has been used in Thailand as a building material for more than thousand years. Not only was it used in Khmer architecture in the northeast of Thailand, it was also widely used in the other architectural styles of Thailand in the other regions. In Khmer architecture, it was mainly used as the foundation of sandstone or brick monuments; however, it was also used as walls and other structural parts of buildings. Therefore, its capacity to bear structural loads should be discussed in order to consider whether we should continue using it as a building material or in the repair of monuments. Moreover, to decide whether or not ancient laterite needs to be conserved, its durability to withstand the effects of environmental decay agents should be analysed and discussed.

7.2.1 Strength of laterite

According to the test in Chapter VI with the consideration of all laterite samples as the representative of common laterite, the average compression strength of laterite is 802.66 pounds/inch^2 (56.43 kilograms/centimeter^2 or 5.64x10^3 kN/m^2) when wet and 1268.53 pounds/inch^2 (196.62 kilograms/centimeter^2 or 1.97x10^4 kN/m^2) when dry. If compared with the compressive strength of sandstone, the latter commonly has an incomparably greater capacity for compressive load bearing. For example, even the ferruginous sandstone, which is considered as a weakly cemented sandstone, from the northern gopura of the Phimai complex can bear 2012.50 pounds/inch^2 (311.94 kilograms/centimeter^2 or 3.12x10^4 kN/m^2) when wet and 10650 pounds/inch^2 (1650.75 kilograms/centimeter^2 or 1.65x10^5 kN/m^2) when dry, when the load is parallel to its bedding planes; and bears 2300 pounds/inch^2 (356.50 kilograms/centimeter^2 or 3.5710^4 kN/m^2) when wet and 11825.00 pounds/inch^2 (1832.88 kilograms/centimetre^2 or 1.83x10^5 kN/m^2) when dry, when the load is perpendicular to the beddings (Watsantachad 2001, 99 and see Table 3.10 on pages 154-155) Therefore, in terms of compressive load bearing, laterite displays so much lower a compressive load bearing capacity than sandstone that it should not be used to replace missing sandstone blocks or to support superstructure loads in the same masonry course as sandstone. This is because if laterite is placed in the same course as sandstone masonry, uneven support may be created and result in the cracking, leaning or collapse of the walls and roofs. (Unfortunately, this mistake can be found in some Khmer monuments as discussed in Chapter I.)

The use of laterite as a building material for Khmer dry masonry platforms or walls is to be discussed next. From the average weight of laterite samples tested in Chapter IV, dry laterite cube weighed 253.46 grams/2"x2"x2" (131.10 centimeter^3) or 0.002 kilogram/centimeter^3. However, when weighing the cube, only its surface pressed the weight onto the scale. Therefore, it is possible to say that 25.81 square centimetre of laterite weighed 253.46 grams (9.82 grams/centimeter^2 or 0.01 kilogram/centimeter^2 or 1 kNewton/metre^2). To compare with the strength that only the area of the surface supporting or pressing loads is considered, it may be said that <u>one square centimetre</u> of laterite creates a point load of 0.01 kilogram (1 kiloNewton) onto the block underneath. With its capacity of bearing a compressive load of 56.43 kilograms/centimeter^2 (5.64×10^3 kN/m^2) when wet and 196.62 kilograms/centimeter^2 (1.97×10^4 kN/m^2) when dry, a one-cubic centimetre laterite block in bearing-wall masonry could support compressive loads 5643 times its self-weight when it is wet and about 19662 times when it is dry. In the worst case, that all laterite blocks are saturated (weighs 282.89 grams/8 inch^3 or 0.011 kilogram/centimeter^2 or 1.1 kN/m^2), a wet one-cubic laterite can support compressive loads about 5130 times of its saturated weight while such laterite when dry can do so about 17875 times.

In reality, the height of a Khmer building measured from its platform never exceeded thirty metres; and the height of a masonry block usually ranged from twenty to sixty centimetres. That means, in the most extreme case that all blocks were twenty centimetres high, a thirty-metre monument would have consisted of approximately 600 courses of masonry. In addition, in 1854, Yvon Villarceau (cited in Heyman 1995, 12) advocated that the nominal stresses should be limited to 1/10 of the crushing stress of the material; therefore, the maximum height of a wall made of such laterite, in the worst case when built of wet laterite, would be 560 meters.

Therefore, it is reasonable to conclude that laterite performs well as a foundation to support Khmer laterite walls, or as walls to support a roof, because of its sufficient compressive strength. Furthermore, if a laterite layer is alternated with layers of sandstone, which offer higher compressive strength, the result is a stronger and more durable structure. However, this possibility is limited by the condition that all the loads supported by are not beyond its strength capacity and there is no other type of load such as structural shear, tensile forces or additional pressures caused by other environmental agents such as tree root penetration and soil subsidence.

In terms of using laterite as a structural member to support tensions, it is undoubtedly not recommended. Despite the fact that stone is weak in tension, sandstone performs a greater tensile support than laterite. From the results of the modulus of rupture test on ferruginous sandstone from the northern gopura of the Phimai complex, such stone bears, in a wet state, 294.42 pounds/inch^2 (45.64 kilograms/centimetre^2 or 4.56x10^3 kN/m^2) when the load is parallel to its bedding planes and 233.47 pounds/inch^2 (36.19 kilograms/centimetre^2 or 3.62x10^3 kN/m^2) when the load is perpendicular to the beddings. When dry, the stone bears 1252.07 pounds/inch^2 (194.07 kilograms/centimetre^2 or 1.94x10^4 kN/m^2) with its beddings parallel to the load and 1152.89 pounds/inch^2 (178.70 kilograms/centimetre^2 or 1.79x10^4 kN/m^2) with its bedding planes perpendicular to the load (Watsantachad 2001, 59 and see Table 3.10 page 155) In contrast, from the results of the same test on laterite in Chapter III, there were only four dry samples out of twelve (or out of twenty-four when wet samples are included and none of them could bear such load) able to withstand the flexural load up to 134.22 pounds/inch^2 (20.80 kilograms/centimeter^2 or 2.1x10^3 kN/m^2) which is markedly insufficient. That is why Khmer masons placed sandstone lintels in laterite monuments. (However, it is also not recommended to use sandstone as a tensile support. As previously discussed in the Khmer construction techniques section in Chapter I, the Khmer masons built lintels with sandstone rather than wood; consequently, cracks were created and eventually resulted in the collapse of monuments.)

7.2.2 Durability of laterite

As discussed in Chapter VI, laterites are heterogeneous. Therefore, laterites from different quarries and regions have different properties and are susceptible to deterioration agents, especially extrinsic ones from the environment, in different degrees. However, according to the results of the tests carried out in this thesis, laterites are not affected by such agents so highly that they are at risk. Their unique property of predominantly large pores with only a few micro pores prevents water or salt solution uptake; consequently, salt crystallization tends not to occur within their pores. Although salts are possibly applied into laterites through other means such as air pollution and acid rain, laterites will not deteriorate because the sizes of laterite pores are mostly larger than five microns so that they are not susceptible to salt crystallization. Moreover, since the micro percentage porosity of laterite decreases when laterite is exposed to direct sunlight, under a suitable condition, not only is laterite resistant to wet-dry cycles, but it also becomes stronger after exposure to the sun. Therefore, it is very suitable to be used for building construction in tropical countries such as Thailand where sunlight is intensive.

Laterite is not susceptible to the decay effects of microorganisms. From the results obtained in Chapter VI, although laterite was usually colonised by microorganisms, its properties, especially the strength, were not affected. Therefore, apart from the aesthetic aspect that microorganisms stain the laterite surface, laterite is not susceptible to them as agents of deterioration. In terms of plants and trees, when compared with sandstone composed of much smaller pores, laterite, mainly composed of large continuous pores, is more resistant to tree root penetration. Laterite allows small tree root to penetrate their pores in some degree without being broken. It gives us more time to remove such trees before they cause the building to decay. However, if the tree roots create shear pressure to the materials, sandstone can withstand such pressure better than laterite.

7.2.3 Summary

In summary, laterite not only offers acceptable compressive strength, but it is also resistant to weathering and deterioration. In fact, laterite is the final product of weathering rocks (Campbell 1917, 67-77). Thus, it is hardly susceptible to harm by environmental decay agents; indeed, some agents such as rain and sunlight resulting in the repetition of wet and dry laterite cause it to become more mature and hence stronger. If a comparison is made between ancient laterite and ancient ferruginous sandstone, which has been considered as poor in quality, as low in value, as laterite, and therefore usually used for building minor unimportant monuments, laterite displays a lower degree of decay and deterioration. Therefore, although laterite is not a high quality material if compared with siliceous sandstone or other stone which can withstand higher loads, it can continue to be used as a building material or in the repair of monuments without any doubt.

However, in terms of compressive load bearing, laterite demonstrates such a lower compressive load bearing capacity than sandstone that it should not be used to replace missing sandstone blocks or to support superstructure loads in the same masonry course as sandstone. This is because if laterite is placed in the same course as sandstone masonry, uneven support may be created and result in the cracking, leaning or collapse of the walls and roofs.

It is also worth noting that the only drawback that laterite has, as we have learnt so far, is it is considerably weak in tension resistance. Therefore, it should not be used in any structural part that has to bear shear or combined loads. When shear stresses are created in Khmer structure, laterite is broken more easily than sandstone, which has a higher flexural strength.

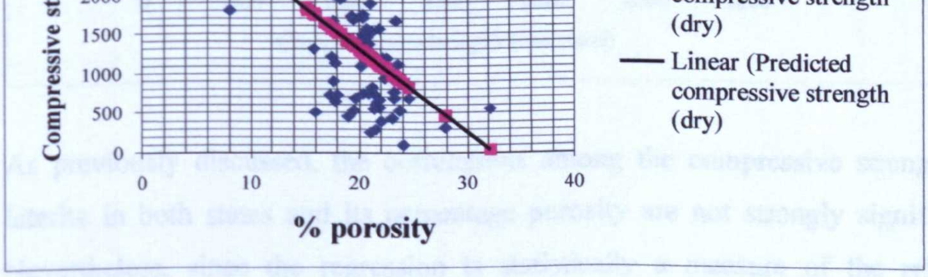
7.4 *A guideline for estimating the strength of laterite*

Since laterite is suitable to be used as a building material, as discussed above, fresh laterite may be very much in demand by conservators and architects either for conservation or new construction purposes. Before placing new laterite in construction or restoration, we have to be assured that such laterite is sufficiently mature and has gained its ultimate strength. Therefore, appropriate strength tests, especially for its compressive load bearing capacity, are recommended. However, in the case where conservators or architects have to select fresh laterite *in situ* or where tools for testing compressive strength are not available, the following guidelines for estimating strength may be helpful.

7.4.1 Estimation of laterite strength by analytical calculation

The discussion about the correlations of the strength and other properties of the tested laterite showed that the percentage of micro pores correlated with its strength significantly. Therefore, in this section, its linear regressions are calculated using the data analysis tool in Microsoft Excel. The regression can then be used for estimating the compressive strength of laterite when the percentage micro porosity is known.

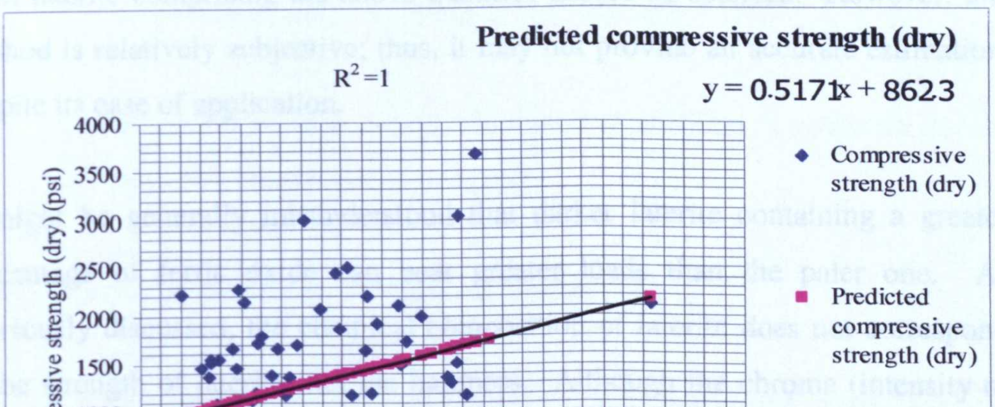
Chart 7.1: The prediction of dry compressive strength of laterite



The analytical result is in an equation: y = -105.39x + 3417.5, where y is the dry compressive strength and x is the percentage of micro-porosity. Therefore, if the percentage of micro-porosity of a laterite is known, its compressive strength can also be calculated by replacing x with the percentage of micro-porosity; the result of the calculation indicates the compressive strength.

Furthermore, when the compressive strength of laterite in one condition is known, the strength of the laterite in the other condition can also be predicted following the equation: y = 0.5171x + 862.3, where x = the compressive strength of wet laterite and y = the compressive strength of dry laterite as seen in Chart 7.3. This estimation may be useful in the case that a compression testing machine is available but it is impossible to dry the samples completely before the test. The ultimate strength of laterite when completely dry can be estimated with this equation.

Chart 7.2: The prediction of the other compressive strength of laterite from the other known compressive strength



As previously discussed, the correlations among the compressive strength of laterite in both states and its percentage porosity are not strongly significant. Nevertheless, since the regression is statistically a measure of the relation between the mean value of one variable and corresponding values of other variables, the linear regression equations obtained from the analyses could possibly be applied to predict the compressive strength of laterite when necessary—although a proper standardised compressive strength test is rather recommended. This prediction is rather helpful when the compression machine is not available but the comparison between the strength of laterites with known percentage porosity is required.

7.4.2 Estimation of strength by observation

The other way of estimating compressive strength is observing the macro pore structure of laterite. As discussed above, most of the samples demonstrating a high compressive bearing are slag-like and dense, or semi-pisolitic composed of nodules smaller than 0.5 centimetre in diameter. Therefore, working in situ without any tools for compression testing and information about its porosity, fresh laterite comprising the above qualities should be selected. However, this method is relatively subjective; thus, it may not provide an accurate estimation, despite its ease of application.

It might be generally misunderstood that darker laterite containing a greater percentage of ferric oxide can bear greater loads than the paler one. As previously discussed, the chemical composition of laterite does not correspond to the strength of laterite, but the hardness. Although the chroma (intensity of colour) of laterite correlates with the chemical composition significantly, the colour of laterite correlates only insignificantly with the strength. Therefore, it is not recommended to predict the durability or load bearing capacity of laterite by observing its colour alone.

7.4.3 Summary

In summary, the compressive strength of laterite may be estimated without any specialised tools or machines. A guideline for estimations can be listed as follows:

1) By calculation from the equation:

$$y = -105.39x + 3417.5,$$

where y = dry compressive strength

x = percentage of micro porosity

or

$$y = 0.5171x + 862.3$$

where x = compressive strength of wet laterite

y = compressive strength of dry laterite

(to be applied when a compression testing machine is available but the samples to be tested cannot be dried)

2) By observation of the pore structure of laterite:

- It is recommended to select a laterite if it is slag-like and dense, or if it is semi-pisolitic composed of nodules smaller than 0.5 centimetre in diameter. Therefore, oolitic laterite is recommended.
- It is not recommended to select a laterite based on the darkness of its colour.

It is to be noted that the estimations of the compressive strength of laterite suggested here are rather helpful when the compression machine is not available. A proper standardised compressive strength test is, however, still recommended.

7.5 Summary

In this chapter, the questions of this thesis can be successfully answered based on the proved results and discussions above as follows:

1) Laterite is suitable to be used as a building material because of its acceptable compressive strength and deterioration resistance.

2) Laterite used in Khmer architecture in Thailand does not need urgent conservation, especially in terms of material treatment. However, stabilization of the structure still needs to be conducted after an investigation of the causes of structural failure of the monuments site by site.

Not only are these questions answered, but the aim of this thesis to broaden knowledge of laterite, especially that used in Khmer constructions in Thailand, is also achieved. This research on laterite should therefore broaden the knowledge of laterite characteristics and encourage conservators to conserve laterite buildings with more knowledgeable approaches.

Figure 7.1: Ta Prohm Temple
Siem Reap, Cambodia
(in 2002)

CHAPTER VIII

CONCLUSION AND RECOMMENDATIONS

Laterite has been widely used around the world particularly in tropical countries where it is abundant. Although according to geologists, laterite and lateritic gravels create soils not suitable for agriculture, the view of engineers and architects is that laterite once exposed to the air and hardened is useful for construction. Engineers and researchers have studied laterite gravels used for road construction, but have barely investigated laterite properties used as a building material, and have not followed up its decay mechanisms over time. Therefore, laterite is used and ancient laterite is conserved without knowing its capacity limits and the causes of its deterioration. This lack of knowledge is the origin of this thesis, which set out to broaden knowledge of laterite especially as used in Khmer building constructions in Thailand, addressing these two questions: 1) whether or not it is suitable to be used as a building material; and 2) whether or not ancient laterite is in need of conservation.

In this chapter, all research, studies and investigations which have been carried out in the previous chapters will be reviewed in an attempt to answer the questions addressed here. In addition, the advantages and disadvantages of my research methods for studying laterite will be discussed at the end. Recommendations for further studies are included.

8.1. Khmer architecture

At its greatest extent the 'Khmer Empire' stretched from the Gulf of Siam to Vientien and from Saigon to the Valley of Menam including present-day Cambodia, the greater part of the Indochina Peninsula, the southern part of Laos and the east and northeastern parts of Thailand (Cedés 1970, 1). Evidence of ancient Khmer culture and civilization (see Map 1.1 on page 80), especially Khmer arts and architecture, remains in several parts of these countries today, but only Khmer religious architecture, mainly built of stone or brick and laterite with a unique construction technique called 'drystone masonry', remains while Khmer houses built of wood vanished. Therefore, in this thesis, religious architecture has been the only focus of study.

When the Khmer Empire controlled the Indochina Peninsula (about 540-1230 AD), Thailand— called Siam at that period — formed the border of the empire. Therefore, evidence of Khmer architecture dating to the sixth and seventh centuries AD can be found in '*Isan*' or Northeastern Thailand. The surviving Khmer monuments in Thailand are built of sandstone, laterite, and fired brick, served as temples, hospitals (*arogayasala)* or rest houses (*dharmmasala*). Laterite samples tested in this research are all from such monuments.

In the pre-Angkor period (prior to the twelfth century), fired bricks were a chief building material being used by Khmer masons while sandstone was used only for door and window frames, or for decoration, as in pediments and lintels. The dominant building material changed to sandstone and laterite in the Classical Angkor period onward (or from the twelfth century to the end of the empire). A drystone masonry technique, that is, stone blocks laid over one another without any adhesive mortar was the technique that Khmer masons adopted for constructing their buildings. The structure depends upon the weight and strength of stone alone to stabilise it against all active forces. Each stone acts as a compressive support and transforms loads through the stones beneath and in some cases to empty spaces below. That is why the main focus of this thesis is upon the strength of the materials, and strength was the principal attribute to be addressed when laterite was characterised and analysed.

When Khmer architecture fell into disrepair it was mainly a result of the failure of its foundations. Because of the heavy superstructure loads and the infiltration of rainwater, the laterite foundation was crushed and disaggregated while the clay layers did not uniformly subside resulting in uneven load-bearing foundations. The misuse of material, including the incompatibility of adjacent materials which had different load bearing capacities, was the other cause of the deformation and collapse of the monuments. Other causes included error in the construction process, such as a lack of bond at the wall corners, and inappropriate design such as the skeuomorphs of carpentry joints in stone window- and doorframes. The failure of construction to withstand combined forces tended to be the other important cause of the collapse of Khmer structures. When extrinsic decay agents, such as tree root penetration and landslip, were present, drystone Khmer walls, supporting only compressive stresses, failed to withstand lateral, shearing or flexural stresses.

As discussed above, laterite was one of the materials usually used from the Angkorian period onwards and it was often used in enclosure walls, hidden structures, or foundations, as well as providing a main building material for minor monuments, particularly hospitals and rest houses. Khmer architecture was usually constructed on a spread footing acting as a platform over a hill—either natural or artificial. In the case of the artificial hill, laterite and clay were usually used as filling layers. Since it has been generally accepted that the deterioration of laterite is also one of the causes of Khmer structural failures, the study of its properties and decay mechanisms undertaken in this project has aimed to provide empirical evidence to test this assumption.

8.2. The aims and achievement of the research and how they contribute to existing knowledge

Today, the Khmer stone monuments of Thailand are in a critical condition and conservation has focussed only on architectural and structural restoration, or reconstruction, with little consideration of the value and importance of the original building materials and construction techniques. Such consideration as there is for original building materials appears to be a little one-sided; Thai and international conservators have shown interest only in sandstone, and little in laterite. Such inaction in the study and conservation of laterite, especially in Thailand, therefore, needs to be countered.

The other necessity for studying laterite is that most of the major sandstone monuments in Thailand have already been restored but many laterite monuments remain in a state of decay. Moreover, given the general assumption that the use of laterite is possibly one of the main factors causing Khmer architecture to suffer damage or to collapse, an appropriate conservation approach for laterite monuments is needed.

Therefore, this thesis has investigated the characteristics and decay mechanisms of laterite, particularly its mechanical strength and other properties, and sought to discover environmental decay agents that alter the strength of laterite, and which have scarcely been the concern of international researchers and conservators; and, eventually, to provide the necessary information to conservators to apply an appropriate conservation approach to laterite, especially that found in Khmer architecture.

The aims of the thesis have been:

1) To broaden the knowledge of laterite properties and its decay mechanisms.
2) To assess whether laterite can continue to be used in building construction and conservation.

These aims have been addressed through the two research questions as stated at the beginning of this chapter and in the Introduction Chapter:

1) Is laterite suitable for use as a building material?
2) Does ancient laterite need to be conserved, and why?

After all the work that has been done in order to write this thesis, these questions can be confidently answered:

1) Laterite is suitable for use as a building material because it is durable and efficiently strong to bear compressive stresses. It is easily quarried, and in a short period gains its maximum strength.
2) The received wisdom that laterite, as a material, is prone to deterioration has been disproved. Ancient laterite does not need to be conserved because it is resistant to deterioration when used for appropriate structural purposes. Rather, structural stabilization of Khmer monuments is more urgently required in order to maintain the overall structure and to prevent further decay of the buildings and their materials.

Not only have these two questions addressed in this thesis been answered, but the aims of the thesis were also satisfactorily achieved. The research provides thorough information about laterite used in building construction that had hardly been studied and discussed before. In addition, as discussed in Chapter I, laterite was commonly used together with sandstone for constructing Khmer buildings; therefore, the comparisons of their properties and decay mechanisms were also accomplished, and the information provided in this thesis can enhance Thai and international conservators' understanding of these two materials when they are used together.

Hopefully, the knowledge provided and the action proposed in this thesis can be useful for Thai, as well as international, researchers who are interested in laterite as an architectural building material; they can realise its significance and have a detailed understanding of its characteristics, decay mechanisms and usefulness. Furthermore, this research may encourage conservators to find successful ways to conserve Khmer architecture in Thailand and to maintain laterite as one of its major building materials.

The following sections are the conclusions of the research and analyses. The characteristics and decay mechanisms of laterite are established, again confirming that laterite is a strong and durable material and can be suitably used as a building material and in building conservation.

8.3. Laterite properties and decay mechanisms

In chapter II, existing literature and previous research were reviewed. Current literature states that laterite is a natural tropical ferruginous material, mainly composed of silicon dioxide, aluminium and iron oxides and derived from a specific type of soil called lateritic soil which is the product of weathering rocks, mostly igneous and sedimentary. It is porous, indurated and concretionary and is usually red to reddish brown in colour. Laterite is soft when it is underground but can become hard, particularly when exposed to the air. The process of physical and chemical weathering of iron-rich parent materials into laterite under a tropical climate is called laterization. Laterization also includes the process of the hardening of laterite when exposed to the environment.

There are several criteria for classifying laterite, such as to its division into two groups—slag-like cellular and pisolitic structure—based on their observable physical forms. In my own characterization tests, reported in Chapter III, I found this criterion of visible physical attributes to be the best and simplest way to classify laterite for conservation purposes, since strength is the critical characteristic in assessing the performance of laterite in structures—and laterite strength is very much related to its pore structure. It was also useful when no classification tools were available.

However, since most researchers had focussed on the origins and definitions of laterite, and laterite properties were still not clear, it was necessary to establish whether or not laterite was suitable to be used as a building material. Thus, the properties of laterite and decay mechanisms required further investigation and this is described in Chapter III, V, VI and VII. As laterite, once exposed to the air, hardens irreversibly and shows stone-like properties, despite being derived from soils, standard tests for soil properties cannot be applied to test hardened laterite. Therefore, in order to investigate laterite properties properly, testing methods for stone suggested by standard organizations such as ASTM and RILEM were chosen for the purposes of this thesis. Whether or not all standard tests for stone properties can be applied to test laterite was, indeed, the subject of Chapters III and V, and therefore the pilot tests were carried out to investigate their usefulness and efficiency before applying them to selected laterite in Chapter VI.

From the pilot tests carried out in Chapter III, only the porosity, chemical composition and compressive strength tests yielded useful data for studying the strength of laterite. The results of tests confirm that observation only of apparent colours is insufficient to determine the maturity and hence the strength of a laterite. Rather, observing the colour together with its pore structure and the intensity of cementing material could provide a rational and reliable prediction of its strength. However, these conclusions were merely to identify the effective tests that are described in Chapter VI; therefore, when these properties were characterised more thoroughly in Chapter VI, some of the conclusion might have changed. (See the summary of laterite properties below)

The data of the basic laterite characterization in Chapter III were confirmed statistically by the data from the tests described in Chapter VI carried out on a larger number of laterite samples. Therefore, the conclusions of laterite properties below are mainly based on the data obtained in Chapter VI. These main properties of the tested laterite are now summarised as follows:

1) It is mainly composed of about 45% of silicon dioxide, 8% of aluminium oxide and 36% of ferric oxide on average resulting in the ratios of silicon dioxide to aluminium oxide of 5.8, to ferric oxide of 1.3 and to the sesquioxides of 1.1.
2) Laterite is heterogeneous when quarried from different locations or in different periods, but most of the laterite blocks are homogeneous individually.
3) The colour of mature laterite blocks is strong brown (7.5 YR) with the value ranged from four to five and the chroma ranged from six to eight in Munsell Colour Charts.

