FLORA IN THE CONSERVATION OF HISTORIC BUILDINGS WITH SPECIAL REFERENCE TO LICHENS AND RUINS

VOLUME 1 OF 2

CHAPTERS

PETER F GOULDSBOROUGH MA RIBA

SUBMITTED FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

The University of York

Department of Archaeology
incorporating
Institute of Advanced Architectural Studies

Centre for Conservation

2002

ABSTRACT

This research investigates the ways in which mosses and lichens growing on masonry ruins influence three primary weathering processes: frost action, the effects of soluble salts, and acid rain. The research was carried out in relation to the physical properties and weathering characteristics of selected stone types from four case study sites in Yorkshire: the temples at Duncombe Park, Rievaulx Abbey, Harewood and Slingsby Castles. These stone types were from the Jurassic system of North Yorkshire and the Carboniferous system of West Yorkshire.

The physical properties and weathering characteristics of the stone types from the case study sites were investigated by laboratory tests, and a new laboratory test method was developed whereby the influence of mosses and lichens on water uptake and subsequent evaporation from stone could be investigated. This provided an indication of the potential of those two plant groups to influence the effects of the three primary weathering mechanisms.

As a result, a method of assessing the risk to historic masonry posed by plants has been developed. This method considers the physical properties and weathering characteristics of differing stone types, construction methods, plant species composition and abundance.

Of the three primary weathering mechanisms, the action of acid rain has emerged as a key cause of weathering, particularly to some of the Jurassic stones investigated. It is generally believed that levels of atmospheric sulphur dioxide pollution have decreased over the past thirty years, but this research has shown that levels in rural North Yorkshire have increased; consequently, and in the absence of local pollution monitoring stations, a method has been developed whereby the lichen flora at historic sites can be analysed in order to determine the direction of change in levels of atmospheric sulphur dioxide pollution. This will provide a reliable indication of the risk which acid rain poses to vulnerable masonry.

LIST OF CONTENTS

VOLUME 1

LIST OF FIGURES

LIST OF TABLES

LIST OF CONTENTS

VOLUME 2

A FURTHER EXAMINATION OF THE ALTERNATIVE TEST METHOD

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

Acknowledgements are due to the following people:

My supervisor Peter Burman.

The members of my Thesis Advisory Panel: Professor Don Brothwell, Dr Kevin Walsh, Dr James Barrett, Peter Goodchild.

Those who provided guidance in the early stages: Jane Grenville, Rachel Thomas of English Nature and, David Wells and Keith Emerick of English Heritage.

The contributors to the one-day workshop *Flora in the Conservation of Historic Buildings* which was held on 25 February 1999 at The University of York Department of Archaeology as part of this research: Professor Mark Seaward, Dr Heather Viles, Dr Oliver Gilbert, Dr Glyn Coppack, Dr Maureen Young, David Wells, Peter Burman.

The facilitators: Lord and Lady Feversham, who provided unrestricted free access to the temples at Duncombe Park; the staff of the Helmsley Estate Office; Keith Emerick, for arranging free access to Rievaulx Abbey; The National Trust York, for allowing free access to Rievaulx Terrace; Ed Dennison, who arranged access to Harewood Castle and Slingsby Castle; Nicola Charlton, who provided use of laboratory facilities in the University of York Department of Biology, Don Smith, for his invaluable assistance with lichen surveys; Dr Maureen Young of the Masonry Research Unit at the Robert Gordon University Aberdeen, for carrying out the porosimetry tests; Professor Dr Šefka Horvat-Kurbegovič, of the Academy of Fine Arts, University of Zagreb, Croatia, who was part of the Academic Links and Interchange Scheme and who supported my lectures in Croatia; Victoria Osborne of the City of York Art Gallery.