4) The percentage porosity of micro pores in the laterite samples (measured with ASTM method) ranges from 15.28% to 25.47% with an average of 20.28%.
5) The water absorption capacity of micro pores in the laterite samples ranges from 7.85 to 12.98 with an average of 9.89.
6) The large pores of the laterite samples (measured by the wax encapsulation method) account for approximately ten percent additional porosity to that measured by the standard method (or approximately six percent additional water absorption capacity).
7) The average of the compression strength of laterite is about 800 pounds/inch^2 (about 56 kilograms/centimeter^2 or 5.6×10^3 kN/m^2) when wet and about 1270 pounds/inch^2 (about 196 kilograms/centimeter^2 or 1.96×10^4 kN/m^2) when dry. However, it is not always the case that laterite loses its compressive strength when wet. Indeed in some tests, it gained strength.
8) The flexural strength of laterite is so little that most of the samples will be broken before bearing a measurable load (according to the test carried out in Chapter III).
9) The percentage of aluminium oxide significantly correlates with the percentage of ferric oxide—the more the aluminium oxide, the more the ferric oxide.
10) As expected, the ratio of silicon dioxide to aluminium dioxide significantly correlates with the ratio of the percentage of silicon dioxide to the percentage of ferric oxide.
11) The correlations amongst the three main chemical compositions of laterite may be useful, when the percentage of one compound is known, for estimating the amount of the others. Additionally, the percentage of aluminium oxide can indicate the strength of a laterite. The lower the former, the greater the latter.
12) The silicon dioxide and ferric oxide of a laterite correlate with its colour intensity significantly. The smaller the percentage of silicon dioxide in laterite, the more intense the colour. However, this conclusion possibly applies only to brownish laterite.

13) In contrast, the greater the percentage of ferric oxide, the higher the intensity of laterite colour.
14) Unexpectedly, it is not true that ferric oxide makes laterite darker (approaching black), but it actually makes a colour closer to rusty brown. The rustier the colour, the larger the percentage of ferric oxide hence the more mature the laterite.
15) The maturity of laterite indicates the hardness of laterite but it does not indicate the strength.
16) There is no significant correlation between the colour of laterite and its compressive strength. Therefore, we cannot predict the strength of laterite by observing its colour.
17) Knowing the percentage of micro-porosity of a laterite can be helpful for its strength prediction. The lower the percentage of micro pores in a dry laterite, the greater the strength.
18) In contrast, there is no significant correlation between the compressive strength of laterite and the percentage of overall porosity. Therefore, it is unnecessary to measure the percentage of overall porosity in order to predict its strength.
19) Testing the strength of a wet laterite can yield a result that can helpfully be used for estimating its ultimate strength, especially in the case that laterite to be tested cannot be dried completely.

In order to investigate the decay mechanisms of laterite, in Chapter V, the salts in the laterite samples were analysed and the samples were exposed to some simulated main weathering processes—by wet-dry cycles and salt crystallization. The results can be summarised as follows:

1) The qualitative analysis of salt contents in the laterite samples showed that laterite was hardly affected by salts. Only small amounts of sodium chloride were found in the samples.

2) All samples were broken in the salt crystallization test because of the use of sodium sulphate decahydrate in the test instead of sodium chloride which actually presents in laterite.
3) When compared with ferruginous sandstone used in Khmer architecture, laterite is not very much decayed by environmental salts. In the tests, when laterite was attacked by sulphate, it decayed less severely than sandstone.
4) Most of the samples remained intact after eighteen cycles of wet and dry conditions; therefore, the repetition of wet and dry conditions is possibly not the main environmental agent that causes laterite to decay or incur damage.

Chapter VI assessed other environmental decay agents, such as sunlight, plants and microorganisms. Based on photographic records of the façades and tests which were carried out on twenty-four samples collected from different positions of a selected site, the results of the investigation of environmental decay mechanisms can be summarised as follows:

1) The north façade of laterite monuments is affected by microorganisms and cracks the most, but affected by root penetration the least.
2) The west façade is affected by plant growth the most and has the largest area of tree root, but has the smallest area of cracks.
3) The environment affects the silicon dioxide of laterite blocks placed on the east façade the most. Silicon dioxide in laterite is possibly leached out when exposed to such an environment.
4) The environment altered the percentage of aluminium oxide in laterite blocks placed on the top of the walls the most. Aluminium oxide in laterite is likely to be transformed when exposed to the air directly (at least two sides of the block are exposed to the air)
5) Ferric oxide in laterite blocks is altered the most when the blocks are placed at the bottom of the walls, especially when buried under the soil for a period. Ferric oxide in laterite seems to be transformed when in contact with the soil.
6) The percentage porosity of mature laterite used as façade walls tends to decrease when exposed to the environment for a period.

7) There is no significant correlation between the percentage of microorganic deposits and the change in the chemical composition of laterite, its percentage porosity and its compressive strength, leading to the conclusion that these laterite properties are not susceptible to the decay mechanisms of microorganisms.
8) Compared with sandstone, composed of much smaller pores, laterite, mainly composed of large continuous pores, is more resistant to tree root penetration. Laterite allows small tree roots to penetrate the pores in some degree without breaking.
9) Interestingly, laterite becomes stronger when exposed to the environment, especially to direct sunlight. A significant relationship between the decrease of micro pores of laterite and the strong sunlight confirms that the more direct the exposure to the sun, the lower the micro percentage porosity, hence the higher the compressive strength.
10) Therefore, the strength of laterite is not altered by environmental agents that cause its decay on a micro scale. (Agents such as tree roots causing cracks or other observable deterioration are excluded.) However, it remains a tentative conclusion that neither location of laterite nor environmental decay agents affect a change in its compressive strength over time and further study may be needed to confirm this conclusion.

In summary, laterite offers acceptable compressive strength and it is resistant to weathering and deterioration. A comparison between ancient laterite and ancient ferruginous sandstone, which was usually used for building minor unimportant monuments in the same way as laterite, shows that, despite having lower strength, laterite shows a lower degree of decay and deterioration. Therefore, although laterite is not generally considered to be a high quality material if compared with siliceous sandstone or other stone which can withstand higher loads, it can undoubtedly continue to be used as a building material or in the repair of monuments. Moreover, with its acceptably durable quality, there is no urgent need to apply conservation treatments to ancient individual laterite blocks, unless they crack or are broken resulting in a loss of strength.

It is worth noting that the majority of the results in this research comes from the tests on one small site, and, although comprehensive in their scope, cannot be generally assumed to be the representative of all laterite in Khmer monuments. However, although much more research needs to be carried out to verify the results of this research, it is reasonable to believe that these results, in the absence of any other relevant research, can confidently be used as a basis to provide guidance for the future conservation of laterite monuments, particularly in Thailand.

8.4. Recommendations for research methods

The characteristics and decay mechanisms of laterite used in Khmer architecture in Thailand have been revealed. Hopefully, this research can inspire researchers to pay attention to this ignored material and desire to understand it better, and it can also be a start for furthering the study of laterite as used in other styles of architecture. Therefore, the recommendations below will help them avoid problems and unnecessary research and to follow these suggestions to achieve more useful and thorough research in the near future.

Inevitably, lessons are learnt during the experimental stages of research. In this section, the advantages and disadvantages of my research methods for studying laterite, including recommended further studies, are reviewed:

1) In terms of the efficacy of the proposed pilot testing programme for characterising laterite properties, the results obtained in Chapter III revealed that only the chemical composition analysis (through wet chemical analysis method and AAS), porosity analysis and compressive strength tests (recommended by ASTM) are acceptably effective. Therefore, these tests are recommended for characterising laterite, especially when the strength of laterite is focussed upon and the tests are conducted by conservation architects or other researchers with a non-geological or limited science background.

2) However, analysing the porosity of laterite with the total immersion test cannot measure the real percentage porosity of laterite. This is because laterite is mainly composed of large pores and when the laterite is taken out of the immersion tray, such large pores cannot retain water and hence the percentage of the large pores cannot be measured. Therefore, if the total percentage porosity of a laterite is required, other methods or tools for porosity measurement are needed. Mercury porosimeters might work but

one would need to be aware that filling large pores with mercury, or other gases, is time-consuming and, inevitably, the test becomes costly.

3) The wax encapsulation method for measuring the percentage of large pores in laterite is another option. It is an inexpensive laboratory test that has been proved to be effective (in Chapter VI) and thus recommended. This method succeeds in retaining water trapped in large pores thus allowing the measurement of its weight and volume. However, it is relatively complicated to encapsulate samples with wax and melt the wax from the samples when the immersion is finished. Moreover, this method takes a long time for water to saturate the samples. In addition, as previously discussed, although I have developed a method by which the total porosity of laterite samples can be measured, the results of subsequent tests have shown that this property is of little relevance to either strength, or resistance to weathering. Hence, the measurement of large pores in laterite may be unnecessary.

4) It is impossible to measure the capillary rise of laterite with the test recommended in the Laboratory Manual for Architectural Conservators. If the measurement of this laterite property is required, the investigation of an effective method is needed and awaited for a further study.

5) Since laterite is usually heterogeneous, testing on a small number of samples may yield a conclusion different from that of tests carried out on a larger number of samples; and the latter is more trustworthy statistically. Therefore, it is recommended to characterise a large number of laterite samples, in order to obtain a statistically accurate set of data. Even then, some inconsistent results may arise from local difference in pore structure.

6) Because of the significant correlations between the percentage of microporosity and the compressive strength of laterite, the costly compressive

strength test may be substituted by the inexpensive total immersion test (in this case the exact value of the compressive strength is not required).

7) Moreover, although the colour and maturity of laterite cannot indicate the laterite strength, theoretically, mature laterite displays a stone-like behaviour and hence a higher load-bearing capacity than the freshly quarried material. Therefore, observing the colour of laterite to estimate its maturity before applying a compressive strength test may eliminate the possibility of wasting time, money and material on testing the immature laterite samples.

8) Regarding the observation of laterite colour, a further invention of a colour scale to be used for measuring the maturity of laterite should be useful, especially to be used *in situ*, and is therefore recommended.

9) With newly quarried laterite, a further study on the length of time that immature laterite (or plinthite) needs to become mature laterite is also strongly recommended. Knowing the period of laterization from plinthite or lateritic soil to laterite can ensure the effectiveness of the compressive strength test and can be useful for time estimation in the management of conservation projects, but such a long term test was not possible within the time constraints of a Ph.D. project.

However, the list above may not cover all the advantages and disadvantages of the research, nor is it an exhaustive consideration of further research. Therefore, further wide discussions are much needed. Such discussions will universally broaden and improve the field of laterite conservation.

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APPENDIX I

CHRONOLOGY OF KHMER EMPIRES AND CONQUERORS[1]

The Khmer Empire was one of the greatest empires conquering the land of present-day Southeast Asia. Where the early people in the Khmer Empire came from and when they migrated to this land is still debated. Several scholars referred below suggest its history should be dated from around about the beginning of the Christian era, while archaeologists and some historians believe that the beginning of the settlement is as early as 4200 BC. Archaeologists have found evidence of this early date through such artefacts as pottery and tools, while art historians have found evidence through inscriptions and early written records. However, in this section, the whole history of the Khmer Empire will be summarized and divided into periods according to the evolution of its people, settlement and civilization based on selected bibliographies.

- **Pre-Historic Period**

As previously mentioned, the origin of the Khmers is still disputed. However, Carbon-14 dating conducted in a cave at *Laang Spean* in northwest Cambodia suggests that people who knew how to make pots lived in the cave in 4200 BC (Chandler 1983, 9). The people might include the Proto-malayan Indonesian forebears of the present-day Chams and of the tribes, Phnong Moi, in present-day Vietnam (Steinberg 1959, 2). Moreover, Chandler suggests that recent discoveries reveal that there was a relatively sophisticated culture in Indochina. Examples of culture and civilization include pottery making, rice cultivation and bronze casting. Some traditions such as methods of pottery making have remained unchanged in the region for six thousand years. It may be assumed that this group of ancient people could be the ancestors of the Khmers. This assumption can also be confirmed by the languages used throughout the time. The Khmer and Vietnamese languages are in the Austro-Asiatic language family developed in China. Therefore, it is possibly

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[1] See Table A1.1: Chronology of historical events and main monuments.

that the predecessors of the Khmers migrated from China about four or five thousand years ago and settled in this region (Heidhues 2001, 17).

- **Funan Period**

Funan was the area where Funanese had overcome the other two tribes—Chams and Khmers—who also settled in this region, the lower Mekong Plateau. SarDesai mentioned Funanese as earlier arrivals of the Mon-Khmer people (1997, 23). Steinberg described these tribes as people who had lived in this area since the first century AD. They were gradually Hindunised, and then completely Indianised in the fourth century AD (1958, 9).[2] According to an ancient myth, Funanese people can trace their origins back to the marriage of a Brahman named Kaundinya and a *naga*, whose father was the king of a waterlogged country. To increase the Brahman's possessions, the king drank up the water that covered the land, and his son-in-law then built a capital called "Kambuja" (Chandler 1983, 13). Generally, the real history may have been interwoven with tales when narrated from generation to generation. Hence, the myth might imply that some Indian people—Brahmins imported to northeastern Indochina by the rulers—came to the region and blended with the local people. As a Hindu caste, Brahmins are scholars who have as much—or even more—power than kings. Therefore, Brahmins may have been powerful in the Funanese society. In another interpretation, the myth of the Brahmin and the serpent may have given the Funanese dynasty a dual legitimacy with an Indian origin and Naga, which people in the region believed in and respected, in order to proclaim their rights to rule the land. The story in the myth can also confirm the existence of Indianization in the country, according to Heidhues's suggestion. Chandler also stated that the definition of Indianization in Cambodia is as follows (Chandler 1983, 11):

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[2] Heidhues suggests that Indianization was, for Southeast Asian rulers, a way to acquire power and legitimacy, and does not mean that the lands were conquered by India. It served their purposes, not India's (2001, 23). In the first century AD, Indianization in the region was in form of Hindu and Buddhist influences; therefore evidence of Indianization could be seen in the writing system, the Sanskrit language, religions (Hindu and Buddhism), the idea of universal kingship, etc. Further evidence is the influence on politics, sociology, astronomy, arts, architecture and iconography, which is also derived from the religious beliefs and concepts.

> "...This was the phenomenon known as Indianization, whereby elements of Indian culture were absorbed or chosen by the Cambodian people in a process that lasted more than a thousand years..."

According to Chinese inscriptions, Funan was referred to as an empire that made contact with China by sending tributary goods and, at the same time, securing China's support for their rulers' authorities (Heidhues 2001, 23). From archaeological evidence of canals linking from this land to the Gulf of Thailand, it is believed that the lands of the Funan Empire were used as an entrepôt for the trade between China and India from the second to sixth centuries AD. In the third century during the reign of Fan Shih-man, the Funan Empire surpassed all others in the region and expanded its territory to the present-day lands of South Vietnam, Cambodia, central Thailand, northern Malaya, and southern Myanmar. (See Map 1.1.2 in Chapter I) The capital of the empire was Vyadhapura, located near present-day Phnom Penh. Fan Shih-mam promoted shipbuilding, navigation, and foreign trade. Thereafter, Fan Shih-man's successors exploited the strategic position of their empire to build a commercial monopoly, setting a model for the rulers of Srivijaya and Sailendra to follow (SarDesai 1997, 24).[3] With regard to their politics and art, the Funan Empire functioned as a civilized nation. They also understood agriculture and metal-crafts.

According to Cedés, who used linguistic evidence, the Funan period extended from the first century through to the middle of the sixth century (Cedés 1970, 1; Chandler 1983, 14). Nonetheless, Macdonald suggests that Khmer history might begin before the Christian era when Indian merchants and adventurers sailed across the Indian Ocean to the shores of Southeast Asia—to Indochina and Java. (Macdonald 1987, 34)

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[3] Although SarDesai mentioned Malacca rulers in the Funan period, he later stated that Malacca was a new city of a new empire in the fifteenth century (SarDesai 1997, 60-61). Therefore, the author concludes that only the rulers of the Srivijaya and Sailendra Empires were relevant to the Funan Empire.

- **Pre- Angkor (Chenla) Period**

According to Cedès, Kambujas (Khmer or ancient Cambodia) occupied the land in the northern part of the Funan Empire (on the shores of the middle of the Mekong River (Cedès 1970, 2). Migrating from either southwest China or northeast India eastward along the Mekong River, Khmers first settled in the area where the present-day southern Laos and the Korat Plateau in Thailand are, and established the state of Chenla (SarDesai1997, 26). Thereafter, since the land was unsuitable for agriculture, they moved southward to the Mekong Delta. (See Map A1a) At first the state of Chenla was a vassal of the Funan Empire. The ruler of the state during the middle of the sixth century was King Bhavavarman. He was a prince of the royal family of Funan and married a princess of Kambuja lineage. According to records, he was the first ruler of the country. He, with the support of his brother, later declared himself independent of Funan and after a war, was forced to move to land south of the Dangrek Mountains.[4] (See Map A1b) Although this period was not the first in the history of the country, we may consider it as the beginning of the Khmer dynasties. Nevertheless, Steinberg suggests that another king, Kambu Svayambhuva, was the founder of the Khmer dynasties, and the country was named, Kambuja—"Cambodge in French or "Cambodia" in English, after him (1958, 10). However, no further information about this king can be found. According to the Khmer Myth, he may be the wise hermit named "Kambu" who married the celestial nymph named "Mera" and they became the mythical ancestors of Khmers.

From the seventh century, King Bhavavarman's descendants succeeded in annexing and expanding the empire. The important kings of this period include Isanavarman, who founded a city in Kompong Thom province and built the earliest architecture that remains today in Sombor Prei Kuk; and Jayavarman I, who might have found a capital of the empire at Angkor Borei. Nevertheless, the prosperity of the Pre-Angkor Empire lasted only about two hundred years. It ended in the eighth century when the country was divided into two states called *Upper Chenla* or *Chenla of the*

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[4] This was the first record of the antagonism between the north and the south of Cambodia, with the Dangrek Mountain as the border, continuing throughout its entire history.

land, located in the middle of the Mekong Valley north of the Dangrek Mountain range; and *Lower Chenla* or *Chenla of the sea*, located in present-day Cambodia and the Mekong Delta in South Vietnam[5] (Cedès 1970, 2; Macdonald 1987, 40; SarDesai 1997, 27). (See Map 1.1.3 in Chapter I) At this time, Kambujas was probably invaded and partly conquered by Java,[6] an empire located in the south of the Indochina Peninsula.

The title "Chenla" has also been used by some scholars to identify the Pre-Angkor period. Since the main sources of Pre-Angkorian information come only from a Chinese document, the name of the empire varies according to researchers. Macdonald considered the empire that was ruled by these kings as Chenla rather than Pre-Angkor or Kambujas, which he considered to be the later period. (Macdonald 1987, 37 and 44) However, he stated that Chenla plains and valleys were the homeland of the Khmer people.

- **Angkor Period**

According to Macdonald, Prince Jayavarman (later became a king, Jayavarman II), one of the princes of Chenla, was brought to Java after the Chenla Empire was defeated by the king of Java. He was brought as a subordinate to Java in order to perform an act of allegiance and as a pupil to practice the art of kingship. About 790 AD, Prince Jayavarman returned to Chenla and established a unified Khmer Empire. As mentioned above, Macdonald stated it was Jayavarman II who used the word "Kambuja" to describe his country throughout his reign (802-850 AD)[7] and for the next six centuries of the empire (Macdonald 1987, 44).

The first place that Jayavarman II established his capital was the valley of the great Mekong River named *Indrapura*, located east of Kampong Cham. (See Map A2)

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[5] The suffix "varman" was derived from an Indian title that means "protector". It became the common suffix to all the names of the kings of Chenla and Kambujas. (Macdonald 1987, 37)

[6] Java is an Indianised Empire located south of Southeast Asia, but comprising far more than modern Java. It occupied the land of present-day Sumatra, the Java Islands and Malaya (the Malay Peninsula).

[7] The periods of conquer in parentheses are based on Rooney's (2000).

Later, he migrated to the region, where Angkor is now located. After shifting a few miles from Angkor Thom, and then from the area where the West Baray stands, Jayavarman II raised the capital of the empire on Phnom Kulen Mountain in 802 AD. In a ceremony conducted by a renowned Brahmin, he then declared his country independent of Java.

With an extraordinary ceremony, not only did Jayavarman II declare independence, he also established a new religious rite, which created the importance of kingship. It stated that the king not only ruled by divine consent, but also acquired the nature of a deity. (Macdonald 1987, 46) This rite is called "*Devaraja*" or "God-king" which means that the king is the representative of Heaven on Earth, whom everyone must worship and obey.[8] Belief in this religious rite, possibly borrowed from Java, then became a new cult and religion in Kambujas and throughout the entire empire. Linga or Shivalinga, the phallic symbol representative of Shiva, was usually used as a symbol of the king's divine powers since most of the kings proclaimed themselves as an incarnation of Shiva. However, some kings established themselves as an incarnation of Vishnu and others as *Harihara*—a god who is the combination of Vishnu and Shiva.

Jayavarman II again moved his capital to a region called *Hariharalaya* (or *Roluos*)[9], located in the lowlands of the empire where food supplies for his people were more easily attained. This city became the capital of the empire for the next two reigns of Jayavarman III (854-877 AD)—a son of Jayavarman II, and Indravarman I (877-889 AD). Within the reign of Jayavarman II, he reunited the Chenla Empire and expanded his kingdom to present-day Laos and most of present-day Thailand.

Yasovarman I (889-910 AD) was the son of Indravarman I. After staying in Hariharalaya for sometime, Yasovarman I moved his capital to a place slightly farther east of Angkor Thom called *Yasodharapura* or present-day Angkor. (See

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[8] The Devaraja rite is a very good example of Indianization according to Heidhues' s definition. Rulers expressed their powers by comparing themselves with Hindu gods to whom everyone had to pay respect. This rite was first established in Ancient Java and then brought to Kambuja.

[9] However, the monuments, such as Bakong, Preah Ko and Lolei, located in Roluos, were not constructed during his reign, but in the eleventh century AD.

Map A2) Yasodharapura covered an area of over sixteen square kilometres. Although it does not officially appear in written records, Yasovarman I may have established the temple of *Phnom Bakeng* as the centre of Yasodharapura. He also dug a large reservoir (*East Baray*[10]), and many ponds—some of which remain today—and constructed surrounding buildings. The city was the capital of the empire for about forty years under the rules of Yasovarman I and his successors. Then, a later king, Jayavarman IV (928-941 AD), moved the capital from Yasodharapura to *Koh Ker.*[11]

When Rajendravarman (944-968 AD), a son of Jayavarman IV, ascended the throne, he returned the capital to Yasodharapura. There, a new custom was established—that each king would build a new sanctuary to house his linga and to be his mausoleum after his death. (Macdonald 1987, 51) That explains why, rather than restoring Phnom Bakeng, Rajendravarman II dedicated a new temple, *Phimeanakas.* Since the new temple had to be in the centre of the city, the city boundary was shifted, and partly overlapped the former one. During the reign of Rajendravarman II, Yasodharapura enjoyed one of its most peaceful and prosperous periods. The empire spread over present-day Cambodia, the southern part of Vietnam, Laos, most of Thailand, and sections of Annam, Burma (Myanmar) and China. The peace and prosperity continued through the reign of Jayavarman V (968-1001), Rajendravarman II's son, which was one of the greatest periods of cultural development and philosophic and artistic achievement in the history of the Khmers.

Suryavarman I, a foreign invader from the Choa Phraya River in Thailand, conquered the empire from 1001 AD to 1050AD.[12] He proclaimed himself as the rightful heir—through his mother—of Indravarman I. Although Suryavarman I was a dictator and was abhorred by his people, the Khmer civilization prospered and was at its noblest during his reign. (Macdonald 1987, 53) This improvement could be

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[10] Baray means a large pond.

[11] The year of the move is still debatable. Cedés mentioned the year as 921 AD (Cedés 1970, 3), which is earlier than the period of Jayavarman IV's reign as stated in Rooney's book (2000), which the author put in the parenthesis after the king's names.

[12] Before this reign, two kings named Udayadityavarman I and Jayaviravarman ruled the empire. However, because of their brief reigns, there was little significant progress during these periods.

evidenced by the large amount of architecture that was created and the city planning that was put into places during his reign. He shaped the city that we now know as "Angkor". He constructed the *Royal Palace* and its enclosure and the *Grand Plaza.* He also introduced a new system of waterways and built a huge reservoir called the *West Baray.*

Nevertheless, it was Udayadityavarman II (1050-1066 AD), the king who succeeded Suryavarman I, who fulfilled the idealistic design concept of "Universe" to Angkor. He built *Baphuon* as the centre of the city to represent the Meru Mountain, which is considered the centre of the universe. This temple was the largest building of the Khmers at that time, and remains the second largest Khmer monument throughout the empire era. (The largest monument is *Bayon* which will be described below.)

The other period of prosperity for the Khmer Empire was during the reign of Suryavarman II (1113-1150 AD). Before his reign, the empire had been somewhat in crisis until he seized the throne and restored unity and peace to the empire in 1113 AD. The reign of Suryavarman II lasted for almost forty years, making him one of the greatest kings in Khmer history. He constructed the renowned *Angkor Wat.* During his reign, he waged and won several wars against neighbors, especially against Chams[13] (which later defeated and destroyed Angkor in revenge). At this time, the art and architecture evolution reached its climax in terms of aesthetics, beauty and size.

After the death of Suryavarman II, who was probably succeeded by a cousin, the empire was in somewhat of a confused state and invaded by the Champa Empire. Thereafter, it was Prince Jayavarman, a son of the king[14] who ruled the country after Suryavarman II, who salvaged the empire from Chams restoring the unity of the empire. In 1181, Prince Jayavarman was crowned Jayavarman VII (1181-1220 AD). Possibly because of his fury, he not only drove the Cham invaders from his country, but also sought revenge against Chams by attacking the country, sacking

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[13] Chams or Champa was an Indianised empire located on the shore of Annam.

[14] It was possible that the king who ruled the country from 1150-1160 AD was Dharanindravarman II. His reign was the darkest age for the Khmers.

the capital and dethroning their king. After the defeat, Chams became a province of Kambujas. Jayavarman VII also extended his masterful influence east, west and south. Hence, the Khmer Empire was even wider and mightier than at any other time in history (Macdonald 1987, 57). (See Map 1.1.4 in Chapter I)

During the reign of Jayavarnam VII, Mahayana Buddhism became the national religion of the country. Rather than placing linga in the centre of shrines, Jayavarman VII installed images of Buddha. He proclaimed himself—and he absolutely believed in his divinity—as an incarnation of *Lokesvara* or the Buddha before enlightenment.[15] He put hundreds or perhaps thousands of the faces of Lokesvara on the wall of his temples. This can be seen in *Bayon*, the largest and most elaborate monument in Khmers. However, Jayavarman VII's idealization of himself as a "god-king" is so exaggerated that Macdonald stated Jayavarman VII earned the reputation of a megalomaniac. (Macdonald 1987, 59)

Not only did Jayavarman VII restore the city after it was ruined and burnt by Chams, but he also established a new capital called *Angkor Thom* within the old city and built Bayon as the centre. Moreover, numbers of Khmer complexes and buildings were constructed over the country during his reign. To further make his mark as a great king, Jayavarman VII constructed a widespread road system, hospitals, resthouses for travelers, libraries, schools and wayside shrines for devout worshippers. Due to his virtue and military might, Jayavarman VII was thus considered one of the greatest kings of the Khmer Empire.