Colleagues and friends who have provided help, advice and encouragement: Professor Clifford Price, Dr James Merryweather, Dr Susan Buckham, Dr Enrico Fodde, Dr Alasdair Brooks, Dr Mark Beech, Kevin Calpin, Rachel Nowakowski, Eduarda Paz, Pam and Gavin Ward, Priscilla Roxburgh, Pat Haywood, Val and Gordon Goodwin, Emeritus Professor John Paynter, Charles Cockburn and Susi Final, Steve Warburton, and my brother Michael.

AUTHOR'S DECLARATION

There are areas of this research which have already been presented in public and others which have been produced for purposes additional to their inclusion in this dissertation.

Chapter Two is built upon the keynote paper which was presented at a one-day workshop, held on 25 February 1999 at The University of York Department of Archaeology, entitled *Flora in the Conservation of Historic Buildings.* The proceedings of the workshop are unpublished.

The developing research methods for both the laboratory work and the fieldwork investigations of this research were presented as a series of lectures given in March 1999, March 2000 and March 2001, to students of restoration at The Academy of Fine Arts, The University of Zagreb, Croatia. These lectures were given as part of the Academic Links and Interchange Scheme (ALIS) sponsored by The British Council.

The lichen surveys of Harewood Castle and Slngsby Castle were commissioned by Ed Dennison Archaeological Services of Beverly. The species lists for these two sites, included in Appendix 8 and the plans, elevations and illustrations which are included in Appendix 9, were originally prepared as part of lichen survey reports. They are now incorporated into the respective Conservation Plans for those two sites. The method of analysis of the lichen flora used in this dissertation is a development of that used in those two reports and is, therefore, unique to this dissertation.

CHAPTER ONE

RESEARCH FRAMEWORK

BACKGROUND

> 'These little plants first clothe the naked rock; some of them almost too small for vision, unless accumulated in myriads, are yet the simple agents employed to change the rocky mountain into the waving forest, or the sandy desert into the fruitful province. So slow is the process at first that many years must elapse before the newly-erected edifice becomes even grey with age, or in other words puts on its first clothing of vegetation. After this the progress of vegetable life is more rapid. The lichens in their decay leave a little earth where a green Moss soon springs up; this collects more earth, and the Fern or a Grass, or some other plant succeeds, and thus a bed of flowers arises even upon the barren cliff and mouldering wall; but not here only are the lichens found, the earth abounds with various species, and on the trunks of trees they are still more numerous.'
>
> (Francis 1842, p.198)

G W Francis wrote the above lines in 1842, in *The Little English Flora, or a Botanical and Popular Account of all our Common Field Flowers*, a book :

> 'To the Young Ladies of England, whose occupation, tastes and sensibilities, render The Science of Botany so peculiarly a proper object for their study, this work is respectfully dedicated, as an entertaining and scientific introduction to the simple, the elegant and the sweet little flowers of our Native Land.'
>
> (Francis 1842, follows title page)

This quotation embodies three important matters which are germane to the investigations which will be pursued in the following chapters. The first is the propensity of buildings, particularly ruins, to support over time an increasing diversity and abundance of flora. The second is the propensity of buildings ultimately to be returned, by a variety of agencies including flora, to earth. The third matter concerns our relationship with the natural world, particularly the botanical world, and the cyclical process of that changing relationship over time.

The subject of the botanical 'living layer' of historic buildings and ruins has been written about from several distinct points of view. The earliest references are probably from the Anglo-Saxon period in poems such as *The Ruin* and *The Wanderer* which appear in Bradley's anthology (Bradley 1982), but from the middle of the eighteenth century, references were from a visual, but distinctly philosophical point of view. Ruins clothed with plants were valued as part of what was to grow into the Picturesque movement, and that aspect will be discussed further in Chapter Two. The subject has also been written about from the point of view of the botanical interest in the species supported, from the ecological point of view of the individual species and from the point of view of flora on buildings being a minor, but dispensable, irritant in the process of conserving historic buildings. Only recently have there been attempts at co-ordinated efforts, involving all the respective disciplines of botany, biology, ecology, nature conservation and historic building conservation, to assess the value of flora, including lichens, and this research was originally conceived to investigate the potential of plants to give *additional* value to ruins in the form of protection to masonry. Historical precedents would suggest, however, that if such a trend continues, it could be one fraught with dangers, and historical events which have lead to the present trend will be discussed in Chapter Two, along with a consideration of the potential consequences.