- **Post-Angkor to the Fall of the Khmer Empire**

Despite the success of his reign, the extravagant expression of the most richness and greatness of Jayavarman VII caused impoverishment to Kambujas, which subsequently led to the fall of the empire. To serve his desire, Jayavarman VII overworked, overtaxed, and overstrained his people who gave him their faithfulness

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[15] This is a belief of the Mahayana Buddhists, who worship Buddha and his previous lives before enlightenment.

and respect. Consequently, the empire shrank, and eventually fell, not long after the death of Jayavarman VII in 1220 AD. Chams was the first nation to rebel against and invade the empire in order to reclaim their independence. However, the most ardent invaders were the Thais, who later conquered the empire. They extended their territory and authority south to Kambujas and to some parts of northern Malaya. Angkor then became a part of a province of Siam (ancient Thailand) named *Siem Reap*[16] in 1430 AD.

The most important factor that saw an end to the great Angkor was the change of the religion from Hindu and *Mahayana* Buddhism to *Theravada* Buddhism, which was spread from Langa through Siam to Kambuja. This new religion believed in simplicity and modesty and was against the idea of constructing huge temples and of a King-god and a Buddha-god. The Khmer people, who had been overwhelmed with the extravagant expression of kingship, easily accepted a new religion into their lives and mentally and physically supported invaders who might release them from the oppression of their kings.

During this period, which lasted about two hundred years (1220-1430 AD), there was no important event in Kambujas and no civilization of which to speak. The rulers during this period each took a turn on the throne, but none of them could express their kingship powers. Also, as previously described, due to the impoverished state of the country at the time, there were no significant structures built, resulting in very little representative architecture for this period.

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[16] Siem Reap means the state of Siam.

Table A1.1: Chronology of important historical events and main monuments

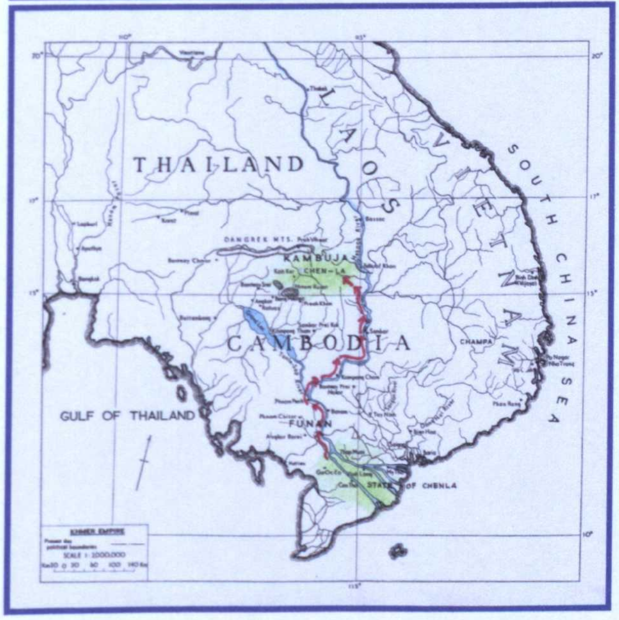
YEAR	BUILDER/REIGN	EVENT	MONUMENT	ARCHITECTURAL STYLE
3rdC	Fan Shih-man (Funan Empire)	Expanded the territory over Indochina Peninsula	-	-
Md.6thC	Bhavavarman (Chenla Empire)	Established the Khmer Dynasty	-	-
2nd hf 8thC	Jayavarman I (Chenla)	-	Prasat Ak Yum	Pre-Angkorian
end 8thC	Unknown	Chenla Empire divided into two parts	-	-
802-850	Jayavarman II	Unified the Khmer Empire (Kambuja)	-	-
877-889	Indravarman I	-	Preah Ko (879)	Angkorian
			Bakong (881)	Angkorian
889-910	Yasovarman I	Built Yasodharapura, "Angkor"	Lolei (893)	Angkorian
			Phnom Bakheng (893)	Angkorian
928-941	Jayavarman IV	-	Koh Ker Temple	Angkorian
944-968	Rajendravarman	Established a new custom of constructing each king's temple and mausoleum	East Mebon (952)	Angkorian
			Phimeanakas (957-978)	Angkorian
			Pre Rup (961)	Angkorian
	Brahmin Vajayavarha	-	Banteay Srei (967)	Angkorian
968-1001	Jayavarman V	One of the greatest period of cultural, philosophic and artistic achievement	Klengs (N&S)	Angkorian
			Ta Keo (970-1010)	Angkorian
1001-1050	Suryavarman I	Shaped Angkor, established city planning and waterway system	Royal Palace	Angkorian
			Phnom Jisor	Angkorian
			Preah Vihear	Angkorian
			Meung Tum	Angkorian
			West Baray& Temple	Angkorian
			Baphuon (1050-1066)	Angkorian
1050-1066	Udayadityavarman II	-	Baphuon (1050-1066)	Angkorian
1066-1113	Unclear	Crisis and confusion	-	-
1080-1113?	Dharanindravarman I	-	Phimai (1108)	Angkorian
			Beng Mealea (1107-1156)	Angkorian
1113-1150	Suryavarman II	Reunified and extended the empire	Beng Mealea (1107-1156)	Angkorian
		Climax of artistic and architectural achievement	Angkor Wat	Classical Angkorian
			Chau Say Tevoda	Classical Angkorian
			Banteay Samre (1150-1175)	Classical Angkorian
			Preah Khan	Classical Angkorian
			Phnom Rung	Classical Angkorian

Table A1.1: Chronology of important historical events and main monuments (continued)

YEAR	BUILDER/REIGN	EVENT	MONUMENT	ARCHITECTURAL STYLE
1150-1181	Haranya (1150?)	Crisis and confusion, invaded by Chams	-	-
1150-1160	Dharanindravarman II		-	-
1160-1165	Yasovarman II		-	-
1165-1181	Tribhuvanandityavarman		-	-
1181-1220	Jayavarman VII	Savaged Chams Unified and expanded the empire Changed national religion from Hindu to Mahayana Buddhism	Ta Prohm (1186)	Post-classical Angkorian
			Angkor Thom (1190-1210)	Post-classical Angkorian
			Bayon (1190-1210)	Post-classical Angkorian
			Preah Khan (1191-?)	Post-classical Angkorian
			Banteay Chmar	Post-classical Angkorian
1220-1430	Several kings	Confronted with poverty Changed national religion from Hindu and Mahayana Buddhism to Theravada Buddhism Invaded by Thais	-	-

Map A1a: Khmer Settlements
(6th century AD)
The settlements of Khmers at Korat Plateau and Mekong Delta.

(Created on the map copied from Cedès 1966)



Map A1b: Chenla Empire
(6th century AD)
After the war, Khmers moved to the south of Dangrek Mountain and established the Chenla Empire
(Created on the map copied
from Cedès 1966)

Map A2:
Locations of Khmer capitals
(since 800 AD)

(Created on the map
copied from Cedès 1966)

APPENDIX II

LIST OF LITERATURE

(Reversed Chronological Order and following the order in Table 2.1)

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APPENDIX III

DATA FROM CHARACTERIZATION TESTS IN CHAPTER III

Data Set 1: Water absorption and percentage porosity tests

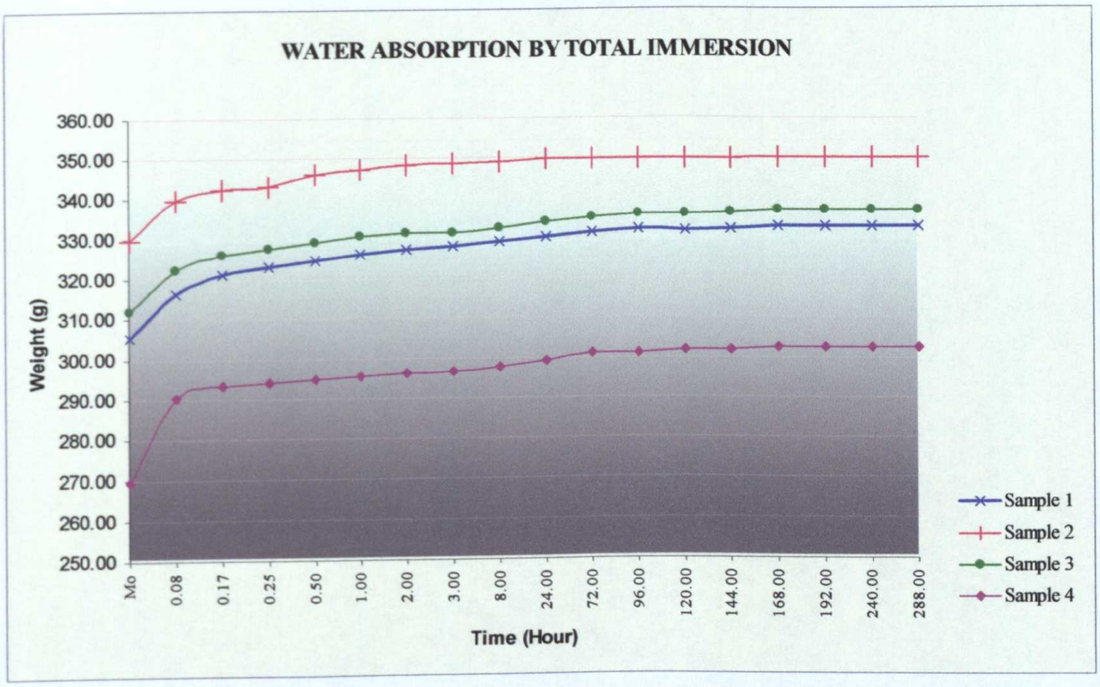
POROSITY BY WATER ABSORPTION

	Mass of Pore = Volume of Pore	Apparent V.	% Porosity
SAMPLE	Mp = Vp	Va (cc)	% voids
A1a	28.60	125.80	22.73
A1b	21.65	118.60	18.25
A1c	32.05	136.80	23.43
Average	**27.43**	**127.067**	**21.47**
A2a	19.85	123.30	16.10
A2b	23.20	127.80	18.15
A2c	17.35	112.80	15.38
Average	**20.13**	**121.3**	**16.54**
A3a	21.35	144.40	14.79
A3b	32.40	120.00	27.00
A3c	21.15	105.10	20.12
Average	**24.97**	**123.167**	**20.64**
A4a	31.50	135.15	23.31
A4b	35.70	137.80	25.91
A4c	31.95	127.50	25.06
Average	**33.05**	**133.483**	**24.76**

WATER ABSORPTION CAPACITY (WAC)

	Orginal dried weight	Saturated weight.	Redried weight	
SAMPLE	Mo(g)	Mmax(g)	Md(g)	WAC
A1a	293.40	322.00	288.20	11.73
A1b	306.55	328.20	305.60	7.40
A1c	316.05	348.10	310.60	12.07
Average	**305.33**	**332.77**	**301.47**	**10.40**
A2a	322.75	342.60	317.10	8.04
A2b	350.55	373.75	348.75	7.17
A2c	316.20	333.55	312.00	6.91
Average	**329.83**	**349.97**	**325.95**	**7.37**
A3a	367.15	388.50	365.55	6.28
A3b	274.35	306.75	272.40	12.61
A3c	294.00	315.15	290.70	8.41
Average	**311.83**	**336.80**	**309.55**	**9.10**
A4a	288.00	319.50	285.00	12.11
A4b	274.50	310.20	271.00	14.46
A4c	246.05	278.00	243.00	14.40
Average	**269.52**	**302.57**	**266.33**	**13.66**

Sample	% Porosity (Ave.)	%WA (Ave.)	WAC (Ave.)	Max Rate WA (Ave.)	Max Rate WE (Ave.)
				(g/min)	(g/min)
1	21.47	8.98	10.4	131.4	11.2
2	16.54	6.09	7.37	118.6	7
3	20.64	8.27	9.1	128	7.6
4	24.76	12.31	13.66	247.8	5.4


WATER ABSORPTION BY TOTAL IMMERSION
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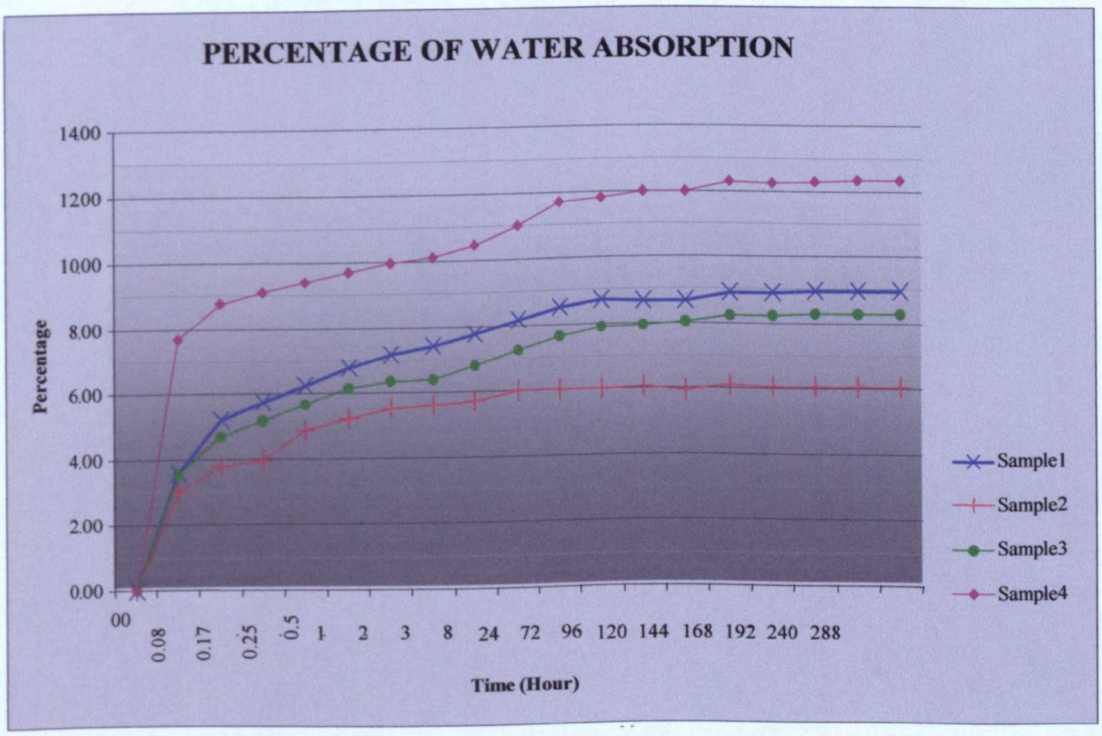
350.00
340.00
330.00
320.00
310.00
300.00
290.00
280.00
270.00
260.00
250.00
Weight (g)
Mo
0.08
0.17
0.25
0.50
1.00
2.00
3.00
8.00
24.00
72.00
96.00
120.00
144.00
168.00
192.00
240.00
288.00
Time (Hour)
Sample 1
Sample 2
Sample 3
Sample 4


PERCENTAGE OF WATER ABSORPTION
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12.00
10.00
8.00
6.00
4.00
2.00
0.00
Percentage
00
0.08
0.17
0.25
0.5
1
2
3
8
24
72
96
120
144
168
192
240
288
Time (Hour)
Sample1
Sample2
Sample3
Sample4

WATER ABSORPTION BY TOTAL IMMERSION

Time (hour)		Weight of Sample (grams)																
Sample	M_o	0.08	0.17	0.25	0.50	1.00	2.00	3.00	8.00	24.00	72.00	96.00	120.00	144.00	168.00	192.00	240.00	288.00	M_{max}
A1a	293.40	306.80	308.75	310.65	313.05	315.90	317.00	317.90	318.30	319.80	321.20	321.95	321.75	321.95	322.40	322.10	322.00	**322.00**	322.00
A1b	306.55	320.00	321.55	322.35	323.10	323.40	323.80	324.55	324.80	325.50	326.75	327.35	327.00	327.00	328.00	327.95	328.10	**328.20**	328.20
A1c	316.05	322.05	333.70	335.90	337.40	338.80	341.00	341.65	344.25	345.50	346.00	346.60	346.50	346.70	347.50	347.80	348.00	**348.10**	348.10
Ave	**305.33**	**316.28**	**321.33**	**322.97**	**324.52**	**326.03**	**327.27**	**328.03**	**329.12**	**330.27**	**331.32**	**331.97**	**331.75**	**331.88**	**332.63**	**332.62**	**332.70**	**332.77**	**332.77**
A2a	322.75	334.05	336.85	337.10	339.30	340.35	341.50	341.80	342.25	342.95	343.20	343.20	343.60	342.30	343.30	342.60	342.50	**342.60**	342.60
A2b	350.55	360.65	363.95	365.00	369.00	370.05	371.05	371.25	372.20	373.40	372.80	372.55	372.50	373.20	373.20	373.60	373.70	**373.75**	373.75
A2c	316.20	324.45	326.30	326.65	329.50	331.00	331.75	332.10	331.85	332.70	332.95	333.45	333.40	333.40	333.50	333.50	**333.55**	333.55	333.55
Ave	**329.83**	**339.72**	**342.37**	**342.92**	**345.93**	**347.13**	**348.10**	**348.38**	**348.77**	**349.68**	**349.65**	**349.73**	**349.83**	**349.63**	**350.00**	**349.90**	**349.92**	**349.97**	**349.97**
A3a	367.15	375.25	378.20	379.85	381.55	383.15	384.15	384.50	386.00	386.90	387.15	387.75	387.70	388.00	388.50	388.50	**388.50**	388.50	388.50
A3b	274.35	289.25	293.50	294.80	296.20	297.50	298.10	298.15	299.35	301.55	303.95	304.75	305.05	305.40	306.30	306.70	306.70	**306.75**	306.75
A3c	294.00	303.00	305.90	307.50	309.25	310.90	311.15	311.15	311.95	312.90	313.80	314.35	314.45	315.00	315.40	315.00	315.10	**315.15**	315.15
Ave	**311.83**	**322.50**	**325.87**	**327.38**	**329.00**	**330.52**	**331.13**	**331.27**	**332.43**	**333.78**	**334.97**	**335.62**	**335.73**	**336.13**	**336.73**	**336.73**	**336.77**	**336.80**	**336.80**
A4a	288.00	307.20	309.35	310.25	311.40	311.45	312.95	313.20	313.95	314.95	317.40	317.50	318.55	318.20	319.30	319.10	319.30	**319.50**	319.50
A4b	274.5	297.70	300.80	301.75	301.90	303.80	304.00	304.15	305.40	307.10	309.00	309.15	309.40	309.60	310.20	310.00	310.10	**310.20**	310.20
A4c	246.05	265.60	269.05	269.85	270.95	271.35	271.90	272.45	273.45	274.80	276.25	276.65	277.00	277.30	277.90	277.90	**278.00**	278.00	278.00
Ave	**269.52**	**290.17**	**293.07**	**293.95**	**294.75**	**295.53**	**296.28**	**296.60**	**297.60**	**298.95**	**300.88**	**301.10**	**301.65**	**301.70**	**302.47**	**302.33**	**302.47**	**302.57**	**302.57**

Percentage of Water Absorption (%WA)

Time (Hour)									Percentage									
SAMPLE	0	0.08	0.17	0.25	0.50	1	2	3	8	24	72	96	120	144	168	192	240	288	Mmax
A1a	0.00	4.57	5.23	5.88	6.70	7.67	8.04	8.35	8.49	9.00	9.48	9.73	9.66	9.73	9.88	9.78	9.75	9.75	9.75
A1b	0.00	4.39	4.89	5.15	5.40	5.50	5.63	5.87	5.95	6.18	6.59	6.79	6.67	6.67	7.00	6.98	7.03	7.06	7.06
A1c	0.00	1.90	5.58	6.28	6.76	7.20	7.89	8.10	8.92	9.32	9.48	9.67	9.63	9.70	9.95	10.05	10.11	10.14	10.14
Average	**0.00**	**3.62**	**5.24**	**5.77**	**6.28**	**6.79**	**7.19**	**7.44**	**7.79**	**8.17**	**8.51**	**8.73**	**8.66**	**8.70**	**8.94**	**8.94**	**8.96**	**8.98**	**8.98**
A2a	0.00	3.50	4.37	4.45	5.13	5.45	5.81	5.90	6.04	6.26	6.34	6.34	6.46	6.06	6.37	6.15	6.12	6.15	6.15
A2b	0.00	2.88	3.82	4.12	5.26	5.56	5.85	5.91	6.18	6.52	6.35	6.28	6.26	6.46	6.46	6.58	6.60	6.62	6.62
A2c	0.00	2.61	3.19	3.30	4.21	4.68	4.92	5.03	4.95	5.22	5.30	5.46	5.44	5.44	5.47	5.47	5.49	5.49	5.49
Average	**0.00**	**3.00**	**3.80**	**3.96**	**4.87**	**5.23**	**5.53**	**5.61**	**5.72**	**6.00**	**5.99**	**6.02**	**6.05**	**5.99**	**6.10**	**6.07**	**6.07**	**6.09**	**6.09**
A3a	0.00	2.21	3.01	3.46	3.92	4.36	4.63	4.73	5.13	5.38	5.45	5.61	5.60	5.68	5.82	5.82	5.82	5.82	5.82
A3b	0.00	5.43	6.98	7.45	7.96	8.44	8.66	8.68	9.11	9.91	10.79	11.08	11.19	11.32	11.65	11.79	11.79	11.81	11.81
A3c	0.00	3.06	4.05	4.59	5.19	5.75	5.83	5.83	6.11	6.43	6.73	6.92	6.96	7.14	7.28	7.14	7.18	7.19	7.19
Average	**0.00**	**3.57**	**4.68**	**5.17**	**5.69**	**6.18**	**6.37**	**6.41**	**6.78**	**7.24**	**7.66**	**7.87**	**7.91**	**8.05**	**8.25**	**8.25**	**8.26**	**8.27**	**8.27**
A4a	0.00	6.67	7.41	7.73	8.12	8.14	8.66	8.75	9.01	9.36	10.21	10.24	10.61	10.49	10.87	10.80	10.87	10.94	10.94
A4b	0.00	8.45	9.58	9.93	9.98	10.67	10.75	10.80	11.26	11.88	12.57	12.62	12.71	12.79	13.01	12.93	12.97	13.01	13.01
A4c	0.00	7.95	9.35	9.67	10.12	10.28	10.51	10.73	11.14	11.68	12.27	12.44	12.58	12.70	12.94	12.94	12.99	12.99	12.99
Average	**0.00**	**7.69**	**8.78**	**9.11**	**9.41**	**9.70**	**9.97**	**10.09**	**10.47**	**10.97**	**11.68**	**11.77**	**11.97**	**11.99**	**12.27**	**12.23**	**12.27**	**12.31**	**12.31**

Total Amount of Absorbed Water

Time (Hour)	Amount of Water absorbed (g)																		
SAMPLE	0	0.08	0.17	0.25	0.50	1	2	3	8	24	48	72	96	120	144	168	192	240	288	Mmax
A1a	0.00	13.40	15.35	17.25	19.65	22.50	23.60	24.50	24.90	26.40	27.20	27.80	28.55	28.35	28.55	29.00	28.70	28.60	28.60	28.60
A1b	0.00	13.45	15.00	15.80	16.55	16.85	17.25	18.00	18.25	18.95	19.65	20.20	20.80	20.45	20.45	21.45	21.40	21.55	21.65	21.65
A1c	0.00	6.00	17.65	19.85	21.35	22.75	24.95	25.60	28.20	29.45	29.75	29.95	30.55	30.45	30.65	31.45	31.75	31.95	32.05	32.05
Average	**0.00**	**10.95**	**16.00**	**17.63**	**19.18**	**20.70**	**21.93**	**22.70**	**23.78**	**24.93**	**25.53**	**25.98**	**26.63**	**26.42**	**26.55**	**27.30**	**27.28**	**27.37**	**27.43**	**27.43**
% of TWA		**39.91**	**58.32**	**64.28**	**69.93**	**75.46**	**79.95**	**82.75**	**86.70**	**90.89**	**93.07**	**94.71**	**97.08**	**96.29**	**96.78**	**99.51**	**99.45**	**99.76**	**100.00**	
A2a	0.00	11.30	14.10	14.35	16.55	17.60	18.75	19.05	19.50	20.20	20.35	20.45	20.45	20.85	19.55	20.55	19.85	19.75	19.85	19.85
A2b	0.00	10.10	13.40	14.45	18.45	19.50	20.50	20.70	21.65	22.85	22.95	22.25	22.00	21.95	22.65	22.65	23.05	23.15	23.20	23.20
A2c	0.00	8.25	10.10	10.45	13.30	14.80	15.55	15.90	15.65	16.50	16.65	16.75	17.25	17.20	17.20	17.30	17.30	17.35	17.35	17.35
Average	**0.00**	**9.88**	**12.53**	**13.08**	**16.10**	**17.30**	**18.27**	**18.55**	**18.93**	**19.85**	**19.98**	**19.82**	**19.90**	**20.00**	**19.80**	**20.17**	**20.07**	**20.08**	**20.13**	**20.13**
% of TWA		**49.09**	**62.25**	**64.98**	**79.97**	**85.93**	**90.73**	**92.14**	**94.04**	**98.59**	**99.25**	**98.43**	**98.84**	**99.34**	**98.34**	**100.17**	**99.67**	**99.75**	**100.00**	
A3a	0.00	8.10	11.05	12.70	14.40	16.00	17.00	17.35	18.85	19.75	19.90	20.00	20.60	20.55	20.85	21.35	21.35	21.35	21.35	21.35
A3b	0.00	14.90	19.15	20.45	21.85	23.15	23.75	23.80	25.00	27.20	28.10	29.60	30.40	30.70	31.05	31.95	32.35	32.35	32.40	32.40
A3c	0.00	9.00	11.90	13.50	15.25	16.90	17.15	17.15	17.95	18.90	19.40	19.80	20.35	20.45	21.00	21.40	21.00	21.10	21.15	21.15
Average	**0.00**	**10.67**	**14.03**	**15.55**	**17.17**	**18.68**	**19.30**	**19.43**	**20.60**	**21.95**	**22.47**	**23.13**	**23.78**	**23.90**	**24.30**	**24.90**	**24.90**	**24.93**	**24.97**	**24.97**
% of TWA		**42.72**	**56.21**	**62.28**	**68.76**	**74.83**	**77.30**	**77.84**	**82.51**	**87.92**	**89.99**	**92.66**	**95.26**	**95.73**	**97.33**	**99.73**	**99.73**	**99.87**	**100.00**	
A4a	0.00	19.20	21.35	22.25	23.40	23.45	24.95	25.20	25.95	26.95	28.50	29.40	29.50	30.55	30.20	31.30	31.10	31.30	31.50	31.50
A4b	0.00	23.20	26.30	27.25	27.40	29.30	29.50	29.65	30.90	32.60	33.90	34.50	34.65	34.90	35.10	35.70	35.50	35.60	35.70	35.70
A4c	0.00	19.55	23.00	23.80	24.90	25.30	25.85	26.40	27.40	28.75	29.60	30.20	30.60	30.95	31.25	31.85	31.85	31.95	31.95	31.95
Average	**0.00**	**20.65**	**23.55**	**24.43**	**25.23**	**26.02**	**26.77**	**27.08**	**28.08**	**29.43**	**30.67**	**31.37**	**31.58**	**32.13**	**32.18**	**32.95**	**32.82**	**32.95**	**33.05**	**33.05**
% of TWA		**62.48**	**71.26**	**73.93**	**76.35**	**78.72**	**80.99**	**81.95**	**84.97**	**89.06**	**92.79**	**94.91**	**95.56**	**97.23**	**97.38**	**99.70**	**99.29**	**99.70**	**100.00**	