The objectives of the conservation of the fabric of historic buildings, and here this means the masonry surfaces of buildings which are exposed to the elements has, in the past, been threefold: to repair and make safe masonry which has been disrupted by plant root growth; to limit or repair the effects of weathering, including weathering induced by flora and to discourage the growth of flora.

There always have been causes of weathering, including those caused by flora, and it is often difficult to determine what effects are promoted by what causes.

Indeed, one of the pressing issues in historic building conservation, stated at the Dahlem Workshop held in Berlin in 1996, is to find ways of diagnosing the causes of the various forms of decay of building fabric in order that appropriate conservation treatments can be implemented (Viles, in: Baer and Snethlage, 1997). The need for a set of indicators of the causes of the decay of stonework was considered at that conference to be one of the most pressing research aims, not just in the conservation of masonry buildings, but equally in the conservation of stone artefacts and sculpture.

Historically, it is evident that the way in which stone weathers, and the role of plants in that process, had been viewed and researched in a particular way. Weathering of masonry surfaces is not caused by individual factors acting in isolation – an impression which might be gained from the literature – but is caused by multiple mechanisms acting together. The consequences of the 'traditional' way of considering stone weathering are two-fold. The first is that the mode of action of individual mechanisms has been investigated, but the way they act in combination is a relatively unexplored area of research. The second consequence is that the role of plants in stone weathering is invariably considered to be just 'further mechanisms'. The result of this way of considering weathering is that the role of plants is invariably considered from the point of view of their direct action.

However, weathering mechanisms are really interdependent processes. If those interdependent processes are considered in order of increasing complexity, that is the number of processes which might exert mutual influence, for better or for worse, then the concept of complex weathering emerges. This concept will be developed further in Chapter Three, and provides a vehicle by which the interaction between processes can better be understood. Once plants are considered in the context of complex weathering, then their role in the process can be seen from a different point of view. Their direct, and indirect influences can be considered as part of a more complex series of interactions. Thus, the role of plants is considered in this research as a component of complex weathering, which can influence, both directly and indirectly, the severity of other mechanisms.

There is one further consideration. It is often implicit in the results of research into the effects of plants on stone, that all types of stone are equally vulnerable. Examples of this might include the damaging effects of mosses, or the effects of lichens. It is well recognised that different types of stone weather in a characteristic manner. This is dependent upon their physical properties, such as mineralogy and pore size distribution, and even stone from different parts of the same quarry can weather differently due to local variations in the rock strata. It is suggested, therefore, that the effects of plants on the weathering of stone, be it direct or indirect, will be influenced by the physical characteristics of the stone. That is an important consideration in this research, and in Chapter Four the laboratory test methods which were developed to determine those characteristics are described in detail.

Emerging from the foregoing are four observations, which together form the rough framework upon which this research is built:

- The current trends towards retaining flora on historic buildings needs to be examined to assess the potential benefits, and the risks;
- weathering processes need to be re-examined, from a different perspective, in order to understand the role of flora;
- the influence of plants on the weathering of specific stone types requires investigation;
- the potential of plants to act as indicators of weathering mechanisms needs to be investigated.

The expression of those observations, as aims, objectives and research questions, will be set out and discussed after the definitions of some key terms have been established.

DEFINITIONS

There are three key terms in this research which need defining from the outset: *flora*, *historic building* and *ruin*. The first term in need of definition, or at least explanation is *Flora*: 'All the plant species that make up the vegetation of a given area...' (Allaby 1996), or, ' ...the plants of a particular region, geological period, or environment.' (Thompson 1995). These would appear to be adequate definitions, but clearly the term *plant* also requires consideration. Taxonomically, it can be defined as a member of the Kingdom Metaphyta, and for reference purposes, the taxonomic hierarchy for the plant Kingdom is included in the Glossary. Included in this Kingdom are organisms from the simple unicellular alga to the large, complex, structures of trees (Allaby 1996), but the distinguishing characteristic of plants, and *ipso facto* flora, is that they usually contain chlorophyll. This enables them to synthesise organic compounds by the reduction of carbon dioxide, using energy absorbed from sunlight (Allaby 1996). Two further distinguishing characteristics of plants are that they have neither sensory organs, nor the ability for voluntary movement.