RATE OF WATER ABSORPTION

Time (Hour)

SAMPLE	0	0.08	0.08	0.08	0.25	0.50	1.00	1.00	5.00	16.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00	48.00	48.00
A1a	0.00	160.80	23.40	22.80	9.60	5.70	1.10	0.90	0.08	0.09	0.03	0.02	0.03	-0.01	0.01	0.02	-0.01	0.00	0.00
A1b	0.00	161.40	18.60	9.60	3.00	0.60	0.40	0.75	0.05	0.04	0.03	0.02	0.03	-0.01	0.00	0.04	0.00	0.00	0.00
A1c	0.00	72.00	139.80	26.40	6.00	2.80	2.20	0.65	0.52	0.08	0.01	0.01	0.03	0.00	0.01	0.03	0.01	0.00	0.00
Average	**0.00**	**131.40**	**60.60**	**19.60**	**6.20**	**3.03**	**1.23**	**0.77**	**0.22**	**0.07**	**0.03**	**0.02**	**0.03**	**-0.01**	**0.01**	**0.03**	**0.00**	**0.00**	**0.00**
A2a	0.00	135.60	33.60	3.00	8.80	2.10	1.15	0.30	0.09	0.04	0.01	0.00	0.00	0.02	-0.05	0.04	-0.03	0.00	0.00
A2b	0.00	121.20	39.60	12.60	16.00	2.10	1.00	0.20	0.19	0.07	0.00	-0.03	-0.01	0.00	0.03	0.00	0.02	0.00	0.00
A2c	0.00	99.00	22.20	4.20	11.40	3.00	0.75	0.35	-0.05	0.05	0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00
Average	**0.00**	**118.60**	**31.80**	**6.60**	**12.07**	**2.40**	**0.97**	**0.28**	**0.08**	**0.06**	**0.01**	**-0.01**	**0.00**	**0.00**	**-0.01**	**0.02**	**0.00**	**0.00**	**0.00**
A3a	0.00	97.20	17.70	6.60	3.40	1.60	0.50	0.12	0.19	0.04	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
A3b	0.00	178.80	51.00	15.60	5.60	2.60	0.60	0.05	0.24	0.14	0.04	0.06	0.03	0.01	0.01	0.04	0.02	0.00	0.00
A3c	0.00	108.00	34.80	19.20	7.00	3.30	0.25	0.00	0.16	0.06	0.02	0.02	0.02	0.00	0.02	0.02	-0.02	0.00	0.00
Average	**0.00**	**128.00**	**34.50**	**13.80**	**5.33**	**2.50**	**0.45**	**0.06**	**0.20**	**0.08**	**0.02**	**0.03**	**0.02**	**0.01**	**0.01**	**0.02**	**0.00**	**0.00**	**0.00**
A4a	0.00	230.40	25.80	10.80	4.60	0.10	1.50	0.25	0.15	0.06	0.06	0.04	0.00	0.04	-0.01	0.05	-0.01	0.00	0.00
A4b	0.00	278.40	37.20	11.40	0.60	3.80	0.20	0.15	0.25	0.11	0.05	0.03	0.01	0.01	0.01	0.02	-0.01	0.00	0.00
A4c	0.00	234.60	41.40	9.60	4.40	0.80	0.55	0.55	0.20	0.08	0.04	0.03	0.02	0.01	0.01	0.02	0.00	0.00	0.00
Average	**0.00**	**247.80**	**34.80**	**10.60**	**3.20**	**1.57**	**0.75**	**0.32**	**0.20**	**0.08**	**0.05**	**0.03**	**0.01**	**0.02**	**0.00**	**0.03**	**-0.01**	**0.00**	**0.00**

WATER EVAROTATION

Temperature=42+/-2 %RH=85% +/-3

Time (Hour)	Weight of Sample (grams)															
SAMPLE	Mo	0.08	0.17	0.25	0.50	1	2	3	8	24	48	72	96	120	144	168	192
A1a	322.20	322.20	321.00	320.80	320.50	318.90	318.00	317.00	308.70	293.50	**288.20**	288.20	288.20	288.20	288.20	288.20	288.20
A1b	330.55	330.30	329.70	329.40	329.00	327.50	326.70	326.30	320.40	309.00	306.00	305.80	**305.60**	305.60	305.60	305.60	305.60
A1c	350	349.90	348.90	348.50	348.20	346.75	345.60	344.70	336.90	317.10	311.10	310.70	**310.60**	310.60	310.60	310.65	310.60
Average	**334.25**	**334.13**	**333.20**	**332.90**	**332.57**	**331.05**	**330.10**	**329.33**	**322.00**	**306.53**	**301.77**	**301.57**	**301.47**	**301.47**	**301.47**	**301.48**	**301.47**
A2a	342.75	341.80	340.95	340.80	340.70	339.60	338.40	337.30	329.70	320.40	317.90	**317.10**	317.10	317.15	317.10	317.10	317.10
A2b	375.8	375.70	375.10	375.00	374.90	373.50	372.70	372.10	366.70	353.65	349.70	348.90	**348.75**	348.80	348.75	348.75	348.75
A2c	335.40	335.40	335.10	334.70	333.00	331.70	330.80	330.00	323.25	315.00	312.30	**312.00**	312.00	312.00	312.05	312.00	**312.00**
Average	**351.32**	**350.97**	**350.38**	**350.17**	**349.53**	**348.27**	**347.30**	**346.47**	**339.88**	**329.68**	**326.63**	**326.00**	**325.95**	**325.98**	**325.97**	**325.95**	**325.95**
A3a	389.30	389.30	388.30	388.30	388.20	386.80	385.70	385.00	378.80	371.00	365.80	365.60	**365.55**	365.55	365.60	365.55	**365.55**
A3b	310.50	310.50	309.90	309.80	309.60	308.70	308.10	307.60	301.15	282.30	272.70	**272.40**	272.50	272.40	272.40	272.40	272.40
A3c	315.30	314.50	313.70	313.70	313.70	312.20	311.20	310.20	304.50	295.10	291.20	290.80	**290.75**	290.75	290.75	290.75	290.75
Average	**338.37**	**338.10**	**337.30**	**337.27**	**337.17**	**335.90**	**335.00**	**334.27**	**328.15**	**316.13**	**309.90**	**309.60**	**309.60**	**309.57**	**309.58**	**309.57**	**309.57**
A4a	320.20	319.70	318.95	318.60	318.20	317.30	315.50	314.20	307.20	291.30	285.40	**285.00**	285.00	285.05	285.00	285.00	285.00
A4b	311.85	311.20	310.50	310.40	310.20	309.90	308.50	307.20	301.20	280.30	271.40	**271.10**	271.00	271.00	271.00	271.00	271.00
A4c	279.00	278.90	279.00	279.00	277.60	277.10	275.80	274.50	268.30	249.60	243.65	243.25	**243.00**	243.00	243.05	243.00	**243.00**
Average	**303.68**	**303.27**	**302.82**	**302.67**	**302.00**	**301.43**	**299.93**	**298.63**	**292.23**	**273.73**	**266.82**	**266.45**	**266.33**	**266.35**	**266.35**	**266.33**	**266.33**

Total Amount of Water Evaporation

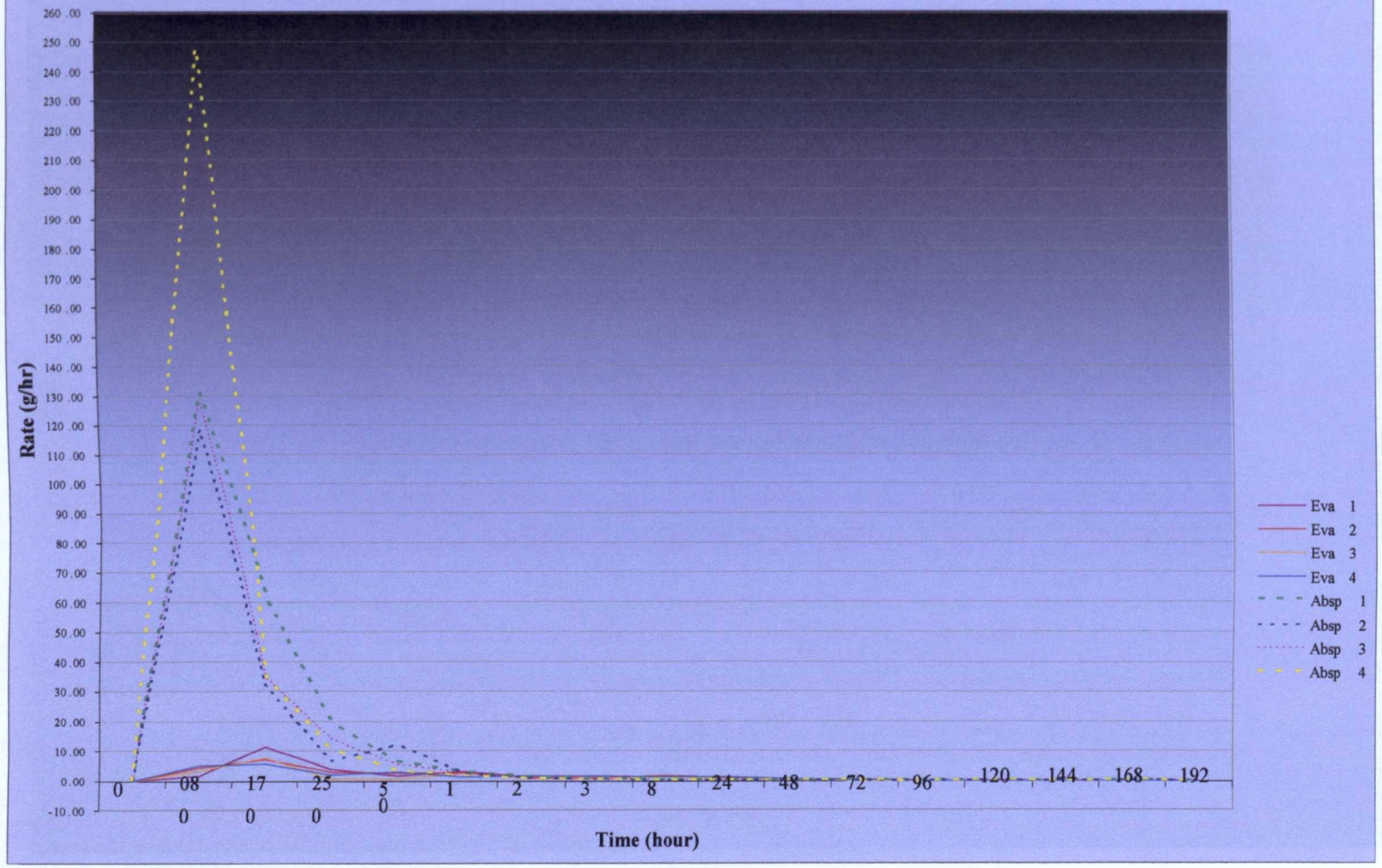
Time (Hour)	Amount of Water evaporation (g)															
SAMPLE	0	0.08	0.17	0.25	0.50	1	2	3	8	24	48	72	96	120	144	168	192
A1a	0.00	0.00	1.20	1.40	1.70	3.30	4.20	5.20	13.50	28.70	34.00	34.00	34.00	34.00	34.00	34.00	34.00
A1b	0.00	0.25	0.85	1.15	1.55	3.05	3.85	4.25	10.15	21.55	24.55	24.75	24.95	24.95	24.95	24.95	24.95
A1c	0.00	0.10	1.10	1.50	1.80	3.25	4.40	5.30	13.10	32.90	38.90	39.30	39.40	39.40	39.40	39.35	39.40
Average	**0.00**	**0.12**	**1.05**	**1.35**	**1.68**	**3.20**	**4.15**	**4.92**	**12.25**	**27.72**	**32.48**	**32.68**	**32.78**	**32.78**	**32.78**	**32.77**	**32.78**
% of TWE		**0.36**	**3.20**	**4.12**	**5.13**	**9.76**	**12.66**	**15.00**	**37.37**	**84.54**	**99.08**	**99.69**	**100.00**	**100.00**	**100.00**	**99.95**	
A2a	0.00	0.95	1.80	1.95	2.05	3.15	4.35	5.45	13.05	22.35	24.85	25.65	25.65	25.60	25.65	25.65	25.65
A2b	0.00	0.10	0.70	0.80	0.90	2.30	3.10	3.70	9.10	22.15	26.10	26.90	27.05	27.00	27.05	27.05	27.05
A2c	0.00	0.00	0.30	0.70	2.40	3.70	4.60	5.40	12.15	20.40	23.10	23.40	23.40	23.40	23.35	23.40	23.40
Average	**0.00**	**0.35**	**0.93**	**1.15**	**1.78**	**3.05**	**4.02**	**4.85**	**11.43**	**21.63**	**24.68**	**25.32**	**25.37**	**25.33**	**25.35**	**25.37**	**25.37**
% of TWE		**1.38**	**3.68**	**4.53**	**7.03**	**12.02**	**15.83**	**19.12**	**45.07**	**85.28**	**97.31**	**99.80**	**100.00**	**99.87**	**99.93**	**100.00**	
A3a	0.00	0.00	1.00	1.00	1.10	2.50	3.60	4.30	10.50	18.30	23.50	23.70	23.75	23.75	23.70	23.75	23.75
A3b	0.00	0.00	0.60	0.70	0.90	1.80	2.40	2.90	9.35	28.20	37.80	38.10	38.00	38.10	38.10	38.10	38.10
A3c	0.00	0.80	1.60	1.60	1.60	3.10	4.10	5.10	10.80	20.20	24.10	24.50	24.55	24.55	24.55	24.55	24.55
Average	**0.00**	**0.27**	**1.07**	**1.10**	**1.20**	**2.47**	**3.37**	**4.10**	**10.22**	**22.23**	**28.47**	**28.77**	**28.77**	**28.80**	**28.78**	**28.80**	**28.80**
% of TWE		**0.93**	**3.70**	**3.82**	**4.17**	**8.56**	**11.69**	**14.24**	**35.47**	**77.20**	**98.84**	**99.88**	**99.88**	**100.00**	**99.94**	**100.00**	
A4a	0.00	0.50	1.25	1.60	2.00	2.90	4.70	6.00	13.00	28.90	34.80	35.20	35.20	35.15	35.20	35.20	35.20
A4b	0.00	0.65	1.35	1.45	1.65	1.95	3.35	4.65	10.65	31.55	40.45	40.75	40.85	40.85	40.85	40.85	40.85
A4c	0.00	0.10	0.00	0.00	1.40	1.90	3.20	4.50	10.70	29.40	35.35	35.75	36.00	36.00	35.95	36.00	36.00
Average	**0.00**	**0.42**	**0.87**	**1.02**	**1.68**	**2.25**	**3.75**	**5.05**	**11.45**	**29.95**	**36.87**	**37.23**	**37.35**	**37.33**	**37.33**	**37.35**	**37.35**
% of TWE		**1.12**	**2.32**	**2.72**	**4.51**	**6.02**	**10.04**	**13.52**	**30.66**	**80.19**	**98.71**	**99.69**	**100.00**	**99.96**	**99.96**	**100.00**	

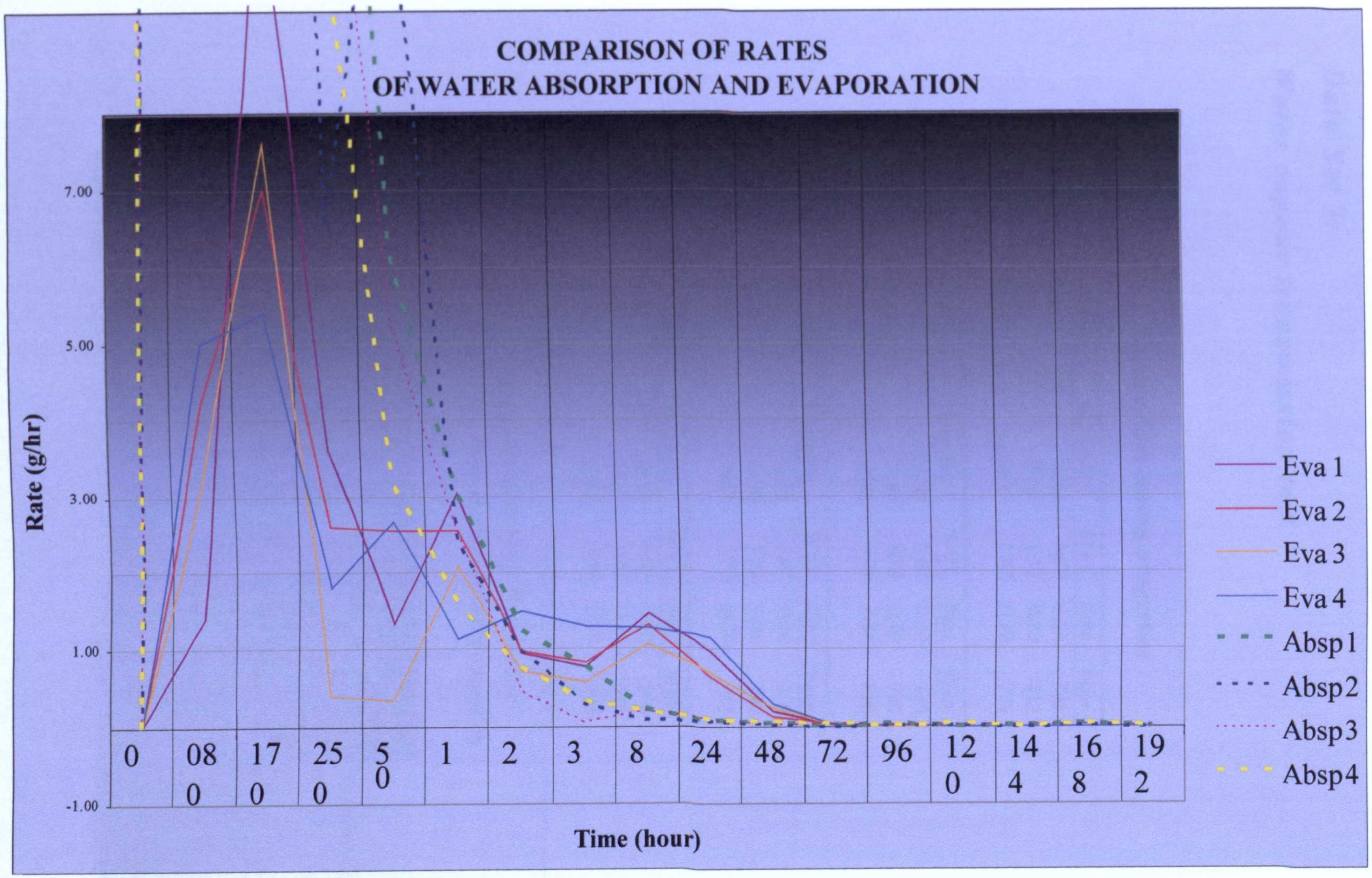
RATE OF WATER EVAPORATION

Time (Hour)

SAMPLE	0	0.08	0.08	0.08	0.25	0.50	1.00	1.00	5.00	16.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00
A1a	0.00	0.00	14.40	2.40	1.20	3.20	0.90	1.00	1.66	0.95	0.22	0.00	0.00	0.00	0.00	0.00	0.00
A1b	0.00	3.00	7.20	3.60	1.60	3.00	0.80	0.40	1.18	0.71	0.13	0.01	0.01	0.00	0.00	0.00	0.00
A1c	0.00	1.20	12.00	4.80	1.20	2.90	1.15	0.90	1.56	1.24	0.25	0.02	0.00	0.00	0.00	0.00	0.00
Average	**0.00**	**1.40**	**11.20**	**3.60**	**1.33**	**3.03**	**0.95**	**0.77**	**1.47**	**0.97**	**0.20**	**0.01**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
A2a	0.00	11.40	10.20	1.80	0.40	2.20	1.20	1.10	1.52	0.58	0.10	0.03	0.00	0.00	0.00	0.00	0.00
A2b	0.00	1.20	7.20	1.20	0.40	2.80	0.80	0.60	1.08	0.82	0.16	0.03	0.01	0.00	0.00	0.00	0.00
A2c	0.00	0.00	3.60	4.80	6.80	2.60	0.90	0.80	1.35	0.52	0.11	0.01	0.00	0.00	0.00	0.00	0.00
Average	**0.00**	**4.20**	**7.00**	**2.60**	**2.53**	**2.53**	**0.97**	**0.83**	**1.32**	**0.64**	**0.13**	**0.03**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
A3a	0.00	0.00	6.00	0.00	0.20	1.40	0.55	0.23	0.77	0.33	0.11	0.00	0.00	0.00	0.00	0.00	0.00
A3b	0.00	0.00	7.20	1.20	0.80	1.80	0.60	0.50	1.29	1.18	0.40	0.01	0.00	0.00	0.00	0.00	0.00
A3c	0.00	9.60	9.60	0.00	0.00	3.00	1.00	1.00	1.14	0.59	0.16	0.02	0.00	0.00	0.00	0.00	0.00
Average	**0.00**	**3.20**	**7.60**	**0.40**	**0.33**	**2.07**	**0.72**	**0.58**	**1.07**	**0.70**	**0.22**	**0.01**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
A4a	0.00	6.00	9.00	4.20	1.60	1.80	1.80	1.30	1.40	0.99	0.25	0.02	0.00	0.00	0.00	0.00	0.00
A4b	0.00	7.80	8.40	1.20	0.80	0.60	1.40	1.30	1.20	1.31	0.37	0.01	0.00	0.00	0.00	0.00	0.00
A4c	0.00	1.20	-1.20	0.00	5.60	1.00	1.30	1.30	1.24	1.17	0.25	0.02	0.01	0.00	0.00	0.00	0.00
Average	**0.00**	**5.00**	**5.40**	**1.80**	**2.67**	**1.13**	**1.50**	**1.30**	**1.28**	**1.16**	**0.29**	**0.02**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**

COMPARISON OF RATES
OF WATER ABSORPTION AND EVAPORATION




COMPARISON OF RATES
OF WATER ABSORPTION AND EVAPORATION
Rate (g/hr)
7.00
5.00
3.00
1.00
-1.00
0
08 0
17 0
25 0
5 0
1
2
3
8
24
48
72
96
12 0
14 4
16 8
19 2
Time (hour)
Eva 1
Eva 2
Eva 3
Eva 4
Absp1
Absp2
Absp3
Absp4

Data Set 2:
Water vapour transmission test

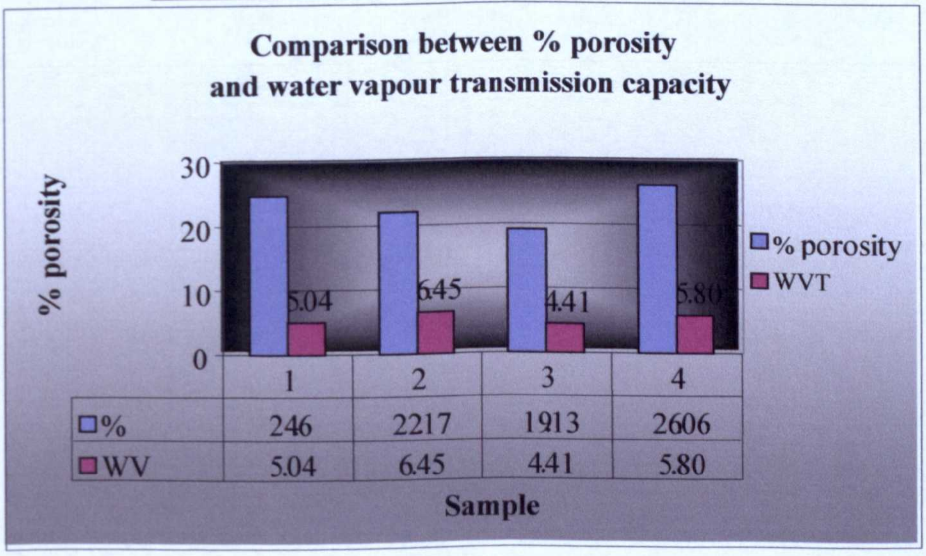
Comparison among properties

Sample	%porosity	WVT	Rate	Hour
G1a	15.64	4.37	0.20	528
G1b	25.70	5.32	0.30	428
G1c	32.46	5.42	0.30	299

Sample	%porosity	WVT	Rate	Hour
G2a	24.85	6.01	0.30	405
G2b	23.66	8.04	0.40	769
G2c	18.01	5.30	0.30	528

Sample	%porosity	WVT	Rate	Hour
G3a	23.51	5.67	0.30	299
G3b	17.82	3.83	0.20	299
G3c	16.06	3.73	0.20	646

Sample	%porosity	WVT	Rate	Hour
G4a	26.71	6.00	0.30	299
G4b	24.83	5.91	0.30	299
G4c	26.63	5.49	0.20	528