There are, however, two particular groups of plants which will be under consideration in this research. They are lichens and mosses, and there are three main reasons why these two groups are under consideration. The first is that they comprise conspicuous species which grow in, or on the surface of the stone and conceal, to a greater or lesser degree, the original surface. The second reason is that they have both been implicated in direct weathering of stone and are relatively well studied in that respect. The third reason is that they are both acknowledged to have intrinsic values from a visual and an ecological point of view in the historic building context. Other plant groups such as fungi or algae are less well studied and are more difficult to identify than lichens and mosses. Algae in particular are often seen as disfiguring rather than enhancing to stone surfaces, and so these two groups are not under consideration, neither are vascular flowering plants; they normally root in mortar joints of masonry and are not usually perceived as contributing to stone weathering. One further group of plants which was to have been considered in this research were climbing plants, particularly species of ivy. These have been associated with historic buildings, particularly ruins, and have been a serious cause of disruption to masonry structures; however, the outbreak of foot-and-mouth disease in England during 2001 meant that the necessary fieldwork could not be undertaken because of restrictions on access. This group of plants has therefore been excluded from this research.

Lichens, although they contain chlorophyll, are not plants in the strict botanical sense, because they are composite organisms consisting of an association between a fungus and an alga, or a cyanobacter. The bulk of the lichen is made up of the fungal partner while, unseen, the algal partner manufactures carbohydrates by photosynthesis. This is an association often referred to as symbiosis, in which there is, hypothetically at least, a mutual benefit in the association. Symbiosis is a prolonged permanent association between dissimilar organisms (Allaby 1996), and is often referred to in lichenological literature to describe the fungal/algal association. Some writers doubt that such a state really exists in that association (Smith 1973), while others believe it does (Honneger 1998). A state of parasitism it clearly is not, because parasitism implies a degree of harm by the parasite to the host, with the eventual death of the host. The association between fungus and alga in lichens has been observed to be both stable and long-lived, often in hostile environments where neither partner could survive alone. Lichens belong to the taxonomic group Lichenes, and most are ranked according to the fungal partner of the association. So although lichens are not strictly speaking plants, they are often referred to as such , and because they contain chlorophyll they will be included in our definition of plants in this research.

Mosses are classified in the division of Bryophytes. There are, however, classification problems because mosses fall halfway between thallophytes, which are plants that are not differentiated into root, stem and leaf, and cormophytes, comprising all the plants with stems and roots (Jahns 1983, p.15). 'Mosses have leafy stems, but the fine hair-like structures which anchor them to the soil are not true roots...' (Jahns 1983, p.15), and it should be noted that from the point of view of the succession of species on ruins it is usually a prerequisite of colonisation by mosses that there is the presence of a soil, formed by the aerobic decomposition of organic matter, mainly by bacteria and fungi, such that the complex organic molecules are broken down into simple organic and inorganic molecules which can then be assimilated by plants, including mosses (Allaby 1998, pp.113-114 and p.205). Many mosses are also species of permanently damp or humid environments and that is sometimes influenced by the orientation and aspect of the stone surface, and these are important considerations in assessing their role in stone weathering.