Comparison between % porosity and water vapour transmission capacity

WATER VAPOUR TRANSMISSION TEST

No. of Rec	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21												WVT
Day		1	2	2	3	4	5	6	7	8	9	10	12	13	15	16	17	19	20	22	23	24	26	27	28	30	31	32	33	34	35	36	38	
Time (Hour)		24	48	66	91	115	139	164	187	215	236	263	299	332	378	405	428	458	492	528	552	597	646	670	696	725	738	769	794	819	843	868	917	
Time Diff(Hr)		24.00	24.00	18.00	25.00	24.00	24.00	25.00	23.00	28.00	21.00	27.00	36.00	33.00	46.00	26.50	23.50	30.00	34.00	36.00	24.00	44.50	49.50	23.50	26.50	28.50	13.00	31.50	24.50	25.00	24.00	25.00	49.00	
Temp (C)	30.0	30.0	31.0	33.0	32.5	32.5	32.5	32.0	32.5	31.0	32.0	31.0	33.0	32.0	32.5	32.0	32.0	29.5	34.0	31.0	31.0	32.0	31.5	32.0	31.0	29.0	33.0	31.0	31.0	31.0	30.5	31.0	31.0	
%RH	18	24	20	18	18	18	19	19	19	18	18	18	19	19	18	18	18	18	18	18	17	18	19	19	18	18	18	17	18	18	18	19	18	
Area(squm)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	
U1-Dummy	147.40	147.00	146.95	147.00	147.00	147.00	147.15	147.00	147.00	147.00	147.00	147.00	147.00	147.00	147.00	147.05	147.00	147.00	147.00	147.00	147.00	147.00	146.90	146.90	146.90									
U1-1	269.50	269.45	269.00	268.95	268.30	267.95	267.55	267.00	266.60	265.95	265.15	264.90	264.10	263.10	262.10	261.50	260.90	260.00	259.10	258.40	257.95	257.00	255.80	255.25	254.60									
Wt.Chng (g)		0.05	0.45	0.05	0.65	0.35	0.40	0.55	0.40	0.65	0.80	0.25	0.80	1.00	1.00	0.60	0.60	0.90	0.90	0.70	0.45	0.95	1.20	0.55	0.65									
G/t		0.00	0.02	0.00	0.03	0.01	0.02	0.02	0.02	0.02	0.04	0.01	0.02	0.03	0.02	0.02	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02									
WVT		0.41	3.73	0.55	5.17	2.90	3.31	4.38	3.46	4.62	7.58	1.84	4.42	6.03	4.32	4.50	5.08	5.97	5.26	3.87	3.73	4.25	4.82	4.65	4.88	4.37								4.37
U1-2	246.70	244.50	242.80	242.25	241.50	240.90	240.00	239.20	238.70	238.00	237.45	236.80	235.90	235.00	233.10	232.70	232.10	231.30	230.40	229.40	228.75	227.55												
Wt.Chng (g)		2.20	1.70	0.55	0.75	0.60	0.90	0.80	0.50	0.70	0.55	0.65	0.90	0.90	1.90	0.40	0.60	0.80	0.90	1.00	0.65	1.20												
G/t		0.09	0.07	0.03	0.03	0.02	0.04	0.03	0.02	0.02	0.03	0.02	0.03	0.03	0.04	0.02	0.03	0.03	0.03	0.03	0.03	0.03												
WVT		18.23	14.09	6.08	5.97	4.97	7.46	6.36	4.32	4.97	5.21	4.79	4.97	5.42	8.21	3.00	5.08	5.30	5.26	5.52	5.39	5.36	5.32											5.32
U1-3	228.15	227.00	226.00	225.70	225.20	224.10	224.10	223.40	222.80	221.90	221.30	220.65	220.00	219.30	217.90	217.40	216.50	216.00	215.10	214.20	213.50	212.30	211.00	210.30										
Wt.Chng (g)		1.15	1.00	0.30	0.50	1.10	0.00	0.70	0.60	0.90	0.60	0.65	0.65	0.70	1.40	0.50	0.90	0.50	0.90	0.90	0.70	1.20	1.30	0.70										
G/t		0.05	0.04	0.02	0.02	0.05	0.00	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.02	0.04	0.02	0.03	0.03	0.03	0.03	0.03	0.03										
WVT		9.53	8.29	3.31	3.98	9.11	0.00	5.57	5.19	6.39	5.68	4.79	3.59	4.22	6.05	3.75	7.62	3.31	5.26	4.97	5.80	5.36	5.22	5.92	5.42									5.42
Ave. WVT		9.39	8.70	3.31	5.04	5.66	3.59	5.44	4.32	5.33	6.16	3.81	4.33	5.22	6.20	3.75	5.92	4.86	5.26	4.79	4.97	4.99												5.04
U2-Dummy	142.40	142.00	142.00	142.05	142.10	141.95	142.15	142.00	142.05	142.00	141.90	142.00	142.15	142.20	142.00	142.05	142.00	142.00	141.90	142.10	141.95	141.95	142.00	141.85	141.85	141.90	142.10	141.85	142.00	142.00	141.90	142.20	142.10	
U2-1	226.75	223.85	223.75	222.45	221.95	221.25	220.80	219.95	219.60	218.95	218.20	217.55	216.90	216.10	215.00	214.20	213.40	212.50	211.50	210.40	209.75													
Wt.Chng (g)		2.90	0.10	1.30	0.50	0.70	0.45	0.85	0.35	0.65	0.75	0.65	0.65	0.80	1.10	0.80	0.80	0.90	1.00	1.10	0.65													
G/t		0.12	0.00	0.07	0.02	0.03	0.02	0.03	0.02	0.02	0.04	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03													
WVT		24.03	0.83	14.36	3.98	5.80	3.73	6.76	3.03	4.62	7.10	4.79	3.59	4.82	4.76	6.00	6.77	5.97	5.85	6.08	5.39	6.01												6.01
U2-2	271.45	270.80	269.70	269.25	268.80	268.30	267.65	267.05	266.75	265.85	265.30	264.95	264.10	263.00	261.90	261.50	260.80	260.00	259.20	257.70	256.50	256.00	254.50	253.50	253.15	252.00	251.40	250.00	249.00	248.00	247.10	246.00	244.10	
Wt.Chng (g)		0.65	1.10	0.45	0.45	0.50	0.65	0.60	0.30	0.90	0.55	0.35	0.85	1.10	1.10	0.40	0.70	0.80	0.80	1.50	1.20	0.50	1.50	1.00	0.35	1.15	0.60	1.40	1.00	1.00	0.90	1.10	1.90	
G/t		0.03	0.05	0.02	0.02	0.02	0.03	0.02	0.01	0.03	0.03	0.01	0.02	0.03	0.02	0.02	0.03	0.03	0.02	0.04	0.05	0.01	0.03	0.04	0.01	0.04	0.05	0.04	0.04	0.04	0.04	0.04	0.04	
WVT		5.39	9.11	4.97	3.58	4.14	5.39	4.77	2.59	6.39	5.21	2.58	4.70	6.63	4.76	3.00	5.92	5.30	4.68	8.29	9.94	2.23	6.03	8.46	2.63	8.02	9.18	8.84	8.12	7.95	7.46	8.75	7.71	8.04
U2-3	285.25	284.50	283.60	283.00	282.60	282.20	281.40	281.00	280.40	279.55	279.00	278.45	277.50	276.50	275.30	274.45	274.00	273.40	272.60	271.60	271.00	269.85	268.40	267.80	267.10									
Wt.Chng (g)		0.75	0.90	0.60	0.40	0.40	0.80	0.40	0.60	0.85	0.55	0.55	0.95	1.00	1.20	0.85	0.45	0.60	0.80	1.00	0.60	1.15	1.45	0.60	0.70									
G/t		0.03	0.04	0.03	0.02	0.02	0.03	0.02	0.03	0.03	0.03	0.02	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03									
WVT		6.21	7.46	6.63	3.18	3.31	6.63	3.18	5.19	6.04	5.21	4.05	5.25	6.03	5.19	6.38	3.81	44.50	4.68	5.52	4.97	5.14	5.83	5.08	5.25	5.30								5.30
Ave. WVT		11.88	5.80	8.65	3.58	4.42	5.25	4.91	3.60	5.68	5.84	3.81	4.51	5.83	4.90	5.13	5.50	18.59	5.07	6.63	6.77													6.45
U3-Dummy	198.35	197.95	197.90	197.90	197.90	197.95	197.90	197.90	197.80	197.75	197.80	197.90	197.90	197.90	197.90	197.95	197.95	197.90	197.80	197.85	197.80	197.70	197.80	197.90	197.90	197.90	197.90	197.80						
U3-1	227.75	227.45	227.45	225.50	224.00	223.00	222.35	221.50	220.85	220.10	219.30	218.95	217.85	217.00	215.70	214.85	214.20	213.40																
Wt.Chng (g)		0.30	0.00	1.95	1.50	1.00	0.65	0.85	0.65	0.75	0.80	0.35	1.10	0.85	1.30	0.85	0.65	0.80																
G/t		0.01	0.00	0.11	0.06	0.04	0.03	0.03	0.03	0.03	0.04	0.01	0.03	0.03	0.03	0.03	0.03	0.03																
WVT		2.49	0.00	21.54	11.93	8.29	5.39	6.76	5.62	5.33	7.58	2.58	6.08	5.12	5.62	6.38	5.50	5.30	5.67															5.67
U3-2	261.05	260.60	260.20	259.90	259.70	259.35	258.75	258.35	258.05	257.60	257.00	256.80	256.20	255.50	254.70	254.05	253.60	253.10																
Wt.Chng (g)		0.45	0.40	0.30	0.20	0.35	0.60	0.40	0.30	0.45	0.60	0.20	0.60	0.70	0.80	0.65	0.45	0.50																
G/t		0.02	0.02	0.02	0.01	0.01	0.03	0.02	0.01	0.02	0.03	0.01	0.02	0.02	0.02	0.02	0.02	0.02																
WVT		3.73	3.31	3.31	1.59	2.90	4.97	3.18	2.59	3.20	5.68	1.47	3.31	4.22	3.46	4.88	3.81	3.31	3.83															3.83
U3-3	339.40	338.80	338.80	338.45	338.40	338.00	337.90	337.20	337.15	336.60	336.20	335.90	335.50	335.10	334.30	334.05	333.65	333.15	332.80	332.30	331.85	331.30	330.50	330.00	329.50	329.05	328.75	328.20						
Wt.Chng (g)		0.60	0.00	0.35	0.05	0.40	0.10	0.70	0.05	0.55	0.40	0.30	0.40	0.40	0.80	0.25	0.40	0.50	0.35	0.50	0.45	0.55	0.80	0.50	0.50	0.45	0.30	0.55						
G/t		0.02	0.00	0.02	0.00	0.02	0.00	0.03	0.00	0.02	0.02	0.01	0.01	0.01	0.02	0.01	0.02	0.02	0.01	0.01	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02						
WVT		4.97	0.00	3.87	0.40	3.31	0.83	5.57	0.43	3.91	3.79	2.21	2.21	2.41	3.46	1.88	3.38	3.31	2.05	2.76	3.73	2.46	3.21	4.23	3.75	3.14	4.59	3.47	3.73					3.73
Ave. WVT		3.73	1.10	9.57	4.64	4.83	3.73	5.17	2.88	4.14	5.68	2.09	3.87	3.92	4.18	4.38	4.23	3.98																4.41
U5-Dummy	162.05	161.60	161.50	161.55	161.65	161.80	161.75	161.75	161.60	161.60	161.60	161.60	161.65	161.60	161.80	161.80	161.90	161.70	161.60	161.60	161.80	161.80	161.50	161.50	161.50	161.50								
U5-1	247.10	245.90	245.10	244.95	244.20	243.00	241.75	240.35	239.65	238.55	238.00	237.00	236.00	235.00	233.70	232.80	232.00	231.20																
Wt.Chng (g)		1.20	0.80	0.15	0.75	1.20	1.25	1.40	0.70	1.10	0.55	1.00	1.00	1.00	1.30	0.90	0.80	0.80																
G/t		0.05	0.03	0.01	0.03	0.05	0.05	0.06	0.03	0.04	0.03	0.04	0.03	0.03	0.03	0.03	0.03	0.03																
WVT		9.94	6.63	1.66	5.97	9.94	10.36	11.14	6.05	7.81	5.21	7.37	5.52	6.03	5.62	6.75	6.77	5.30	6.00															6.00
U5-2	247.35	246.90	245.20	244.75	243.90	243.30	242.85	242.00	241.25	240.45	239.80	239.20	238.15	237.30	235.80	235.05	234.25	233.40																
Wt.Chng (g)		0.45	1.70	0.45	0.85	0.60	0.45	0.85	0.75	0.80	0.65	0.60	1.05	0.85	1.50	0.75	0.80	0.85																
G/t		0.02	0.07	0.02	0.03	0.02	0.02	0.03	0.03	0.03	0.03	0.02	0.03	0.03	0.03	0.03	0.03	0.03																
WVT		3.73	14.09	4.97	6.76	4.97	3.73	6.76	6.48	5.68	6.16	4.42	5.80	5.12	6.48	5.63	6.77	5.63	5.91															5.91
U5-3	232.00	232.20	230.35	229.95	229.10	228.75	228.15	227.70	226.95	226.00	225.40	224.70	223.90	223.00	222.00	221.10	220.40	219.70	219.00	217.80	217.20	216.05	214.80	214.10	213.40									
Wt.Chng (g)		-0.20	1.85	0.40	0.85	0.35	0.60	0.45	0.75	0.95	0.60	0.70	0.80	0.90	1.00	0.90	0.70	0.70	0.70	1.20	0.60	1.15	1.25	0.70	0.70									
G/t		-0.01	0.08	0.02	0.03	0.01	0.02	0.02	0.03	0.03	0.03	0.03	0.02	0.03	0.02	0.03	0.03	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03									
WVT		-1.66	15.33	4.42	6.76	2.90	4.97	3.58	6.48	6.75	5.68	5.16	4.42	5.42	4.32	6.75	5.92	4.64	4.09	6.63	4.97	5.14	5.02	5.92	5.25	5.49								5.49
Ave. WVT		4.00	12.01	3.68	6.50	5.94	6.35	7.16	6.34	6.75	5.68	5.65	5.25	5.52	5.48	6.38	6.49	5.19																5.80

Data Set 3: Mechanical strength tests

Compressive strength test

Sample	WET CONDITION								DRY CONDITION						
		Load(kg)	Load (lbs.)	A (sqcm)	A (sqi)	% porosity	Comp. Str(psi)	%Diff		Load(kg)	Load (lbs.)	A (sqcm)	A (sqi)	% porosity	Comp. Str(psi)
1	A1a	n/a	n/a	n/a	n/a	n/a	n/a		B1a	n/a	n/a	n/a	n/a	n/a	n/a
	A1b(B1a)	-70	-154	25.00	3.81	17.74	-40.37		B1b	-825	-1815	30.78	4.70	20.99	-386.45
	A1c	-120	-264	29.70	4.53	23.43	-58.25		B1c	-900	-1980	31.86	4.86	15.38	-407.29
	Average	-95.00	-209.00	27.35	4.17	20.59	**-50.08**	87.39	**Average**	-862.50	-1897.50	31.32	4.78	18.19	**-397.05**
2	A2a	-1765	-3883	27.00	4.12	16.10	-942.50		B2a	-1000	-2200	24.44	3.73	20.85	-589.93
	A2b	-2310	-5082	28.05	4.28	18.15	-1187.36		B2b	-1590	-3498	34.20	5.22	24.02	-670.31
	A2c	-1235	-2717	25.50	3.89	15.38	-698.28		B2c	-410	-902	32.45	4.95	18.13	-182.17
	Average	-1770.00	-3894.00	26.85	4.10	16.54	**-950.46**	-100.16	**Average**	-1000.00	-2200.00	30.36	4.63	21.00	**-474.85**
3	A3a	-1340	-2948	26.00	3.97	14.79	-743.08		B3a	-1380	-3036	29.64	4.52	19.31	-671.28
	A3b	-320	-704	28.56	4.36	27.00	-161.55		B3b	-1225	-2695	25.00	3.81	26.75	-706.48
	A3c	-660	-1452	25.50	3.89	20.12	-373.17		B3c	-3155	-6941	33.48	5.11	20.20	-1358.68
	Average	-773.33	-1701.33	26.69	4.07	20.64	**-417.81**	55.67	**Average**	-1920.00	-4224.00	29.37	4.48	22.09	**-942.43**
4	T1	-530	-1166	28.08	4.28	23.31	-272.13		B4a	-1410	-3102	28.60	4.36	25.67	-710.81
	T2	-220	-484	28.08	4.28	25.91	-112.96		B4b	-1410	-3102	32.00	4.88	25.94	-635.29
	T3	-50	-110	25.00	3.81	25.06	-28.84		B4c	-2060	-4532	33.06	5.04	27.19	-898.39
	Average	-266.67	-586.67	27.05	4.13	24.76	**-142.12**	81.08	**Average**	-1626.67	-3578.67	31.22	4.76	26.27	**-751.22**

Note: Data are negative due to they are compression loads/ strength values.

Flexural strength test

WET CONDITION									DRY CONDITION							
Sample	Load (kg)	Load (lbs.)	Span (in.)	b (cm)xd	b (i)xdxd	2 (bxdxd)	*R* (psi)	% *Diff*	Sample	Load (kg)	Load (lbs.)	Span (in.)	b (cm)xd	b (i)xdxd	2 (bxdxd)	*R* (psi)
H1a	0	0	2	5.5x2.7	2.39	4.78	0.00		I1a	0	0	2	5.5x2.5	2.05	4.10	0.00
H1b	0	0	2	5.8x3.2	3.54	7.08	0.00		I1b	0	0	2	5.5x2.4	1.89	3.78	0.00
H1c	0	0	2	5.6x2.7	2.43	4.87	0.00		I1c	0	0	2	5.7x2.9	2.86	5.71	0.00
Ave	**0**	0	**2**		2.79	5.58	**0.00**	**n/a**	**Ave**	**0**	0	**2**		2.26	4.53	**0.00**
H2a	0	0	2	5.0x2.8	2.34	4.67	0.00		I2a	-20	-44	2	6.0x3.0	3.22	6.44	-41.01
H2b	-25	-55	2	5.4x2.5	2.01	4.02	-82.02		I2b	-60	-132	2	5.5x3.0	2.95	5.90	-134.22
H2c	0	0	2	5.3x2.8	2.48	4.95	0.00		I2c	0	0	2	5.0x3.0	2.68	5.36	0.00
Ave	**-8.33**	-18.33	**2**		2.27	4.55	**-24.18**	**59.47**	**Ave**	**-26.67**	-58.67	**2**		2.95	5.90	**-59.65**
H3a	0	0	2	5.9x3.0	3.17	6.33	0.00		I3a	0	0	2	5.3x3.1	3.04	6.07	0.00
H3b	0	0	2	5.8x2.8	2.71	5.42	0.00		I3b	-50	-110	2	5.4x3.0	2.90	5.79	-113.92
H3c	0	0	2	5.3x3.0	2.84	5.69	0.00		I3c	0	0	2	5.6x3.0	3.00	6.01	0.00
Ave	**0**	0	**2**		2.91	5.81	**0.00**	**100.00**	**Ave**	**-17**	-36.67	**2**		2.98	5.96	**-36.93**
H4a	0	0	2	4.7x3.1	2.69	5.38	0.00		I4a	0	0	2	5.5x2.7	2.39	4.78	0.00
H4b	0	0	2	5.7x2.8	2.66	5.33	0.00		I4b	0	0	2	5.2x2.8	2.43	4.86	0.00
H4c	0	0	2	5.6x2.6	2.26	4.51	0.00		I4c	0	0	2	5.4x3.2	3.30	6.59	0.00
Ave	**0**	0	**2**		2.54	5.07	**0.00**	**n/a**	**Ave**	**0**	0	**2**		2.71	5.41	**0.00**

Data Set 4: Number of cases and standard deviation of the averages of data

Sample	%porosity			%WA			WAC			Max rate WA			Max rate WE		
	Ave	Std dev	n	Ave	Std dev	n	Ave	Std dev	n	Ave	Std dev	n	Ave	Std dev	n
1	21.47	2.81	3	8.98	1.68	3	10.40	2.61	3	131.40	51.44	3	11.20	3.67	3
2	16.54	1.44	3	6.09	0.57	3	7.37	0.59	3	118.60	18.44	3	7.00	3.31	3
3	20.64	6.12	3	8.27	3.14	3	13.66	1.34	3	247.80	26.58	3	5.40	5.72	3
4	24.76	1.33	3	12.31	1.19	3	13.66	1.34	3	247.80	26.58	3	5.40	5.72	3

Sample	%porosity			Wet comp strength			%porosity			Dry comp strength		
	Ave	Std dev	n	Ave	Std dev	n	Ave	Std dev	n	Ave	Std dev	n
1	20.59	4.02	2	-49.31	12.65	2	18.19	3.97	2	-396.87	14.74	2
2	16.54	1.44	3	-942.71	224.54	3	21.00	2.95	3	-480.80	261.73	3
3	20.64	6.12	3	-425.93	294.33	3	22.09	4.06	3	-912.15	387.11	3
4	24.76	1.33	3	-137.98	123.56	3	26.27	0.81	3	-748.17	135.47	3

Sample	Wet flex strength			Dry flex strength		
	Ave	Std dev	n	Ave	Std dev	n
1	0.00	0.00	3	0.00	0.00	3
2	-24.18	47.36	3	-59.65	68.78	3
3	0.00	0.00	3	-36.93	65.77	3
4	0.00	0.00	3	0.00	0.00	3

Sample	%porosity			WVT		
	Ave	Std dev	n	Ave	Std dev	n
1	24.60	8.46	3	5.04	0.58	3
2	22.17	3.65	3	6.45	1.42	3
3	19.13	3.89	3	4.41	1.09	3
4	26.06	1.06	3	5.80	0.27	3

Data Set 5: Correlation analyses

Correlations (Spearman's *rho*)

	POROSITY	WA	WAC	WA RATE	WE RATE	WVT	SiO_2	Al_2O_3	Fe_2O_3	Dry Strength	Wet Strength
POROSITY	1.000	.965**	.951**	.636**	.162	.559	.000	.400	-.600	.400	-.345
WA	.965**	1.000	.972**	727**	.134	-.077	.000	.400	-.600	.464	-.691*
WAC	.951**	.972**	1.000	.727**	.197	-.070	.000	.400	-.600	.409	-.636*
WA RATE*	.636**	.727**	.727**	1.000	-.134	.147	.000	.400	-.600	.327	-.418
WE RATE	.162	.134	.197	-.134	1.000	-.063	.400	-.800	-.200	.037	.092
WVT	.559	-.077	-.070	.147	.147	1.000	.000	.400	-.200	-.400	.400
SiO_2	.000	.000	.000	.000	.400	.000	1.000	-.800	-.800	1.000**	.400
Al_2O_3	.400	.400	.400	.400	-.800	.400	-.800	1.000	.400	-.800	-.200
Fe_2O_3	-.600	-.600	-.600	-.600	-.200	-.200	-.800	.400	1.000	-.800	-.800
Dry Strength	.400	.464	.409	.327	.037	-.400	1.000**	-.800	-.800	1.000	-.045
Wet Strength	-.345	-.691*	-.636*	-.418	.092	.400	.400	-.200	-.800	-.045	1.000

Correlations

* Correlation is significant at the .05 level (2-tailed).

** Correlation is significant at the .01 level (2-tailed).

Note:

The correlations were calculated as follows:

- The correlations between percentage porosity, percentage water absorption, water absorption capacity, water absorption rate and water evaporation rate (the number of samples was 12)
- The correlations between the compressive strength in both conditions of the tested laterite samples and their percentage porosity, percentage water absorption, water absorption capacity, water absorption rate and water evaporation rate (the number of samples was 11)
- The correlations between the main chemical composition of four sets of laterite and their compression strength in both conditions, percentage porosity, percentage water absorption, water absorption capacity, water absorption rate and water evaporation rate (the number of samples was 4)
- The correlations between the water vapour transmission capacity of four sets of laterite and their main chemical composition and compressive strength in both conditions (the number of samples was 4)
- The correlations between the water vapour transmission capacity of the tested laterite and their porosity, percentage water absorption, water absorption capacity, water absorption rate and water evaporation rate (the number of samples was 12)

APPENDIX IV
A GLOSSARY
OF
HISTORIC MASONRY DETERIORATION PROBLEMS[1]

Blistering

This term is used to describe swelling accompanied by rupturing of a thin uniform skin both across and parallel to the bedding plane. Blistering is generally found on a surface close to the ground. It may remain a relatively constant condition scattered over the masonry surface, but it eventually results in greater surface peeling (exfoliation, delamination or spalling).

Cracking

This term is used to describe narrow fissures from 1/16 to ½ inch wide in a block of masonry. Small cracks within a single block of masonry may not be serious, but longer and wider cracks extending over a larger area can lead to a greater damage such as masonry breaking or structural collapse.

Crumbling

This term is used to describe the condition of brittleness or tendency of masonry to break up or dissolve. It may be caused by an inherent weakness of the masonry and gradual dissolution of cementing material, or it may be the result of external factors, such as salts or moisture, that can affect the strength or durability of the masonry.

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[1] The content of this appendix is modified from Anne E. Grimmer's book: *A Glossary of Historic Masonry Deterioration Problems and Preservation Treatments* (1984).

Delamination

This term is used to describe a condition of stone in which the outer surface of the stone splits apart into laminae or thin layers and peels off the face of the stone. Because of their layered composition, this may be a natural condition of sedimentary stones. The presence of clay-rich layer can accelerate the process of delamination. Delamination takes place along the natural bedding planes of the stone.

Delamination differs from spalling in that it is a condition confined to natural stone and it is not a condition that occurs in manufactured products, such as brick.

Exfoliation

This term is used to describe natural stone deterioration: peeling, scaling, or flaking off of the stone surface in thin layers. Exfoliation is caused by the expansion and contraction of trapped moisture, the chemical action of stone composition, or the stone weathering. The process often occurs along natural bedding planes, resulting in an unevenly layered surface.

Flaking

This term is used to describe an early stage of peeling, exfoliation, delamination, or spalling. The appearance of detachment of small, flat, thin pieces of the outer layers of stone from a larger piece of stone can be explained as flaking. The process is usually caused by capillary moisture or freeze-thaw cycles that occur within the stone. It commonly occurs in masonry coatings, the areas that have lost the adhesion between the coating and the masonry substrate, or masonry on which a water repellant has been applied resulting in trapped moisture.

Friability

This term is used to describe an inherent characteristic of some types of stone, such as sandstone or limestone, which have a tendency to break up, crumble or powder easily.

Sugaring

This term is used to describe a characteristic of some masonry having gradual surface disintegration problem. The process may be caused by salts dissolved in and transported through the stone by moisture, and consequently results in dissolution of cementing material.

APPENDIX V

DATA OF EFFECTS OF SOME ENVIRONMENTAL DECAY AGENTS ON LATERITE IN CHAPTER V

WET-DRY CYCLE TEST

SAMPLE SET: D

		Mo	1	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Md
1	a	223.45	221.15	216.10	213.25	212.55	211.85	211.35	210.85	210.55	210.10	209.95	209.40	208.75	208.10	207.50	206.95	206.45	206.40	
	b	249.35	246.10	239.00	235.40	232.90	231.80	230.55	229.45	228.50	227.70	227.15	226.55	226.00	225.20	224.55	223.50	222.70	222.00	
	c	306.90	304.55	302.60	301.45	301.25	301.00	300.80	300.65	300.45	300.20	300.15	300.00	299.80	299.70	299.60	299.50	299.00	299.00	
	Ave	**259.90**	257.27	252.57	250.03	248.90	248.22	247.57	246.98	246.50	246.00	245.75	245.32	244.85	244.33	243.88	243.32	242.72	**242.47**	**242.47**
	%lost		1.01	1.08	1.00	0.45	0.27	0.26	0.24	0.20	0.20	0.10	0.18	0.19	0.21	0.18	0.23	0.25	**0.10**	
	%TL		1.04	2.82	3.80	4.23	4.50	4.75	4.97	5.16	5.35	5.44	5.61	5.79	5.99	6.16	6.38	6.61	**6.71**	
2	a	235.90	235.75	235.60	224.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	b	262.55	261.45	260.00	259.25	258.80	258.40	258.15	257.60	257.40	257.25	257.10	257.00	256.70	256.45	256.30	256.00	255.25	255.00	
	c	285.55	284.10	282.00	281.55	281.20	280.85	280.45	280.20	280.05	279.90	279.80	279.75	279.65	279.60	279.60	279.50	278.70	279.00	
	Ave	**261.33**	260.43	259.20	255.20	180.00	179.75	179.53	179.27	179.15	179.05	178.97	178.92	178.78	178.68	178.63	178.50	177.98	178.00	**178.00**
	%lost		0.34	0.17	1.54	29.47	0.14	0.12	0.15	0.07	0.06	0.05	0.03	0.07	0.06	0.03	0.07	0.29	**-0.01**	
	%TL		0.34	0.82	2.35	31.12	31.22	31.30	31.40	31.45	31.49	31.52	31.54	31.59	31.63	31.65	31.70	31.89	**31.89**	
3	a	322.65	319.80	314.20	311.35	309.80	308.10	307.55	306.60	306.25	305.80	305.25	304.80	304.45	301.00	300.80	300.65	300.10	300.40	
	b	316.85	315.30	313.40	313.15	312.90	312.75	312.65	312.50	312.30	312.20	312.20	312.10	312.15	312.10	311.10	310.95	310.30	311.20	
	c	349.75	347.65	344.20	343.40	342.70	341.85	338.80	337.60	335.85	334.30	332.75	330.80	328.90	327.20	325.40	323.70	321.80	323.00	
	Ave	**329.75**	327.58	323.93	322.63	321.80	320.90	319.67	318.90	318.13	317.43	316.73	315.90	315.17	313.43	312.43	311.77	310.73	311.53	**310.00**
	%lost		0.66	0.55	0.40	0.26	0.28	0.38	0.24	0.24	0.22	0.22	0.26	0.23	0.55	0.32	0.21	0.33	**-0.26**	
	%TL		1.04	1.76	2.16	2.41	2.68	3.06	3.29	3.52	3.74	3.95	4.20	4.42	4.95	5.25	5.45	5.77	**5.52**	
4	a	302.45	301.30	297.85	297.00	296.30	296.05	295.65	295.30	294.85	294.30	291.20	209.40	208.75	208.10	207.50	0.00	0.00	0.00	
	b	250.70	249.80	245.95	245.60	245.35	245.15	244.90	244.70	244.20	243.45	242.60	242.35	241.95	241.60	241.15	240.50	239.60	238.70	
	c	294.95	293.50	291.05	289.30	288.10	287.40	286.70	285.85	285.30	284.55	283.60	282.00	281.30	280.70	280.15	279.70	279.10	279.50	
	Ave	**282.70**	281.53	278.28	277.30	276.58	276.20	275.75	275.28	274.78	274.10	272.47	244.58	244.00	243.47	242.93	173.40	172.90	172.73	**172.00**
	%lost		0.41	0.65	0.35	0.26	0.14	0.16	0.17	0.18	0.25	0.60	10.23	0.24	0.22	0.22	28.62	0.29	**0.10**	
	%TL		1.04	1.56	1.91	2.16	2.30	2.46	2.62	2.80	3.04	3.62	13.48	13.69	13.88	14.07	38.66	38.84	**38.90**	

SALT CRYSTALIZATION TEST

SET: F			Mo	cycle 1	cycle 2	cycle 3	cycle 4	cycle 5	cycle 6
1	a	Wet		146.60	147.30	147.80	148.90	148.40	133.70
		Dry	134.15	134.40	135.10	135.00	136.90	136.10	**70.30**
	b	Wet		156.20	156.60	156.45	156.55	156.70	156.90
		Dry	142.15	142.15	142.90	141.70	141.20	140.80	**0.00**
	c	Wet		151.80	152.30	152.90	154.70	153.30	153.50
		Dry	138.50	138.50	139.00	138.80	134.70	134.50	**0.00**
Ave		Wet		151.53	152.07	152.38	153.38	152.80	148.03
		Dry	138.27	138.35	139.00	138.50	137.60	137.13	**23.43**
		%lost		-0.06	-0.47	0.36	0.65	0.34	**82.91**
		%TL		-0.06	-0.53	-0.17	0.48	0.82	**83.05**

SET: F			Mo	cycle 1	cycle 2	cycle 3	cycle 4	cycle 5	cycle 6	cycle 7	cycle 8	cycle 9	cycle 10
2	a	Wet		168.80	169.80	169.00	170.90	169.20	164.90	162.60	160.75	155.80	69.70
		Dry	157.25	157.10	157.35	155.85	155.95	153.00	153.30	149.55	143.70	140.40	**57.00**
	b	Wet		165.70	166.50	165.90	166.65	166.00	166.70	166.70	160.90		
		Dry	154.10	154.00	153.90	153.90	153.50	153.20	151.95	149.80	**73.00**		
	c	Wet		217.40	219.20	218.45	219.20	219.50	217.90	211.50	133.25		
		Dry	206.40	205.90	206.15	206.20	206.30	206.55	204.00	197.50	**0.00**		
Ave		Wet		183.97	185.17	184.45	185.58	184.90	183.17	180.27	151.63	51.93	23.23
		Dry	172.58	172.33	172.47	171.98	171.92	170.92	169.75	165.62	72.23	46.80	**19.00**
		%lost		0.14	-0.08	0.28	0.04	0.58	0.68	2.43	56.39	35.21	**59.40**
		%TL		0.14	0.07	0.35	0.39	0.97	1.64	4.04	58.15	72.88	**88.99**

SET: F			Mo	cycle 1	cycle 2	cycle 3	cycle 4	cycle 5	cycle 6
3	a	Wet		180.25	181.90	181.00	180.95	180.10	**0.00**
		Dry	166.35	166.40	152.90	165.30	164.70	155.30	0.00
	b	Wet		162.50	162.70	162.00	164.00	161.70	**0.00**
		Dry	153.40	142.15	152.15	151.30	150.85	150.00	0.00
	c	Wet		181.10	182.05	181.95	182.95	183.20	**0.00**
		Dry	170.90	170.95	170.35	171.70	171.65	171.60	0.00
Ave		Wet		174.62	175.55	174.98	175.97	175.00	0.00
		Dry	163.55	159.83	158.47	162.77	162.40	158.97	**0.00**
		%lost		2.27	0.86	-2.71	0.23	2.11	**100.00**
		%TL		2.27	3.11	0.48	0.70	2.80	**100.00**

SET: F			Mo	cycle 1	cycle 2	cycle 3	cycle 4	cycle 5	cycle 6
4	a	Wet		146.50	147.30	146.45	151.00	**0.00**	
		Dry	133.50	133.40	133.60	133.50	134.90	0.00	
	b	Wet		146.25	147.00	145.35	148.85	148.50	68.40
		Dry	132.10	132.10	132.10	130.25	133.15	132.70	**62.80**
	c	Wet		153.50	153.75	151.95	137.90	**0.00**	
		Dry	139.90	139.90	139.90	137.15	114.50	0.00	
Ave		Wet		148.75	149.35	147.92	145.92	49.50	**22.80**
		Dry	135.17	135.13	135.20	133.63	127.52	44.23	**20.93**
		%lost		0.02	-0.05	1.16	4.58	65.31	**52.68**
		%TL		0.02	-0.02	1.13	5.66	67.27	**84.51**

SUMMARY OF SALT CRYSTALIZATION TEST

Sample			Mo	cycle 1	cycle 2	cycle 3	cycle 4	cycle 5	cycle 6	cycle 7	cycle 8	cycle 9	cycle 10
1	a	Dry	134.15	134.40	135.10	135.00	136.90	136.10	**70.30**				
	b	Dry	142.15	142.15	142.90	141.70	141.20	140.80	**0.00**				
	c	Dry	138.50	138.50	139.00	138.80	134.70	134.50	**0.00**				
2	a	Dry	157.25	157.10	157.35	155.85	155.95	153.00	153.30	149.55	143.70	140.40	**57.00**
	b	Dry	154.10	154.00	153.90	153.90	153.50	153.20	151.95	149.80	**73.00**		
	c	Dry	206.40	205.90	206.15	206.20	206.30	206.55	204.00	197.50	**0.00**		
3	a	Dry	166.35	166.40	152.90	165.30	164.70	155.30	**0.00**				
	b	Dry	153.40	142.15	152.15	151.30	150.85	150.00	**0.00**				
	c	Dry	170.90	170.95	170.35	171.70	171.65	171.60	**0.00**				
4	a	Dry	133.50	133.40	133.60	133.50	134.90	**0.00**					
	b	Dry	132.10	132.10	132.10	130.25	133.15	132.70	**62.80**				
	c	Dry	139.90	139.90	139.90	137.15	114.50	**0.00**					

APPENDIX VI

DATA OF DETERIORATION ASSESSMENTS OF LATERITE FAÇADES IN CHAPTER VI

Data Set 1: Chemical composition

Code	Sample	Chemical Compound (%)					Ratio	
		SiO_2	Al_2O_3	Fe_2O_3	K_2O	MnO	SiO_2: Al_2O_3	SiO_2: Fe_2O_3
WTX	1	45.38	7.26	36.04	0.17	1.75	6.25	1.26
WTN	2	39.77	9.02	39.78	0.20	1.30	4.41	1.00
WMX	3	36.02	8.89	44.17	0.11	0.20	4.05	0.82
WMN	4	38.66	8.59	42.10	0.12	0.22	4.50	0.92
WBX	5	53.05	7.06	30.43	0.16	0.88	7.51	1.74
WBN	6	51.48	7.35	31.42	0.16	1.02	7.00	1.64
NMX	7	47.04	8.14	33.29	0.36	1.80	5.78	1.41
NMN	8	46.70	8.05	34.29	0.33	1.39	5.80	1.36
NTX	9	46.93	7.35	34.74	0.14	1.40	6.39	1.35
NTN	10	49.10	7.45	32.56	0.14	1.64	6.59	1.51
NBX	11	46.11	7.93	35.50	0.30	1.06	5.81	1.30
NBN	12	42.22	8.58	37.69	0.33	1.62	4.92	1.12
ETX	13	41.47	7.96	39.20	0.14	1.29	5.21	1.06
ETN	14	42.07	8.77	38.10	0.19	1.31	4.80	1.10
EMX	15	39.63	10.33	38.94	0.31	0.71	3.84	1.02
EMN	16	40.20	9.24	39.48	0.21	1.08	4.35	1.02
EBX	17	45.69	8.05	34.79	0.17	2.09	5.68	1.31
EBN	18	46.30	7.74	35.29	0.15	1.57	5.98	1.31
STX	19	49.37	6.89	33.81	0.12	1.01	7.17	1.46
STN	20	47.90	6.96	34.87	0.13	1.25	6.88	1.37
SMX	21	48.83	7.11	34.15	0.14	1.27	6.87	1.43
SMN	22	46.91	7.96	33.62	0.16	2.10	5.89	1.40
SBX	23	45.61	6.93	35.31	0.15	2.52	6.58	1.29
SBN	24	48.75	6.68	32.25	0.17	2.96	7.30	1.51

Data Set 2: Water absorption capacity and the percentage porosity

WATER ABSORPTION CAPACITY - POROSITY CALCULATION

	Mo (g)	Mmax (g)	Md (g)	% WA	WAC	Mo-Md	% Lost	Mp = Vp	Va (cc)	% voids
SAMPLE: 1	260.93	282.80	259.32	8.38	9.05	1.62	0.62	21.87	118.30	18.46
d	257.75	277.00	256.50	7.47	7.99	1.25	0.48	19.25	108.00	17.82
e	261.45	284.20	260.35	8.70	9.16	1.10	0.42	22.75	124.60	18.26
f	263.60	287.20	261.10	8.95	10.00	2.50	0.95	23.60	122.30	19.30
Average	260.93	282.80	259.32	8.38	9.05	1.62	0.62	21.87	118.30	18.46
SAMPLE: 2	234.07	256.92	231.87	9.76	10.81	2.20	0.94	22.85	107.00	21.39
d	236.40	258.80	234.00	9.48	10.60	2.40	1.02	22.40	111.20	20.14
e	248.05	272.05	245.60	9.68	10.77	2.45	0.99	24.00	110.40	21.74
f	217.75	239.90	216.00	10.17	11.06	1.75	0.80	22.15	99.40	22.28
Average	234.07	256.92	231.87	9.76	10.81	2.20	0.94	22.85	107.00	21.39
SAMPLE: 3	238.78	263.28	235.52	10.26	11.83	3.27	1.37	24.50	109.50	22.40
d	219.90	241.80	216.05	9.96	11.92	3.85	1.75	21.90	101.60	21.56
e	232.45	257.10	228.50	10.60	12.52	3.95	1.70	24.65	103.80	23.75
f	264.00	290.95	262.00	10.21	11.05	2.00	0.76	26.95	123.10	21.89
Average	238.78	263.28	235.52	10.26	11.83	3.27	1.37	24.50	109.50	22.40
SAMPLE: 4	253.47	277.77	251.20	9.59	10.69	2.27	0.89	24.30	107.30	22.67
d	239.70	263.60	236.40	9.97	11.51	3.30	1.38	23.90	104.10	22.96
e	286.85	311.80	286.00	8.70	9.02	0.85	0.30	24.95	114.20	21.85
f	233.85	257.90	231.20	10.28	11.55	2.65	1.13	24.05	103.60	23.21
Average	253.47	277.77	251.20	9.59	10.69	2.27	0.89	24.30	107.30	22.67
SAMPLE: 5	276.82	301.13	274.48	8.78	9.74	2.33	0.84	24.32	119.03	20.53
d	252.25	274.50	250.50	8.82	9.58	1.75	3.74	22.25	106.40	20.91
e	261.20	285.90	259.15	9.46	10.32	2.05	0.78	24.70	114.30	21.61
f	317.00	343.00	313.80	8.20	9.31	3.20	3.71	26.00	136.40	19.06
Average	276.82	301.13	274.48	8.78	9.74	2.33	0.84	24.32	119.03	20.53
SAMPLE: 6	242.10	260.73	239.97	7.70	8.65	2.13	0.88	18.63	107.77	17.28
d	268.65	288.85	266.00	7.52	8.59	2.65	0.99	20.20	116.60	17.32
e	234.95	253.95	233.00	8.09	8.99	1.95	0.83	19.00	107.40	17.69
f	222.70	239.40	220.90	7.50	8.37	1.80	0.81	16.70	99.30	16.82
Average	242.10	260.73	239.97	7.70	8.65	2.13	0.88	18.63	107.77	17.28
SAMPLE: 7	250.20	269.30	247.47	7.63	8.82	2.73	1.09	19.10	104.33	18.28
d	270.65	292.15	267.70	7.94	9.13	2.95	1.09	21.50	110.40	19.47
e	260.45	279.45	257.50	7.30	8.52	2.95	1.13	19.00	108.20	17.56
f	219.50	236.30	217.20	7.65	8.79	2.30	1.05	16.80	94.40	17.80
Average	250.20	269.30	247.47	7.63	8.82	2.73	1.09	19.10	104.33	18.28
SAMPLE: 8	238.08	256.88	235.00	7.90	9.30	3.08	1.30	18.80	106.57	17.67
d	245.90	266.15	242.50	8.24	9.75	3.40	1.38	20.25	102.60	19.74
e	236.55	255.60	233.50	8.05	9.46	3.05	1.29	19.05	110.50	17.24
f	231.80	248.90	229.00	7.38	8.69	2.80	1.21	17.10	106.60	16.04
Average	238.08	256.88	235.00	7.90	9.30	3.08	1.30	18.80	106.57	17.67

WATER ABSORPTION CAPACITY - POROSITY CALCULATION

(continued)

	Mo (g)	Mmax (g)	Md (g)	% WA	WAC	Mo-Md	% Lost	Mp = Vp	Va (cc)	% voids
SAMPLE: 9	261.23	285.75	259.15	9.29	10.06	2.08	1.86	24.53	116.60	21.21
d	300.55	330.40	296.40	9.93	11.47	4.15	3.72	29.85	140.00	21.32
e	221.90	241.10	221.90	8.65	8.65	0.00	0.00	19.20	93.20	20.60
f	232.60	253.60	230.90	9.03	9.83	1.70	0.73	21.00	96.70	21.72
Average	261.23	285.75	259.15	9.29	10.06	2.08	1.86	24.53	116.60	21.21
SAMPLE: 10	227.23	248.85	225.80	9.51	10.32	1.43	0.63	21.62	94.00	23.28
d	268.00	290.60	266.00	8.43	9.25	2.00	1.78	22.60	109.80	20.58
e	211.50	230.40	210.25	8.94	9.58	1.25	1.66	18.90	88.60	21.33
f	202.20	225.55	201.15	11.55	12.13	1.05	1.75	23.35	83.60	27.93
Average	227.23	248.85	225.80	9.51	10.32	1.43	0.63	21.62	94.00	23.28
SAMPLE: 11	266.75	284.90	264.13	6.80	7.85	2.62	0.98	18.15	118.00	15.38
d	280.10	299.70	277.00	7.00	8.19	3.10	3.12	19.60	124.60	15.73
e	270.00	288.30	267.60	6.78	7.74	2.40	3.16	18.30	121.35	15.08
f	250.15	266.70	247.80	6.62	7.63	2.35	3.20	16.55	108.05	15.32
Average	266.75	284.90	264.13	6.80	7.85	2.62	0.98	18.15	118.00	15.38
SAMPLE: 12	258.60	277.92	257.05	7.47	8.13	1.55	0.60	19.32	109.80	17.63
d	250.20	269.20	248.50	7.59	8.33	1.70	2.76	19.00	108.00	17.59
e	241.65	260.00	240.20	7.59	8.24	1.45	3.00	18.35	100.80	18.20
f	283.95	304.55	282.45	7.25	7.82	1.50	2.84	20.60	120.60	17.08
Average	258.60	277.92	257.05	7.47	8.13	1.55	0.60	19.32	109.80	17.63
SAMPLE: 13	265.57	288.60	264.37	8.67	9.16	1.20	0.45	23.03	109.87	20.98
d	274.40	297.50	273.75	8.42	8.68	0.65	0.24	23.10	111.40	20.74
e	228.30	248.05	227.00	8.65	9.27	1.30	0.57	19.75	93.00	21.24
f	294.00	320.25	292.35	8.93	9.54	1.65	0.56	26.25	125.20	20.97
Average	265.57	288.60	264.37	8.67	9.16	1.20	0.45	23.03	109.87	20.98
SAMPLE: 14	257.40	280.00	255.83	8.78	9.46	1.57	0.61	22.60	107.27	21.06
d	267.70	290.60	266.25	8.55	9.15	1.45	0.54	22.90	112.80	20.30
e	268.95	293.50	268.25	9.13	9.41	0.70	0.26	24.55	109.00	22.52
f	235.55	255.90	233.00	8.64	9.83	2.55	1.08	20.35	100.00	20.35
Average	257.40	280.00	255.83	8.78	9.46	1.57	0.61	22.60	107.27	21.06
SAMPLE: 15	272.57	297.18	269.67	9.03	10.22	2.90	1.06	24.62	124.72	19.79
d	253.60	277.55	251.15	9.44	10.51	2.45	0.97	23.95	114.40	20.94
e	286.00	311.00	283.15	8.74	9.84	2.85	1.00	25.00	131.55	19.00
f	278.10	303.00	274.70	8.95	10.30	3.40	1.22	24.90	128.20	19.42
Average	272.57	297.18	269.67	9.03	10.22	2.90	1.06	24.62	124.72	19.79
SAMPLE: 16	231.90	259.03	229.30	11.70	12.98	2.60	1.12	27.13	108.40	25.47
d	255.80	284.40	252.30	11.18	12.72	3.50	1.37	28.60	118.80	24.07
e	219.25	249.00	217.80	13.57	14.33	1.45	0.66	29.75	92.80	32.06
f	220.65	243.70	217.80	10.45	11.89	2.85	1.29	23.05	113.60	20.29
Average	231.90	259.03	229.30	11.70	12.98	2.60	1.12	27.13	108.40	25.47

WATER ABSORPTION CAPACITY - POROSITY CALCULATION
(continued)

	Mo (g)	Mmax (g)	Md (g)	% WA	WAC	Mo-Md	% Lost	Mp = Vp	Va (cc)	% voids
SAMPLE: 17	220.78	242.40	218.73	9.79	10.82	2.05	0.93	21.62	97.25	22.35
d	216.95	238.00	214.50	9.70	10.96	2.45	1.13	21.05	91.20	23.08
e	205.00	225.55	203.60	10.02	10.78	1.40	0.68	20.55	88.35	23.26
f	240.40	263.65	238.10	9.67	10.73	2.30	0.96	23.25	112.20	20.72
Average	220.78	242.40	218.73	9.79	10.82	2.05	0.93	21.62	97.25	22.35
SAMPLE: 18	259.93	283.77	257.73	9.17	10.11	2.20	0.85	23.83	115.20	20.73
d	249.65	273.40	247.45	9.51	10.49	2.20	0.88	23.75	115.20	20.62
e	268.40	291.70	266.25	8.68	9.56	2.15	0.80	23.30	120.00	19.42
f	261.75	286.20	259.50	9.34	10.29	2.25	0.86	24.45	110.40	22.15
Average	259.93	283.77	257.73	9.17	10.11	2.20	0.85	23.83	115.20	20.73
SAMPLE: 19	263.98	285.43	262.23	8.13	8.87	1.75	0.66	21.45	107.72	19.96
d	277.15	298.90	276.00	7.85	8.30	1.15	0.41	21.75	115.45	18.84
e	260.65	281.75	259.40	8.10	8.62	1.25	0.48	21.10	105.50	20.00
f	254.15	275.65	251.30	8.46	9.69	2.85	1.12	21.50	102.20	21.04
Average	263.98	285.43	262.23	8.13	8.87	1.75	0.66	21.45	107.72	19.96
SAMPLE: 20	239.45	260.35	237.22	8.73	9.75	2.23	0.93	20.90	101.70	20.54
d	236.00	255.44	234.75	8.24	8.81	1.25	0.53	19.44	99.20	19.60
e	243.55	265.40	241.75	8.97	9.78	1.80	0.74	21.85	104.90	20.83
f	238.80	260.20	235.15	8.96	10.65	3.65	1.53	21.40	101.00	21.19
Average	239.45	260.35	237.22	8.73	9.75	2.23	0.93	20.90	101.70	20.54
SAMPLE: 21	280.75	303.13	274.30	7.97	10.52	6.45	2.30	22.38	125.53	17.82
d	272.95	293.50	267.30	7.53	9.80	5.65	2.07	20.55	116.80	17.59
e	273.75	296.70	266.00	8.38	11.54	7.75	2.83	22.95	127.30	18.03
f	295.55	319.20	289.60	8.00	10.22	5.95	2.01	23.65	132.50	17.85
Average	280.75	303.13	274.30	7.97	10.52	6.45	2.30	22.38	125.53	17.82
SAMPLE: 22	276.75	301.97	274.87	9.11	9.84	1.88	0.68	25.22	114.63	22.01
d	293.50	320.50	290.20	9.20	10.44	3.30	1.12	27.00	123.70	21.83
e	256.60	279.50	255.40	8.92	9.44	1.20	0.47	22.90	110.20	20.78
f	280.15	305.90	279.00	9.19	9.64	1.15	0.41	25.75	110.00	23.41
Average	276.75	301.97	274.87	9.11	9.84	1.88	0.68	25.22	114.63	22.01
SAMPLE: 23	284.97	311.43	282.23	9.29	10.32	2.73	0.96	26.47	121.82	21.69
d	301.75	331.70	297.80	9.93	11.38	3.95	1.31	29.95	127.65	23.46
e	285.15	310.30	283.40	8.82	9.49	1.75	0.61	25.15	118.30	21.26
f	268.00	292.30	265.50	9.07	10.09	2.50	0.93	24.30	119.50	20.33
Average	284.97	311.43	282.23	9.29	10.32	2.73	0.96	26.47	121.82	21.69
SAMPLE: 24	220.80	239.00	217.20	8.24	10.12	3.60	1.63	18.20	98.20	18.23
d	229.00	236.40	224.00	3.23	5.54	5.00	2.18	7.40	91.40	8.10
e	212.00	235.60	208.80	11.13	12.84	3.20	1.51	23.60	96.10	24.56
f	221.40	245.00	218.80	10.66	11.97	2.60	1.17	23.60	107.10	22.04
Average	220.80	239.00	217.20	8.24	10.12	3.60	1.63	18.20	98.20	18.23

WATER ABSORPTION CAPACITY - POROSITY CALCULATION

(continued)

	Mo (g)	Mmax (g)	Md (g)	% WA	WAC	Mo-Md	% Lost	Mp = Vp	Va (cc)	% voids
SAMPLE: 1	281.93	305.12	280.67	8.22	8.73	1.27	0.45	23.18	124.65	18.60
a	261.95	284.10	259.80	8.46	9.35	2.15	0.82	22.15	118.70	18.66
b	301.40	325.50	300.20	8.00	8.43	1.20	0.40	24.10	127.90	18.84
c	282.45	305.75	282.00	8.25	8.42	0.45	0.16	23.30	127.35	18.30
Average	281.93	305.12	280.67	8.22	8.73	1.27	0.45	23.18	124.65	18.60
SAMPLE: 2	280.62	305.93	279.28	9.02	9.56	1.33	0.48	25.32	124.20	20.40
a	277.45	306.85	276.20	10.60	11.10	1.25	0.45	29.40	124.40	23.63
b	278.20	302.95	277.00	8.90	9.37	1.20	0.43	24.75	121.40	20.39
c	286.20	308.00	284.65	7.62	8.20	1.55	0.54	21.80	126.80	17.19
Average	280.62	305.93	279.28	9.02	9.56	1.33	0.48	25.32	124.20	20.40
SAMPLE: 3	229.53	251.25	226.23	9.46	11.13	3.30	1.44	21.72	99.13	22.03
a	198.20	219.00	195.00	10.49	12.31	3.20	1.61	20.80	86.60	24.02
b	250.50	272.75	246.00	8.88	10.87	4.50	1.80	22.25	104.40	21.31
c	239.90	262.00	237.70	9.21	10.22	2.20	0.92	22.10	106.40	20.77
Average	229.53	251.25	226.23	9.46	11.13	3.30	1.44	21.72	99.13	22.03
SAMPLE: 4	253.15	278.32	251.42	9.94	10.68	1.73	0.68	25.17	109.77	22.90
a	240.30	263.65	239.95	9.72	9.88	0.35	0.15	23.35	106.60	21.90
b	260.45	288.10	258.30	10.62	11.54	2.15	0.83	27.65	114.00	24.25
c	258.70	283.20	256.00	9.47	10.63	2.70	1.04	24.50	108.70	22.54
Average	253.15	278.32	251.42	9.94	10.68	1.73	0.68	25.17	109.77	22.90
SAMPLE: 5	294.92	319.62	293.88	8.38	8.76	1.03	0.35	24.70	123.93	19.95
a	294.15	317.00	293.35	7.77	8.06	0.80	0.27	22.85	121.40	18.82
b	295.60	319.70	294.50	8.15	8.56	1.10	0.37	24.10	128.10	18.81
c	295.00	322.15	293.80	9.20	9.65	1.20	0.41	27.15	122.30	22.20
Average	294.92	319.62	293.88	8.38	8.76	1.03	0.35	24.70	123.93	19.95
SAMPLE: 6	232.00	251.50	230.45	8.41	9.17	1.55	0.67	19.50	99.03	19.85
a	249.50	270.70	247.15	8.50	9.53	2.35	0.94	21.20	109.00	19.45
b	254.05	274.50	253.20	8.05	8.41	0.85	0.33	20.45	109.50	18.68
c	192.45	209.30	191.00	8.76	9.58	1.45	0.75	16.85	78.60	21.44
Average	232.00	251.50	230.45	8.41	9.17	1.55	0.67	19.50	99.03	19.85
SAMPLE: 7	259.48	279.17	257.78	7.59	8.30	1.70	0.66	19.68	105.07	18.76
a	284.80	306.25	283.00	7.53	8.22	1.80	0.63	21.45	116.40	18.43
b	230.50	248.25	228.85	7.70	8.48	1.65	0.72	17.75	92.40	19.21
c	263.15	283.00	261.50	7.54	8.22	1.65	0.63	19.85	106.40	18.66
Average	259.48	279.17	257.78	7.59	8.30	1.70	0.66	19.68	105.07	18.76
SAMPLE: 8	214.07	229.78	212.12	7.34	8.32	1.95	0.91	15.72	86.30	18.18
a	202.55	218.20	200.95	7.73	8.58	1.60	0.79	15.65	84.50	18.52
b	199.70	213.45	197.70	6.89	7.97	2.00	1.00	13.75	78.60	17.49
c	239.95	257.70	237.70	7.40	8.41	2.25	0.94	17.75	95.80	18.53
Average	214.07	229.78	212.12	7.34	8.32	1.95	0.91	15.72	86.30	18.18