The second key term is *historic building.* For the purposes of this research, the definition of an *historic building* is one which is protected by English statute, under the *Town and Country Planning Acts 1990* (HMSO 1990b), and more specifically, buildings which are listed under the provisions of the *Planning (Listed Buildings and Conservation Areas) Act 1990* (HMSO 1990a), Grade I or II*, which indicates that they are of greater architectural or historical interest than the majority of Listed buildings. The term *historic building* also includes buildings, usually ruins, which appear in the schedules of the *Ancient Monuments and Archaeological Areas Act 1979* (HMSO 1979). The legislation draws a distinction between listed buildings and ancient monuments, but in this research they will be considered under the generic title of historic buildings, because some of the ruins which will be examined are both listed and scheduled. It is important to understand that the finding of this research which relate directly to ruins may not necessarily be applicable to historic buildings in the wider sense of the term, and the reasons why that may be so will be discussed shortly. But what *is* applicable to historic buildings in the wider sense of the term may also be applicable to masonry buildings and structures beyond the historic building context.

The third key term which needs to be defined is a *ruin.* This can be considered to be a building which has passed, for a variety of reasons, from use into disuse and thence into a state of decay from which it is generally no longer economically viable, nor perhaps desirable, to bring it back into beneficial use; consequently, it is usually managed either as an historical record, or as an element in the landscape. Chapter Two will examine in some detail how the buildings in Yorkshire used as case studies came to be ruins, why they remain as such and the conservation implications of their remaining as ruins.

AIMS AND OBJECTIVES

The aims

- To trace changing perceptions and attitudes through time towards the presence of flora on historic building fabric;
- to identify and review the current state of knowledge of the various causes of weathering of historic masonry fabric, including weathering by flora;
- to examine, through laboratory tests and selected case studies, the influences of flora, particularly lichens, on the weathering of historic masonry;
- to investigate the potential *value* of flora on historic fabric.

The objectives

- To draw some conclusions as to the relative impact of various weathering agents, including flora on historic building fabric;
- to develop a complex weathering model for stone, which includes the botanical component, and to demonstrate how an 'impact' matrix for the Jurassic building stones of North Yorkshire could be developed;
- to develop a conservation philosophy towards flora, particularly lichen flora, on the historic masonry fabric of ruins, which acknowledges their intrinsic value, their potential to influence weathering, and explores the potential of their extrinsic values;
- To develop a practical framework for the management of flora on historic building fabric, which has a firm philosophical base, and which is supported by the latest research findings in the various associated disciplines, including the findings of this research.

Research questions

1. What is the current trend towards the management of flora on ruins?
2. Does flora on ruins influence the weathering of the ruin?
3. Can the presence of flora on ruins be used either as a diagnostic tool, or as a tool in the conservation of the masonry fabric?
4. Should flora on historic buildings, particularly ruins, be considered to be part of their cultural significance?

SCOPE OF THE RESEARCH AND HOW IT MAY CONTRIBUTE TO EXISTING KNOWLEDGE

The study area

The scope of the research is limited to the geopolitical area of North Yorkshire, but with one case study site in the West Riding of Yorkshire. Yorkshire is the largest county in Great Britain, and is one of the most diverse in terms of both geology and scenery, the interdependence of which has led over the centuries to a variety of both cultural landscapes and architectural heritage. This gives the county a range of culturally significant environments, with micro-climatic variations and diversity of stone types, in which to study the effects of flora on historic building fabric.

Throughout the twelfth and thirteenth centuries, monastic orders such as the Cistercians and the Cluniacs, the Benedictines and the Gilbertines, all built their abbeys and priories on the banks of the rivers which had, over geological time, helped to form the Yorkshire landscape. The ruined monuments which give evidence of past aspects of our culture are to be found the length and breadth of the county, from the seclusion of Coverham near the head of Wensleydale, to the prominence of St Hilda's Abbey on the cliff-top at Whitby. The diversity of the topography has also provided many physical features which have provided defensive sites suitable for fortified living, including Harewood Castle, near Leeds, Richmond Castle in the north of the County and Scarborough Castle on the east coast.