WATER ABSORPTION CAPACITY - POROSITY CALCULATION
(continued)

	Mo (g)	Mmax (g)	Md (g)	% WA	WAC	Mo-Md	% Lost	Mp = Vp	Va (cc)	% voids
SAMPLE: 9	291.37	317.50	289.30	8.97	9.77	2.07	0.71	26.13	121.97	21.47
a	297.00	324.00	293.30	9.09	10.47	3.70	1.25	27.00	126.80	21.29
b	274.35	301.50	273.20	9.90	10.36	1.15	0.42	27.15	116.00	23.41
c	302.75	327.00	301.40	8.01	8.49	1.35	0.45	24.25	123.10	19.70
Average	291.37	317.50	289.30	8.97	9.77	2.07	0.71	26.13	121.97	21.47
SAMPLE: 10	209.15	230.15	207.33	10.04	11.00	1.82	0.87	21.00	90.07	23.33
a	213.05	234.50	210.70	10.07	11.30	2.35	1.10	21.45	94.60	22.67
b	206.95	228.00	205.65	10.17	10.87	1.30	0.63	21.05	87.40	24.08
c	207.45	227.95	205.65	9.88	10.84	1.80	0.87	20.50	88.20	23.24
Average	209.15	230.15	207.33	10.04	11.00	1.82	0.87	21.00	90.07	23.33
SAMPLE: 11	232.65	248.15	231.12	6.66	7.36	1.53	0.66	15.50	92.57	16.79
a	265.90	284.00	264.00	6.81	7.58	1.90	0.71	18.10	109.80	16.48
b	227.55	242.20	225.95	6.44	7.19	1.60	0.70	14.65	89.20	16.42
c	204.50	218.25	203.40	6.72	7.30	1.10	0.54	13.75	78.70	17.47
Average	232.65	248.15	231.12	6.66	7.36	1.53	0.66	15.50	92.57	16.79
SAMPLE: 12	245.33	262.57	244.13	7.02	7.55	1.20	0.49	17.23	99.83	17.27
a	262.15	280.80	261.00	7.11	7.59	1.15	0.44	18.65	108.80	17.14
b	235.45	251.70	234.00	6.90	7.56	1.45	0.62	16.25	94.10	17.27
c	238.40	255.20	237.40	7.05	7.50	1.00	0.42	16.80	96.60	17.39
Average	245.33	262.57	244.13	7.02	7.55	1.20	0.49	17.23	99.83	17.27
SAMPLE: 13	242.75	263.58	242.33	8.58	8.78	0.42	0.17	20.83	96.23	21.66
a	241.00	262.45	240.75	8.90	9.01	0.25	0.10	21.45	97.30	22.05
b	256.10	277.00	255.50	8.16	8.41	0.60	0.23	20.90	93.60	22.33
c	231.15	251.30	230.75	8.72	8.91	0.40	0.17	20.15	97.80	20.60
Average	242.75	263.58	242.33	8.58	8.78	0.42	0.17	20.83	96.23	21.66
SAMPLE: 14	234.95	254.52	233.50	8.33	9.00	1.45	0.62	19.57	100.70	19.46
a	231.95	250.15	230.50	7.85	8.52	1.45	0.63	18.20	102.40	17.77
b	244.00	264.70	242.50	8.48	9.15	1.50	0.61	20.70	104.60	19.79
c	228.90	248.70	227.50	8.65	9.32	1.40	0.61	19.80	95.10	20.82
Average	234.95	254.52	233.50	8.33	9.00	1.45	0.62	19.57	100.70	19.46
SAMPLE: 15	261.10	286.20	259.73	9.61	10.18	1.37	0.52	25.10	113.50	22.15
a	250.20	274.40	249.00	9.67	10.20	1.20	0.48	24.20	109.20	22.16
b	258.10	282.20	257.20	9.34	9.72	0.90	0.35	24.10	106.00	22.74
c	275.00	302.00	273.00	9.82	10.62	2.00	0.73	27.00	125.30	21.55
Average	261.10	286.20	259.73	9.61	10.18	1.37	0.52	25.10	113.50	22.15
SAMPLE: 16	206.53	224.65	205.05	8.77	9.52	1.48	0.72	18.12	91.80	19.76
a	201.00	211.40	199.25	5.17	6.10	1.75	0.87	10.40	91.80	11.33
b	216.15	238.10	214.70	10.15	10.90	1.45	0.67	21.95	95.60	22.96
c	202.45	224.45	201.20	10.87	11.56	1.25	0.62	22.00	88.00	25.00
Average	206.53	224.65	205.05	8.77	9.52	1.48	0.72	18.12	91.80	19.76

WATER ABSORPTION CAPACITY - POROSITY CALCULATION
(continued)

	Mo (g)	Mmax (g)	Md (g)	% WA	WAC	Mo-Md	% Lost	Mp = Vp	Va (cc)	% voids
SAMPLE: 17	244.27	265.92	241.82	8.86	9.98	2.45	1.00	21.65	102.20	21.23
a	241.95	262.75	239.30	8.60	9.80	2.65	1.10	20.80	96.40	21.58
b	262.00	284.50	259.25	8.59	9.74	2.75	1.05	22.50	111.20	20.23
c	228.85	250.50	226.90	9.46	10.40	1.95	0.85	21.65	99.00	21.87
Average	244.27	265.92	241.82	8.86	9.98	2.45	1.00	21.65	102.20	21.23
SAMPLE: 18	283.93	308.10	282.17	8.51	9.19	1.77	0.62	24.17	116.83	20.73
a	278.25	302.50	277.50	8.72	9.01	0.75	0.27	24.25	110.40	21.97
b	298.40	323.25	295.90	8.33	9.24	2.50	0.84	24.85	125.50	19.80
c	275.15	298.55	273.10	8.50	9.32	2.05	0.75	23.40	114.60	20.42
Average	283.93	308.10	282.17	8.51	9.19	1.77	0.62	24.17	116.83	20.73
SAMPLE: 19	268.27	291.67	266.80	8.72	9.33	1.47	0.55	23.40	111.93	20.95
a	267.00	291.40	266.20	9.14	9.47	0.80	0.30	24.40	110.40	22.10
b	261.15	283.40	258.70	8.52	9.55	2.45	0.94	22.25	105.40	21.11
c	276.65	300.20	275.50	8.51	8.97	1.15	0.42	23.55	120.00	19.63
Average	268.27	291.67	266.80	8.72	9.33	1.47	0.55	23.40	111.93	20.95
SAMPLE: 20	226.22	244.67	225.15	8.16	8.67	1.07	0.47	18.45	89.97	20.51
a	231.20	250.60	230.00	8.39	8.96	1.20	0.52	19.40	94.60	20.51
b	236.70	255.50	235.50	7.94	8.49	1.20	0.51	18.80	92.40	20.35
c	210.75	227.90	209.95	8.14	8.55	0.80	0.38	17.15	82.90	20.69
Average	226.22	244.67	225.15	8.16	8.67	1.07	0.47	18.45	89.97	20.51
SAMPLE: 21	244.78	266.43	241.72	8.84	10.23	3.07	1.25	21.65	108.83	20.15
a	223.10	243.50	220.70	9.14	10.33	2.40	1.08	20.40	89.10	22.90
b	255.15	277.80	252.50	8.88	10.02	2.65	1.04	22.65	117.00	19.36
c	256.10	278.00	251.95	8.55	10.34	4.15	1.62	21.90	120.40	18.19
Average	244.78	266.43	241.72	8.84	10.23	3.07	1.25	21.65	108.83	20.15
SAMPLE: 22	249.78	272.48	246.72	9.09	10.43	3.07	1.23	22.70	107.30	21.12
a	248.95	269.25	245.70	8.15	9.58	3.25	1.31	20.30	98.80	20.55
b	239.80	262.20	237.85	9.34	10.24	1.95	0.81	22.40	107.60	20.82
c	260.60	286.00	256.60	9.75	11.46	4.00	1.53	25.40	115.50	21.99
Average	249.78	272.48	246.72	9.09	10.43	3.07	1.23	22.70	107.30	21.12
SAMPLE: 23	254.00	280.33	250.62	10.37	11.86	3.38	1.33	26.33	110.13	23.89
a	239.30	264.15	235.80	10.38	12.02	3.50	1.46	24.85	108.00	23.01
b	265.90	294.65	262.20	10.81	12.38	3.70	1.39	28.75	112.90	25.47
c	256.80	282.20	253.85	9.89	11.17	2.95	1.15	25.40	109.50	23.20
Average	254.00	280.33	250.62	10.37	11.86	3.38	1.33	26.33	110.13	23.89
SAMPLE: 24	243.93	267.23	241.07	9.55	10.87	2.87	1.18	23.30	108.03	21.58
a	238.55	261.20	236.00	9.49	10.68	2.55	1.07	22.65	103.20	21.95
b	226.20	248.40	223.30	9.81	11.24	2.90	1.28	22.20	103.30	21.49
c	267.05	292.10	263.90	9.38	10.69	3.15	1.18	25.05	117.60	21.30
Average	243.93	267.23	241.07	9.55	10.87	2.87	1.18	23.30	108.03	21.58

POROSITY (WITH WAX WRAPPING METHOD)

	Mo(g)	Mx+Mw(g)	Mwax(g)	Mmax(g)	Md(g)	%WA	WAC	Mo-Md	% Lost	Mp = Vp	Va+w(g)	Vwax (cc)	Va (cc)	% voids	%voids diff
SAMPLE: 1	260.93	295.52	7.37	288.15	259.32	13.25	13.95	1.62	0.62	34.58	141.83	9.82	132.01	26.21	7.75
d	257.75	289.75	7.00	282.75	256.50	12.42	12.96	1.25	0.48	32.00	141.80	9.33	132.47	24.16	6.33
e	261.45	296.90	7.00	289.90	260.35	13.56	14.04	1.10	0.42	35.45	137.90	9.33	128.57	27.57	9.31
f	263.60	299.90	8.10	291.80	261.10	13.77	14.86	2.50	0.95	36.30	145.80	10.80	135.00	26.89	7.59
Average	260.93	295.52	7.37	288.15	259.32	13.25	13.95	1.62	0.62	34.58	141.83	9.82	132.01	26.21	7.75
SAMPLE: 2	234.07	270.60	7.50	263.10	231.87	15.61	16.71	2.20	0.94	36.53	134.35	10.00	124.35	29.35	7.97
d	236.40	270.40	6.45	263.95	234.00	14.38	15.56	2.40	1.02	34.00	131.25	8.60	122.65	27.72	7.58
e	248.05	287.90	7.45	280.45	245.60	16.07	17.22	2.45	0.99	39.85	139.20	9.93	129.27	30.83	9.09
f	217.75	253.50	8.60	244.90	216.00	16.42	17.36	1.75	0.80	35.75	132.60	11.47	121.13	29.51	7.23
Average	234.07	270.60	7.50	263.10	231.87	15.61	16.71	2.20	0.94	36.53	134.35	10.00	124.35	29.35	7.97
SAMPLE: 3	238.78	277.63	8.55	269.08	235.52	16.27	18.02	3.27	1.37	38.85	136.20	11.40	124.80	31.12	8.72
d	219.90	256.50	9.00	247.50	216.05	16.64	18.72	3.85	1.75	36.60	132.40	12.00	120.40	30.40	8.84
e	232.45	273.90	6.00	267.90	228.50	17.83	19.87	3.95	1.70	41.45	134.40	8.00	126.40	32.79	9.05
f	264.00	302.50	10.65	291.85	262.00	14.58	15.46	2.00	0.76	38.50	141.80	14.20	127.60	30.17	8.28
Average	238.78	277.63	8.55	269.08	235.52	16.27	18.02	3.27	1.37	38.85	136.20	11.40	124.80	31.12	8.72
SAMPLE: 4	253.47	295.73	9.25	286.48	251.20	16.68	17.85	2.27	0.89	42.27	137.60	12.33	125.27	33.71	11.03
d	239.70	277.00	10.65	266.35	236.40	15.56	17.17	3.30	1.38	37.30	131.70	14.20	117.50	31.74	8.79
e	286.85	332.43	8.15	324.28	286.00	15.89	16.24	0.85	0.30	45.58	145.70	10.87	134.83	33.81	11.96
f	233.85	277.77	8.95	268.82	231.20	18.78	20.14	2.65	1.13	43.92	135.40	11.93	123.47	35.57	12.36
Average	253.47	295.73	9.25	286.48	251.20	16.68	17.85	2.27	0.89	42.27	137.60	12.33	125.27	33.71	11.03

POROSITY (WITH WAX WRAPPING METHOD) (continued)

	Mo(g)	Mx+Mw(g)	Mwax(g)	Mmax(g)	Md(g)	%WA	WAC	Mo-Md	% Lost	Mp = Vp	Va+w(g)	Vwax(g)	Va (cc)	% voids	%voids diff
SAMPLE: 5	276.82	316.65	9.75	306.90	274.48	14.39	15.54	2.33	0.84	39.83	147.55	13.00	134.55	29.79	9.27
d	252.25	296.87	5.80	291.07	250.50	17.69	18.51	1.75	3.74	44.62	136.50	7.73	128.77	34.65	13.74
e	261.20	297.48	10.70	286.78	259.15	13.89	14.79	2.05	0.78	36.28	140.15	14.27	125.88	28.82	7.21
f	317.00	355.60	12.75	342.85	313.80	12.18	13.32	3.20	3.71	38.60	166.00	17.00	149.00	25.91	6.84
Average	276.82	316.65	9.75	306.90	274.48	14.39	15.54	2.33	0.84	39.83	147.55	13.00	134.55	29.79	9.27
SAMPLE: 6	242.10	270.68	5.35	265.33	239.97	11.81	12.78	2.13	0.88	28.58	131.15	7.13	124.02	22.99	5.72
d	268.65	300.40	6.15	294.25	266.00	11.82	12.93	2.65	0.99	31.75	138.80	8.20	130.60	24.31	6.99
e	234.95	263.90	5.95	257.95	233.00	12.32	13.26	1.95	0.83	28.95	132.60	7.93	124.67	23.22	5.53
f	222.70	247.75	3.95	243.80	220.90	11.25	12.15	1.80	0.81	25.05	122.05	5.27	116.78	21.45	4.63
Average	242.10	270.68	5.35	265.33	239.97	11.81	12.78	2.13	0.88	28.58	131.15	7.13	124.02	22.99	5.72
SAMPLE: 7	250.20	277.48	3.47	274.02	247.47	10.90	12.18	2.73	1.09	27.28	125.97	4.62	121.34	22.70	4.42
d	270.65	299.05	2.45	296.60	267.70	10.49	11.71	2.95	1.09	28.40	143.30	3.27	140.03	20.28	0.81
e	260.45	288.05	3.50	284.55	257.50	10.60	11.86	2.95	1.13	27.60	123.60	4.67	118.93	23.21	5.65
f	219.50	245.35	4.45	240.90	217.20	11.78	12.96	2.30	1.05	25.85	111.00	5.93	105.07	24.60	6.81
Average	250.20	277.48	3.47	274.02	247.47	10.90	12.18	2.73	1.09	27.28	125.97	4.62	121.34	22.70	4.42
SAMPLE: 8	238.08	267.88	5.35	262.53	235.00	12.52	13.99	3.08	1.30	29.80	123.80	7.13	116.67	25.54	7.87
d	245.90	276.90	4.90	272.00	242.50	12.61	14.19	3.40	1.38	31.00	128.60	6.53	122.07	25.40	5.66
e	236.55	266.95	5.15	261.80	233.50	12.85	14.33	3.05	1.29	30.40	121.60	6.87	114.73	26.50	9.26
f	231.80	259.80	6.00	253.80	229.00	12.08	13.45	2.80	1.21	28.00	121.20	8.00	113.20	24.73	8.69
Average	238.08	267.88	5.35	262.53	235.00	12.52	13.99	3.08	1.30	29.80	123.80	7.13	116.67	25.54	7.87

POROSITY (WITH WAX WRAPPING METHOD) (continued)

	Mo(g)	Mx+Mw(g)	Mwax(g)	Mmax(g)	Md(g)	%WA	WAC	Mo-Md	% Lost	Mp = Vp	Va+w(g)	Vwax(g)	Va (cc)	% voids	%voids diff
SAMPLE: 9	261.23	306.05	13.37	292.68	259.15	22.35	23.19	2.08	1.86	57.60	146.20	17.82	128.38	42.85	21.64
d	300.55	361.70	16.45	345.25	296.40	20.35	22.03	4.15	3.72	61.15	178.55	21.93	156.62	39.04	17.72
e	221.90	275.95	12.85	263.10	221.90	24.36	24.36	0.00	0.00	54.05	127.55	17.13	110.42	48.95	28.35
f	232.60	280.50	10.80	269.70	230.90	20.59	21.48	1.70	0.73	47.90	132.50	14.40	118.10	40.56	18.84
Average	261.23	306.05	13.37	292.68	259.15	22.35	23.19	2.08	1.86	57.60	146.20	17.82	128.38	42.85	21.64
SAMPLE: 10	227.23	271.47	10.87	260.60	225.80	19.47	20.57	1.43	0.63	44.23	130.27	14.49	115.78	38.58	15.29
d	268.00	310.20	10.30	299.90	266.00	15.75	16.62	2.00	1.78	42.20	142.70	13.73	128.97	32.72	12.14
e	211.50	258.20	12.40	245.80	210.25	22.08	22.81	1.25	1.66	46.70	123.00	16.53	106.47	43.86	22.53
f	202.20	246.00	9.90	236.10	201.15	21.66	22.30	1.05	1.75	43.80	125.10	13.20	111.90	39.14	11.21
Average	227.23	271.47	10.87	260.60	225.80	19.47	20.57	1.43	0.63	44.23	130.27	14.49	115.78	38.58	15.29
SAMPLE: 11	266.75	293.20	5.45	287.75	264.13	9.92	11.00	2.62	0.98	26.45	127.47	7.27	120.20	22.00	6.62
d	280.10	309.90	7.35	302.55	277.00	10.64	11.88	3.10	3.12	29.80	142.50	9.80	132.70	22.46	6.73
e	270.00	294.20	3.45	290.75	267.60	8.96	9.94	2.40	3.16	24.20	121.50	4.60	116.90	20.70	5.62
f	250.15	275.50	5.55	269.95	247.80	10.13	11.18	2.35	3.20	25.35	118.40	7.40	111.00	22.84	7.52
Average	266.75	293.20	5.45	287.75	264.13	9.92	11.00	2.62	0.98	26.45	127.47	7.27	120.20	22.00	6.62
SAMPLE: 12	258.60	291.48	5.95	285.53	257.05	12.72	13.46	1.55	0.60	32.88	131.30	7.93	123.37	26.72	9.10
d	250.20	285.47	6.10	279.37	248.50	14.10	14.88	1.70	2.76	35.27	132.40	8.13	124.27	28.38	10.79
e	241.65	272.63	5.90	266.73	240.20	12.82	13.50	1.45	3.00	30.98	121.30	7.87	113.43	27.31	9.11
f	283.95	316.35	5.85	310.50	282.45	11.41	12.00	1.50	2.84	32.40	140.20	7.80	132.40	24.47	7.39
Average	258.60	291.48	5.95	285.53	257.05	12.72	13.46	1.55	0.60	32.88	131.30	7.93	123.37	26.72	9.10

POROSITY (WITH WAX WRAPPING METHOD) (continued)

	Mo(g)	Mx+Mw(g)	Mwax(g)	Mmax(g)	Md(g)	%WA	WAC	Mo-Md	% Lost	Mp = Vp	Va+w(g)	Vwax(g)	Va (cc)	% voids	%voids diff
SAMPLE: 13	265.57	307.12	8.53	298.59	264.37	15.65	16.20	1.20	0.45	41.56	139.77	11.38	128.39	32.43	11.45
d	274.40	319.77	8.20	311.57	273.75	16.53	16.81	0.65	0.24	45.37	144.60	10.93	133.67	33.94	13.20
e	228.30	264.02	7.45	256.57	227.00	15.64	16.31	1.30	0.57	35.72	118.90	9.93	108.97	32.78	11.54
f	294.00	337.58	9.95	327.63	292.35	14.82	15.47	1.65	0.56	43.58	155.80	13.27	142.53	30.58	9.61
Average	265.57	307.12	8.53	298.59	264.37	15.65	16.20	1.20	0.45	41.56	139.77	11.38	128.39	32.43	11.45
SAMPLE: 14	257.40	294.04	5.27	288.78	255.83	14.24	14.93	1.57	0.61	36.64	128.33	7.02	121.31	30.13	9.07
d	267.70	302.20	3.30	298.90	266.25	12.89	13.50	1.45	0.54	34.50	128.80	4.40	124.40	27.73	7.43
e	268.95	312.17	4.60	307.57	268.25	16.07	16.37	0.70	0.26	43.22	133.80	6.13	127.67	33.85	11.33
f	235.55	267.77	7.90	259.87	233.00	13.68	14.92	2.55	1.08	32.22	122.40	10.53	111.87	28.80	8.45
Average	257.40	294.04	5.27	288.78	255.83	14.24	14.93	1.57	0.61	36.64	128.33	7.02	121.31	30.13	9.07
SAMPLE: 15	272.57	305.38	9.15	296.23	269.67	12.04	13.37	2.90	1.06	32.82	145.12	12.20	132.92	24.71	4.93
d	253.60	294.15	7.50	286.65	251.15	15.99	17.12	2.45	0.97	40.55	141.00	10.00	131.00	30.95	10.02
e	286.00	317.20	9.90	307.30	283.15	10.91	12.03	2.85	1.00	31.20	150.95	13.20	137.75	22.65	3.65
f	278.10	304.80	10.05	294.75	274.70	9.60	10.96	3.40	1.22	26.70	143.40	13.40	130.00	20.54	1.12
Average	272.57	305.38	9.15	296.23	269.67	12.04	13.37	2.90	1.06	32.82	145.12	12.20	132.92	24.71	4.93
SAMPLE: 16	231.90	264.63	9.27	255.36	229.30	14.11	15.30	2.60	1.12	32.73	126.35	12.36	113.99	28.76	3.29
d	255.80	296.27	10.00	286.27	252.30	15.82	17.43	3.50	1.37	40.47	144.00	13.33	130.67	30.97	6.90
e	219.25	258.43	8.45	249.98	217.80	17.87	18.66	1.45	0.66	39.18	113.50	11.27	102.23	38.33	6.27
f	220.65	239.18	9.35	229.83	217.80	8.40	9.82	2.85	1.29	18.53	121.55	12.47	109.08	16.99	-3.30
Average	231.90	264.63	9.27	255.36	229.30	14.11	15.30	2.60	1.12	32.73	126.35	12.36	113.99	28.76	3.29

POROSITY (WITH WAX WRAPPING METHOD) (continued)

	Mo(g)	Mx+Mw(g)	Mwax(g)	Mmax(g)	Md(g)	%WA	WAC	Mo-Md	% Lost	Mp = Vp	Va+w(g)	Vwax(g)	Va (cc)	% voids	%voids diff
SAMPLE: 17	220.78	255.47	2.75	252.72	218.73	15.71	16.84	2.05	0.93	34.68	113.98	3.67	110.32	31.60	9.24
d	216.95	256.22	3.85	252.37	214.50	18.10	19.45	2.45	1.13	39.27	114.55	5.13	109.42	35.89	12.81
e	205.00	236.00	2.10	233.90	203.60	15.12	15.91	1.40	0.68	31.00	101.60	2.80	98.80	31.38	8.12
f	240.40	274.18	2.30	271.88	238.10	14.05	15.15	2.30	0.96	33.78	125.80	3.07	122.73	27.53	6.80
Average	220.78	255.47	2.75	252.72	218.73	15.71	16.84	2.05	0.93	34.68	113.98	3.67	110.32	31.60	9.24
SAMPLE: 18	259.93	303.91	11.07	292.84	257.73	16.92	17.91	2.20	0.85	43.98	150.10	14.76	135.34	32.49	11.77
d	249.65	289.27	11.35	277.92	247.45	15.87	16.90	2.20	0.88	39.62	146.20	15.13	131.07	30.23	9.61
e	268.40	312.30	13.80	298.50	266.25	16.36	17.30	2.15	0.80	43.90	159.00	18.40	140.60	31.22	11.81
f	261.75	310.17	8.05	302.12	259.50	18.50	19.52	2.25	0.86	48.42	145.10	10.73	134.37	36.03	13.89
Average	259.93	303.91	11.07	292.84	257.73	16.92	17.91	2.20	0.85	43.98	150.10	14.76	135.34	32.49	11.77
SAMPLE: 19	263.98	306.75	10.05	296.70	262.23	16.20	16.99	1.75	0.66	42.77	142.43	13.40	129.03	33.01	13.05
d	277.15	324.75	10.80	313.95	276.00	17.17	17.66	1.15	0.41	47.60	155.70	14.40	141.30	33.69	14.85
e	260.65	294.33	10.85	283.48	259.40	12.92	13.47	1.25	0.48	33.68	132.55	14.47	118.08	28.53	8.53
f	254.15	301.17	8.50	292.67	251.30	18.50	19.84	2.85	1.12	47.02	139.05	11.33	127.72	36.81	15.78
Average	263.98	306.75	10.05	296.70	262.23	16.20	16.99	1.75	0.66	42.77	142.43	13.40	129.03	33.01	13.05
SAMPLE: 20	239.45	274.65	6.60	268.05	237.22	14.70	15.78	2.23	0.93	35.20	124.80	8.80	116.00	30.24	9.70
d	236.00	265.41	3.55	261.86	234.75	12.46	13.06	1.25	0.53	29.41	113.90	4.73	109.17	26.94	7.34
e	243.55	279.07	7.00	272.07	241.75	14.58	15.44	1.80	0.74	35.52	127.90	9.33	118.57	29.96	9.13
f	238.80	279.47	9.25	270.22	235.15	17.03	18.85	3.65	1.53	40.67	132.60	12.33	120.27	33.81	12.63
Average	239.45	274.65	6.60	268.05	237.22	14.70	15.78	2.23	0.93	35.20	124.80	8.80	116.00	30.24	9.70