After the Dissolution of the Monasteries, monastic buildings became ruins. As a consequence, their lands were sold, and during the seventeenth and eighteenth centuries many country houses were established on those lands. Subsequently, designed landscapes were set out, often incorporating buildings in the form of square, or circular temples modelled on Greek and Roman precedents such as the Temple of Athena in Tivoli. These temples might be defined as follies, and were originally designed as part of walks around the designed landscape, to be enjoyed by the owners and visitors to the country house. They were places to picnic or admire the view, but are no longer an integral part of the social life of the country houses to which they belong. They still remain as objects in designed landscapes and as places from which the tourist can view the landscape, and although they are sometimes in a state of advanced decay they have a rich associated flora. Examples include the Temple of the Four Winds, at Castle Howard, and the two temples at Duncombe Park.

It is then, the standing remains at monastic sites, the ruins of castles of the middle ages and the temples which form features in eighteenth-century designed landscapes, each valued as part of the cultural heritage of the county, which provide the raw material for this research. These may seem to be disparate types of buildings but they have one important feature in common compared to buildings-in-use, and that is their potential for botanical colonisation.

Ruins and botanical colonisation

Ruins present a very special set of circumstances in the context of historic building conservation. Not only do they form an important part of our cultural heritage, but by their very nature, they are more vulnerable to all the processes of weathering. They are one step nearer to their complete integration into the local ecology than buildings-in-use. It is, therefore, because of their added vulnerability to weathering that they are invaluable in the study of their relationships to flora, and particularly to lichens. The external fabric of buildings in use, with roofs, and with heating in cold weather, provides a significantly different environment for potential plant colonisation than does the exposed fabric of ruins. Masonry surfaces of heated buildings not only receive insolation during the day, but in colder weather the wall temperature may remain relatively high due to heat losses from within the building. This helps to maintain the evaporation of residual moisture within the pore structure of the masonry, and therefore the masonry will have a considerably lower moisture content than that of ruins. The evidence to support this may be seen in the locations where flora first develops on buildings-in-use: on the tops of cornices, string courses and mouldings; on the ledges of plinths and on the surfaces of walls which are continually fed moisture, either from the ground, or from leaking gutters or rainwater pipes. Colonisation of such surface is also influenced by aspect and orientation, and more abundant growth is often evident on surfaces in partial or permanent shade. The masonry of ruins on the other hand, has a relatively stable, but higher moisture content; daytime insolation and the tendency for the evaporation of moisture will always be compensated by both a relatively damp rubble core, and for every surface receiving insolation, its opposite surface may be supplying moisture, except in exceptional periods of prolonged hot, dry weather.

Geological diversity of Yorkshire

The underlying geology of the county has, over time, resulted in a diversity of scenery, as well as yielding an equal diversity of building stones and built forms.

It was William Smith who, in the late eighteenth-century, discovered the geological stratigraphy of Britain and an account of that discovery can be found in Winchester (2001). As a result of that work, it is now know that the oldest, metamorphic, rocks lie in the north-west, while the youngest, of the Cretaceous period, lie in the south-east. The older rocks are progressively overlaid by younger rocks, with the whole sequence slightly inclined from north-west to south-east. The consequence of this, and of subsequent weathering, is that a sequence of rocks of differing types and ages is exposed in broad bands running north-east to south-west along the length of Britain.

The reason for the geological diversity of Yorkshire is because the county spans almost the full breadth of the country and five of the major sequences of sedimentary rocks in Britain have exposures running the length of the county. The Carboniferous are exposed in the Yorkshire Dales in the west, followed by the Permian rocks to the west of York. The Triassic rocks underlie the Vale of York, the Jurassic rocks are exposed to the north-east of York and the youngest, the Cretaceous rocks extend from the Yorkshire Wolds, to east of York as far as the east coast. This is illustrated on the extract from the geological survey map included in Appendix 9.

This geological diversity and the resultant variety of building stones which have resulted yields a number of different types of substrata and potential habitats where the weathering influences of flora can be studied. These habitats extend the length of England and so the results of research in Yorkshire will have application over a much wider geographical area, but the stone types which will be studied in this research are principally from the Carboniferous and the Jurassic sequences. This is because it is from these two contrasting rock-types which a large number of historic buildings in Yorkshire, many now ruins, were built. The stone types from these two sequences are discussed further in Chapter Three, and descriptions of the stratigraphy local to the case study sites is given in Chapter Six.

The plant types

The two plant groups under consideration have already been mentioned. They frequently colonise ruins, but lichen have been selected for special attention because they are relatively poorly understood in the historic building conservation context. They have a complexity of structure, and a diversity of form which, it could be argued, is unrivalled in the higher plants. The Yorkshire region can boast over 800 taxa, containing more than 700 species (Seaward 1994). The diversity of building stones in North Yorkshire, and the variety of climatic and geographical situations, gives rise to a huge habitat potential for lichen colonisation by a variety of species. Like any other form of vegetation, lichens are opportunist, but their tolerance of habitat and substrate type is strictly limited; they are extremely substrate-specific. They each have an identifiable preference with regard to stone type, acidity or alkalinity of the substrate, moisture content of the substrate, orientation, inclination, illumination and so on, and research into this aspect is well documented (Bachman 1890; see also Bachman 1892; 1904; 1915; Ahmadjian and Hale 1973; Smith 1975, pp.209-251, pp.356-394; Brown *et al.* 1976; Seaward 1977), and most recently Gilbert (2000). They are the accepted pioneer species of most naturally occurring rock habitats and they are extremely persistent individuals commonly living for many decades, and communities may persist for centuries. Not only are they substrate-specific, but they are sensitive to both environmental changes, and to changes to their substrate, the latter sometimes being a consequence of the former. It is because of the sensitivity to change, that lichens have been studied in relation to atmospheric pollution, most notably by Gilbert (1970), Hawksworth and Rose (1976) and Richardson (1992).

Lichens and mosses colonise the surfaces of stones, and that is why they are able to contribute directly to weathering. It is also why they have the capacity to exert an influence over other weathering mechanisms. Sometimes damage is evident on the surface of stone in the form of surface spalling or blisters, apparently caused by lichens, but without microscopic examination or chemical testing it is usually impossible to say whether the visible decay is due to the lichens or to other causes. Research into the damage which lichens cause to masonry substrates has tended in the past to have been carried out either under laboratory conditions with prepared samples, or in remote parts of the world as part of a wider agenda. What is now needed is a method whereby the influence of these plant groups can be studied, and that method, and its development, will be described in Chapter Four.

Mosses are usually understood for their ability to hold water against the surface of stone. The presumption is, therefore, that like lichens, they also have the capacity to influence other weathering processes; therefore, the same research method will be used as that developed to investigate the influence of lichens.

Contribution to existing knowledge

The results of this research will contribute to existing knowledge in three distinct areas:

- The first is that analysis of the physical properties and weathering characteristics of the stone types used at the case study sites will have immediate application in the conservation of those monuments;
- the second is that the investigation of the *indirect* influence of plants on weathering processes will provide important information which will enable conservation parameters to be established in relation to flora on historic buildings in general, and on ruins in particular, and the test methods which have been developed to investigate this aspect will also have wider application. It will also provide an indication as to whether current trends in the management of historic building fabric are sustainable, that is, whether they

can continue without putting historic masonry at risk.. If this proves not to be the case, it may trigger a radical re-think about the role of flora on historic fabric in general, and ruins in particular;

- the third is that the investigation of the power of plants to act as indicators of a specific weathering mechanism on specific stone types will be a valuable conservation aid, notwithstanding any direct, or indirect, weathering by any particular plant group.

There are two further considerations. The findings of this research may have application beyond the study area, because of the wider distribution of the geological strata in Britain, and the results may precipitate further research in the same, or a different direction, which will further add to existing knowledge.

LIMITATIONS OF THE RESEARCH

The life-time of a Ph.D. is short. There is only so much that can be achieved within the prescribed period of time; consequently, the scope of this research has been limited to the study of a manageable number of stone types, and a limited number of plant types, at a few selected sites. The plant types and the study sites have been carefully selected so that the results of the research may have wider application. There are, however, areas of research which, for reasons of either finance, resources, or both, cannot not be pursued, and these are highlighted in the appropriate parts of the chapters which follow. This research has developed over the course of the prescribed period, and has continued to develop since the end of that period. There are, therefore, avenues of investigation which have come to light either during, or as a consequence of this research, and these are described in the concluding chapter, Chapter Seven.