POROSITY (WITH WAX WRAPPING METHOD) (continued)

	Mo(g)	Mx+Mw(g)	Mwax(g)	Mmax(g)	Md(g)	%WA	WAC	Mo-Md	% Lost	Mp = Vp	Va+w(g)	Vwax(g)	Va (cc)	% voids	%voids diff
SAMPLE: 21	287.42	312.91	9.67	303.24	274.30	8.87	14.20	13.12	4.56	25.49	148.20	12.89	135.31	18.73	0.91
d	272.95	315.77	8.35	307.42	267.30	15.69	18.13	5.65	2.07	42.82	150.20	11.13	139.07	30.79	13.19
e	293.75	305.67	10.30	295.37	266.00	4.06	14.91	27.75	9.45	11.92	150.00	13.73	136.27	8.75	-9.28
f	295.55	317.30	10.35	306.95	289.60	7.36	9.56	5.95	2.01	21.75	144.40	13.80	130.60	16.65	-1.20
Average	287.42	312.91	9.67	303.24	274.30	8.87	14.20	13.12	4.56	25.49	148.20	12.89	135.31	18.73	0.91
SAMPLE: 22	276.75	332.00	7.85	324.15	274.87	19.96	20.71	1.88	0.68	55.25	155.13	10.47	144.67	38.07	16.07
d	293.50	351.93	8.60	343.33	290.20	19.91	21.27	3.30	1.12	58.43	166.60	11.47	155.13	37.67	15.84
e	256.60	301.77	6.40	295.37	255.40	17.60	18.15	1.20	0.47	45.17	141.00	8.53	132.47	34.10	13.32
f	280.15	342.30	8.55	333.75	279.00	22.18	22.69	1.15	0.41	62.15	157.80	11.40	146.40	42.45	19.04
Average	276.75	332.00	7.85	324.15	274.87	19.96	20.71	1.88	0.68	55.25	155.13	10.47	144.67	38.07	16.07
SAMPLE: 23	284.97	331.57	10.03	321.54	282.23	16.35	17.45	2.73	0.96	46.61	155.33	13.38	141.96	32.78	11.09
d	301.75	352.55	14.25	338.30	297.80	16.84	18.38	3.95	1.31	50.80	167.50	19.00	148.50	34.21	10.75
e	285.15	332.83	8.45	324.38	283.40	16.72	17.44	1.75	0.61	47.68	152.10	11.27	140.83	33.86	12.60
f	268.00	309.33	7.40	301.93	265.50	15.42	16.51	2.50	0.93	41.33	146.40	9.87	136.53	30.27	9.94
Average	284.97	331.57	10.03	321.54	282.23	16.35	17.45	2.73	0.96	46.61	155.33	13.38	141.96	32.78	11.09
SAMPLE: 24	220.80	256.82	7.88	248.94	217.20	16.31	18.30	3.60	1.63	36.02	126.53	10.51	116.02	31.07	12.84
d	229.00	259.47	7.00	252.47	224.00	13.30	15.83	5.00	2.18	30.47	123.80	9.33	114.47	26.62	18.52
e	212.00	252.43	9.05	243.38	208.80	19.07	20.90	3.20	1.51	40.43	125.00	12.07	112.93	35.80	11.25
f	221.40	258.57	7.60	250.97	218.80	16.79	18.17	2.60	1.17	37.17	130.80	10.13	120.67	30.80	8.77
Average	220.80	256.82	7.88	248.94	217.20	16.31	18.30	3.60	1.63	36.02	126.53	10.51	116.02	31.07	12.84

WATER ABSORPTION CAPACITY - POROSITY CALCULATION

	Org.D.W.	Sat. W.	Redried W.						App. V.	% Prst
	Mo (g)	**Mmax (g)**	**Md (g)**	**% WA**	**WAC**	**Mo-Md**	**% Lost**	**Mp = Vp**	**Va (cc)**	**% voids**
SAMPLE 1	268.85	292.17	266.86	8.69	9.50	2.00	0.85	23.32	115.29	20.35
SAMPLE 2	240.92	262.67	239.28	9.04	9.81	1.64	0.69	21.76	103.47	21.14
SAMPLE 3	247.20	268.05	244.87	8.46	9.51	2.33	0.95	20.85	105.29	19.84
SAMPLE 4	245.61	267.39	243.34	8.85	9.90	2.27	0.94	21.78	106.37	20.39

Data Set 3: Compressive Strength

		WET CONDITION						
Sample		Load(kg)	Load (lbs.)	A (sqcm)	A(sqi)	% pst	Comp.Str(psi)	%Diff
1	a	-1350	-2970	23.92	3.65	18.66	-813.72	
	b	-2070	-4554	25.50	3.89	18.84	-1170.40	
	c	-1040	-2288	26.00	3.97	18.30	-576.72	
	Average	-1555.00	-3421.00	25.75	3.93	18.60	**-853.61**	61.35
2	a	-690	-1518	26.46	4.04	23.63	-375.98	
	b	-1850	-4070	26.46	4.04	20.39	-1008.06	
	c	-1890	-4158	24.96	3.81	17.19	-1091.74	
	Average	-1476.67	-3248.67	25.96	3.96	20.40	**-825.26**	5.78
3	a	-215	-473	21.62	3.30	24.02	-143.38	
	b	-1440	-3168	24.00	3.66	21.31	-865.08	
	c	-1740	-3828	24.00	3.66	20.77	-1045.30	
	Average	-1131.67	-2489.67	23.21	3.54	22.03	**-684.58**	-36.97
4	a	-1980	-4356	23.50	3.59	21.90	-1214.79	
	b	-600	-1320	25.00	3.81	24.25	-346.03	
	c	-780	-1716	24.50	3.74	22.54	-459.02	
	Average	-1120.00	-2464.00	24.33	3.71	22.90	**-673.28**	24.38
5	a	-2615	-5753	24.00	3.66	18.82	-1570.95	
	b	-1780	-3916	24.48	3.74	18.81	-1048.36	
	c	-2730	-6006	25.85	3.94	22.20	-1522.67	
	Average	-2255.00	-4961.00	25.17	3.84	19.94	**-1380.66**	-1.90
6	a	-310	-682	21.62	3.30	19.45	-206.73	
	b	-1735	-3817	22.56	3.44	18.68	-1108.82	
	c	-755	-1661	21.15	3.23	21.44	-514.68	
	Average	-933.33	-2053.33	21.78	3.32	19.86	**-610.08**	69.59
7	a	-740	-1628	23.46	3.58	18.43	-454.79	
	b	-770	-1694	19.60	2.99	19.21	-566.42	
	c	-1475	-3245	22.95	3.50	18.66	-926.64	
	Average	-995.00	-2189.00	22.00	3.36	18.77	**-649.28**	44.49
8	a	-130	-286	19.60	2.99	18.52	-95.63	
	b	-450	-990	16.80	2.56	17.49	-386.19	
	c	-670	-1474	22.00	3.36	18.53	-439.09	
	Average	-416.67	-916.67	19.47	2.97	18.18	**-306.97**	51.99

Sample	**WET CONDITION** (continued)							
		Load(kg)	Load (lbs.)	A (sqcm)	A(sqi)	% pst	Comp.Str (psi)	%Diff
9	a	-1480	-3256	28.91	4.41	21.29	-738.10	
	b	-610	-1342	29.70	4.53	23.41	-296.13	
	c	-1470	-3234	21.62	3.30	19.70	-980.31	
	Average	-1040.00	-2288.00	25.66	3.92	21.47	**-671.51**	29.17
10	a	-770	-1694	23.46	3.58	22.67	-473.22	
	b	-660	-1452	19.78	3.02	24.08	-481.08	
	c	-225	-495	19.78	3.02	23.24	-164.01	
	Average	-551.67	-1213.67	21.01	3.21	23.33	**-372.77**	51.80
11	a	-2675	-5885	24.99	3.81	16.48	-1543.33	
	b	-3625	-7975	20.58	3.14	16.42	-2539.60	
	c	-1595	-3509	18.00	2.75	17.47	-1277.59	
	Average	-2631.67	-5789.67	21.19	3.23	16.79	**-1786.84**	3.21
12	a	-2360	-5192	24.44	3.73	17.14	-1392.24	
	b	-2460	-5412	22.50	3.43	17.27	-1576.36	
	c	-2125	-4675	18.40	2.81	17.39	-1665.11	
	Average	-2315.00	-5093.00	21.78	3.32	17.27	**-1544.57**	46.61
13	a	-1450	-3190	23.50	3.59	22.05	-889.62	
	b	-1825	-4015	23.52	3.59	22.33	-1118.74	
	c	-1480	-3256	21.56	3.29	20.60	-989.73	
	Average	-1652.50	-3635.50	22.54	3.44	21.66	**-999.36**	51.23
14	a	-2000	-4400	21.93	3.35	17.77	-1314.90	
	b	-1070	-2354	21.50	3.28	19.79	-717.54	
	c	-1850	-4070	20.70	3.16	20.82	-1288.56	
	Average	-1640.00	-3608.00	21.38	3.26	19.46	**-1107.00**	24.54
15	a	-230	-506	19.85	3.03	22.16	-167.10	
	b	-390	-858	23.00	3.51	22.74	-244.48	
	c	-480	-1056	20.80	3.17	21.55	-332.72	
	Average	-366.67	-806.67	21.22	3.24	22.15	**-248.10**	39.16

Sample	**WET CONDITION** (continued)							
		Load(kg)	Load (lbs.)	A (sqcm)	A(sqi)	% pst	Comp.Str (psi)	%Diff
16	a	-350	-770	19.36	2.95	11.33	-260.65	
	b	-210	-462	18.92	2.89	22.96	-160.03	
	c	-25	-55	13.69	2.09	25.00	-26.33	
	Average	-195.00	-429.00	17.32	2.64	19.76	**-149.00**	67.51
17	a	-910	-2002	23.03	3.51	21.58	-569.71	
	b	-880	-1936	24.50	3.74	20.23	-517.87	
	c	-640	-1408	23.63	3.60	20.87	-390.58	
	Average	-760.00	-1672.00	24.06	3.67	20.89	**-492.72**	54.61
18	a	-1250	-2750	24.50	3.74	21.97	-735.61	
	b	-1210	-2662	27.00	4.12	19.80	-646.14	
	c	-1980	-4356	25.00	3.81	20.42	-1141.90	
	Average	-1480.00	-3256.00	25.50	3.89	20.73	**-841.21**	36.00
19	a	-1610	-3542	23.97	3.66	22.10	-968.41	
	b	-825	-1815	24.50	3.74	21.11	-485.50	
	c	-2750	-6050	24.50	3.74	19.63	-1618.34	
	Average	-1728.33	-3802.33	24.32	3.71	20.95	**-1024.08**	48.07
20	a	-1425	-3135	20.00	3.05	20.51	-1027.28	
	b	-2220	-4884	18.45	2.82	20.35	-1734.84	
	c	-2015	-4433	20.21	3.08	20.69	-1437.51	
	Average	-1886.67	-4150.67	19.55	2.98	20.52	**-1399.88**	-3.02
21	a	-740	-1628	21.15	3.23	22.90	-504.46	
	b	-935	-2057	22.36	3.41	19.36	-602.90	
	c	-825	-1815	24.50	3.74	18.19	-485.50	
	Average	-880.00	-1936.00	23.43	3.58	20.15	**-530.95**	41.68
22	a	-1690	-3718	19.78	3.02	20.55	-1231.86	
	b	-550	-1210	23.52	3.59	20.82	-337.15	
	c	-980	-2156	21.00	3.20	21.99	-672.84	
	Average	-1073.33	-2361.33	21.43	3.27	21.12	**-747.28**	37.75
23	a	-925	-2035	24.01	3.66	23.01	-555.46	
	b	-610	-1342	25.00	3.81	25.47	-351.80	
	c	-1240	-2728	23.00	3.51	23.20	-777.31	
	Average	-925.00	-2035.00	24.00	3.66	23.89	**-561.52**	61.13
24	a	-1000	-2200	24.00	3.66	21.95	-600.75	
	b	-1100	-2420	22.09	3.37	21.49	-717.96	
	c	-2510	-5522	24.01	3.66	21.30	-1507.25	
	Average	-1536.67	-3380.67	23.37	3.57	21.58	**-941.98**	1.26

DRY CONDITION (continued)

Sample		Load(kg)	Load (lbs.)	A (sqcm)	A(sqi)	% pst	%pst(wx)	Comp.Str(psi)
1	d	-4280	-9416	20.64	3.15	17.82	24.16	-2989.76
	e	-2940	-6468	22.05	3.36	18.26	27.57	-1922.39
	f	-2780	-6116	23.40	3.57	19.30	26.89	-1712.90
	Average	-2860.00	-6292.00	22.73	3.47	18.46	26.21	**-2208.35**
2	d	-1720	-3784	22.68	3.46	20.14	27.72	-1093.42
	e	-1000	-2200	24.01	3.66	21.47	30.83	-600.50
	f	-1430	-3146	22.08	3.37	22.28	29.51	-933.77
	Average	-1383.33	-3043.33	22.92	3.50	21.30	29.35	**-875.90**
3	d	-410	-902	19.74	3.01	21.56	30.40	-299.46
	e	-800	-1760	21.62	3.30	23.75	32.79	-533.50
	f	-1040	-2288	22.50	3.43	21.89	30.17	-666.43
	Average	-750.00	-1650.00	21.29	3.25	22.40	31.12	**-499.80**
4	d	-730	-1606	24.50	3.74	22.96	31.74	-429.60
	e	-2630	-5786	24.44	3.73	21.85	33.81	-1551.52
	f	-1025	-2255	21.42	3.27	23.21	35.57	-689.93
	Average	-1461.67	-3215.67	23.45	3.58	22.67	33.71	**-890.35**
5	d	-2370	-5214	22.50	3.43	20.91	34.65	-1518.69
	e	-1850	-4070	22.54	3.44	21.61	28.82	-1183.37
	f	-2410	-5302	25.50	3.89	19.06	25.91	-1362.63
	Average	-2130.00	-4686.00	24.02	3.67	20.53	29.79	**-1354.90**
6	d	-3860	-8492	25.00	3.81	17.32	24.31	-2226.13
	e	-2365	-5203	20.64	3.15	17.69	23.22	-1652.05
	f	-3210	-7062	21.62	3.30	16.82	21.45	-2140.68
	Average	-3145.00	-6919.00	22.42	3.42	17.28	22.99	**-2006.29**
7	d	-2870	-6314	24.75	3.78	19.47	20.28	-1671.90
	e	-1990	-4378	23.85	3.64	17.56	23.21	-1203.00
	f	-990	-2178	22.50	3.43	17.80	24.60	-634.39
	Average	-1950.00	-4290.00	23.70	3.62	18.28	22.70	**-1169.76**
8	d	-1080	-2376	22.50	3.43	19.74	25.40	-692.06
	e	-1100	-2420	22.00	3.36	17.24	26.50	-720.90
	f	-740	-1628	21.12	3.22	16.04	24.73	-505.17
	Average	-973.33	-2141.33	21.87	3.34	17.67	25.54	**-639.38**

DRY CONDITION (continued)

Sample		Load(kg)	Load (lbs.)	A (sqcm)	A(sqi)	% pst	%pst(wx)	Comp.Str(psi)
9	d	-1320	-2904	25.38	3.87	21.32	39.04	-749.87
	e	-2450	-5390	24.38	3.72	20.60	48.95	-1448.89
	f	-965	-2123	21.56	3.29	21.72	40.56	-645.33
	Average	-1707.50	-3756.50	22.97	3.50	21.21	42.85	**-948.03**
10	d	-2220	-4884	22.05	3.36	20.58	32.72	-1451.60
	e	-720	-1584	18.90	2.88	21.33	43.86	-549.25
	f	-465	-1023	21.00	3.20	27.93	39.14	-319.25
	Average	-1135.00	-2497.00	20.65	3.15	23.28	38.57	**-773.37**
11	d	-2400	-5280	26.40	4.03	15.73	22.46	-1310.72
	e	-2900	-6380	19.78	3.02	15.08	20.70	-2113.85
	f	-3225	-7095	22.00	3.36	15.32	22.84	-2113.54
	Average	-2841.67	-6251.67	22.73	3.47	15.38	22.00	**-1846.04**
12	d	-3050	-6710	22.05	3.36	17.59	28.38	-1994.32
	e	-4840	-10648	23.04	3.52	18.20	27.31	-3028.76
	f	-6450	-14190	25.44	3.88	17.08	24.47	-3655.49
	Average	-4780.00	-10516.00	23.51	3.59	17.62	26.72	**-2892.86**
13	d	-3725	-8195	26.00	3.97	20.74	33.94	-2065.64
	e	-3180	-6996	20.70	3.16	21.24	32.78	-2214.93
	f	-3355	-7381	25.92	3.96	20.97	30.58	-1866.21
	Average	-3267.50	-7188.50	23.31	3.56	20.98	32.43	**-2048.93**
14	d	-2810	-6182	23.40	3.57	20.30	27.73	-1731.38
	e	-1810	-3982	22.05	3.36	22.52	33.85	-1183.51
	f	-1970	-4334	19.11	2.92	20.35	28.80	-1486.31
	Average	-2196.67	-4832.67	21.52	3.28	21.06	30.13	**-1467.07**
15	d	-430	-946	25.00	3.81	20.94	30.95	-247.99
	e	-600	-1320	19.25	2.94	19.00	22.65	-449.39
	f	-530	-1166	14.53	2.22	19.42	20.54	-526.09
	Average	-520.00	-1144.00	19.59	2.99	19.79	24.71	**-407.82**
16	d	-125	-275	19.35	2.95	24.07	30.97	-93.14
	e	-510	-1122	13.50	2.06	32.06	38.33	-544.68
	f	-1280	-2816	25.00	3.81	20.29	16.99	-738.20
	Average	-638.33	-1404.33	19.28	2.94	25.47	28.76	**-458.67**

DRY CONDITION (continued)								
Sample		Load(kg)	Load (lbs.)	A (sqcm)	A(sqi)	% pst	%pst(wx)	Comp.Str(psi)
17	d	-1270	-2794	19.35	2.95	23.08	35.89	-946.29
	e	-940	-2068	18.00	2.75	23.26	31.38	-752.94
	f	-2640	-5808	24.44	3.73	20.72	27.53	-1557.42
	Average	-1790.00	-3938.00	21.22	3.24	22.35	31.60	**-1085.55**
18	d	-2220	-4884	23.52	3.59	20.62	30.23	-1360.88
	e	-2360	-5192	24.50	3.74	19.42	31.22	-1388.83
	f	-1980	-4356	23.92	3.65	22.15	36.03	-1193.46
	Average	-2186.67	-4810.67	23.98	3.66	20.73	32.49	**-1314.39**
19	d	-4065	-8943	23.92	3.65	18.84	33.69	-2450.20
	e	-2975	-6545	18.80	2.87	20.00	28.53	-2281.56
	f	-1650	-3630	20.09	3.07	21.04	36.81	-1184.15
	Average	-2896.67	-6372.67	20.94	3.19	19.96	33.01	**-1971.97**
20	d	-2865	-6303	16.50	2.52	19.60	26.94	-2503.48
	e	-1075	-2365	20.64	3.15	20.83	29.96	-750.93
	f	-1285	-2827	22.54	3.44	21.19	33.81	-821.96
	Average	-1741.67	-3831.67	19.89	3.04	20.54	30.24	**-1358.79**
21	d	-1450	-3190	23.52	3.59	17.59	30.79	-888.86
	e	-1380	-3036	27.84	4.25	18.03	23.42	-714.68
	f	-1760	-3872	22.50	3.43	17.85	16.65	-1127.80
	Average	-1570.00	-3454.00	25.17	3.84	17.82	23.62	**-910.45**
22	d	-890	-1958	22.56	3.44	21.83	37.67	-568.79
	e	-2315	-5093	24.38	3.72	20.78	34.10	-1369.05
	f	-2940	-6468	25.48	3.89	23.41	42.45	-1663.61
	Average	-2048.33	-4506.33	24.14	3.68	22.01	38.07	**-1200.48**
23	d	-2095	-4609	27.00	4.12	23.46	34.21	-1118.72
	e	-2370	-5214	22.56	3.44	21.26	33.86	-1514.65
	f	-2550	-5610	21.62	3.30	20.33	30.27	-1700.54
	Average	-2338.33	-5144.33	23.73	3.62	21.68	32.78	**-1444.64**
24	d	-2740	-6028	22.05	3.36	8.10	26.62	-1791.61
	e	-1090	-2398	23.03	3.51	24.56	35.80	-682.39
	f	-620	-1364	23.04	3.52	22.04	30.80	-387.98
	Average	-1483.33	-3263.33	22.71	3.46	18.23	31.07	**-954.00**

Data Set 4: The number of cases and the standard deviations of the average data

Sample	ASTM method						Wax encapsulation method					
	WAC			% porosity			WAC			% porosity		
Set B (d/e/f)	Average	Standard deviation	Number of cases	Average	Standard deviation	Number of cases	Average	Standard deviation	Number of cases	Average	Standard deviation	Number of cases
1 (WTX)	9.05	1.01	3	18.46	0.76	3	13.95	0.95	3	26.21	1.81	3
2 (WTN)	10.81	0.24	3	21.39	1.11	3	16.71	1.00	3	29.35	1.56	3
3 (WMX)	11.83	0.74	3	22.40	1.18	3	18.02	2.29	3	31.12	1.45	3
4 (WMN)	10.69	1.45	3	22.67	0.73	3	17.85	2.04	3	33.71	1.91	3
5 (WBX)	9.74	0.53	3	20.53	1.32	3	15.54	2.67	3	29.79	4.45	3
6 (WBN)	8.65	0.31	3	17.28	0.44	3	12.78	0.57	3	22.99	1.44	3
7 (NMX)	8.82	0.31	3	18.28	1.04	3	12.18	0.68	3	22.70	2.21	3
8 (NMN)	9.30	0.55	3	17.67	1.89	3	13.99	0.47	3	25.54	0.89	3
9 (NTX)	10.06	1.42	3	21.21	0.57	3	22.62	1.53	3	42.85	5.34	3
10 (NTN)	10.32	1.58	3	23.28	4.04	3	20.57	3.44	3	38.58	5.59	3
11 (NBX)	7.85	0.30	3	15.38	0.33	3	11.00	0.98	3	22.00	1.14	3
12 (NBN)	8.13	0.27	3	17.63	0.56	3	13.46	1.44	3	26.72	2.02	3
13 (ETX)	9.16	0.44	3	20.98	0.25	3	16.20	0.68	3	32.43	1.71	3
14 (ETN)	9.46	0.34	3	21.06	1.27	3	14.93	1.43	3	30.13	3.27	3
15 (EMX)	10.22	0.35	3	19.79	1.02	3	13.37	3.29	3	24.71	5.51	3
16 (EMN)	12.98	1.24	3	25.47	6.01	3	15.30	4.79	3	28.76	10.84	3
17 (EBX)	10.82	0.12	3	22.35	1.42	3	16.84	2.29	3	31.60	4.19	3
18 (EBN)	10.11	0.49	3	20.73	1.37	3	17.91	1.42	3	32.49	3.11	3
19 (STX)	8.87	0.73	3	19.96	1.10	3	16.99	3.24	3	33.01	4.19	3
20 (STN)	9.75	0.92	3	20.54	0.83	3	15.78	2.91	3	30.24	3.45	3
21 (SMX)	10.52	0.91	3	17.82	0.22	3	14.20	4.33	3	18.73	11.17	3
22 (SMN)	9.84	0.53	3	22.01	1.32	3	20.71	2.32	3	38.07	4.19	3
23 (SBX)	10.32	0.97	3	21.69	1.61	3	17.45	0.94	3	32.78	2.18	3
24 (SBN)	10.12	3.99	3	18.23	8.67	3	18.30	2.53	3	31.07	4.60	3

Sample	Compressive Strength (psi)					
	Wet			Dry		
	Average	Standard deviation	No. of cases	Average	Standard deviation	No. of cases
1 (WTX)	-853.61	298.84	3	-2208.35	684.78	3
2 (WTN)	-825.26	391.33	3	-875.90	251.51	3
3 (WMX)	-684.58	477.28	3	-499.80	185.79	3
4 (WMN)	-673.28	472.35	3	-890.35	587.20	3
5 (WBX)	-1380.66	288.79	3	-1354.90	167.79	3
6 (WBN)	-610.08	458.55	3	-2006.29	309.74	3
7 (NMX)	-649.28	246.60	3	-1169.76	519.55	3
8 (NMN)	-306.97	184.93	3	-639.38	117.11	3
9 (NTX)	-671.51	346.92	3	-948.03	436.90	3
10 (NTN)	-372.77	180.84	3	-773.37	598.52	3
11 (NBX)	-1786.84	665.31	3	-1846.04	463.60	3
12 (NBN)	-1544.57	139.19	3	-2892.86	838.88	3
13 (ETX)	-999.36	114.86	3	-2048.93	174.96	3
14 (ETN)	-1107.00	337.54	3	-1467.07	274.44	3
15 (EMX)	-248.10	82.87	3	-407.82	143.64	3
16 (EMN)	-149.00	117.55	3	-458.67	331.02	3
17 (EBX)	-492.72	92.17	3	-1085.55	419.93	3
18 (EBN)	-841.21	264.22	3	-1314.39	105.66	3
19 (STX)	-1024.08	568.47	3	-1971.97	687.46	3
20 (STN)	-1399.88	355.28	3	-1358.79	991.96	3
21 (SMX)	-530.95	63.02	3	-910.45	207.40	3
22 (SMN)	-747.28	451.98	3	-1200.48	566.54	3
23 (SBX)	-561.52	212.82	3	-1444.64	297.16	3
24 (SBN)	-941.98	493.03	3	-954.00	740.18	3