RESEARCH METHODS

No single research method will provide the answers to the research questions. Each question requires a different method, different resources and different sources of information; consequently, the following research strategies have been adopted.

The current trend towards management of flora on ruins

It is important to an understanding of the current trend, to identify also how it arose, because that provides the historical background to this research. This will be investigated by reference to published sources from the eighteenth, nineteenth and twentieth centuries; from twentieth century commentaries on the relevant events of the previous two centuries, and from more recent sources, both published and unpublished.

Flora as an influence on weathering of ruins

To be able to answer this question, it is first necessary to understand the principal mechanisms, such as frost, salts and atmospheric pollution, which cause weathering of stone. This will be achieved by reviewing the published literature on the subject, both past and recent. Stone samples from the case study sites will then be subjected to laboratory tests to determine their physical properties, and their performance under three key simulated weathering tests.

Mention has already be made of the potential for plants to influence weathering, as part of complex weathering, and the presumption is that this is achieved by slowing or acceleration the passage of water into and out of the stone. This has implications for frost action, for damage by the re-crystallisation of soluble salts, and for the action of rainwater in which atmospheric pollutants have been dissolved, or by dry deposition of those pollutants, and this can be investigated by examination of moisture gradients within stone.

There are several techniques available which have the potential to establish moisture gradients within individual stones. Infra-red thermography (Gayo *et al.* 1992) is one, but infra-red photography may prove to be equally effective because it is a method of recording surface temperatures, which are influenced by zones of evaporation of pore water. The lowest temperatures will be recorded from the surfaces from which there is the highest evaporation rate. Ultrasound scanning (Galán *et al.* 1992; Valdeón *et al.* 1992) is another technique which has the potential for plotting moisture gradients, and could be applied to stones with total or partial lichen cover.

A different technique is that of surface contour mapping, to investigate whether lichens and mosses exist on 'islands', or in 'pits' on the surface of stones. If pits can be detected it could be concluded that lichen and moss weathering activity is greater than weathering by other agents. If islands are detected, it might indicate that lichen weathering effects are less than those of other agents. It has to be acknowledged that the pits or islands, if they exist, might be on a microscopic scale and so their detection will depend on the resolution with which the surface contours can be plotted.

What is required for this research is a method whereby the rate of water absorption and subsequent evaporation from stone can be determined. The laboratory measurement of the saturation time, and subsequent drying times of samples of stone, with and without mosses and lichens, will provide the means by which the influence of those two plant groups on weathering can be assessed. By analysis of those times it should be possible to determine the degree to which mosses and lichens influence water movement in and out of stone, whether those differences are significant, and the consequences of that significance for complex weathering. This method was developed specifically for this research, and details of the development process are described in Chapter Four.

Notwithstanding the development of the saturation and drying test, a further test procedure can be developed. The application of a test to simulate the resistance of stone to the action of soluble salts has, in the past, also been used as an indicator of the potential for frost damage. This is because salts test can simulate weathering over a few days, while an out-door frost-weathering test may take many years to provide results. The development of a salts test which could be used on stone samples which had colonisation by mosses and lichens would give an indication of the potential for those plant groups to influence the action of soluble salts and the action of frost. The development of this test method is also described in Chapter Four.

The results of the laboratory tests will be related to the historic building context using fieldwork as the vehicle, by way of selected case studies of ruins. The method of the selection of the case study sites will be described at the end of this section.

Flora as diagnostic and conservation tools

There is evidence to suggest that lichens, and perhaps other plant groups may, under certain circumstances, protect stone from weathering. That evidence will be discussed in Chapter Three, but it remains to be seen if that is universally true. In the case of lichens, there is a body of knowledge concerning their sensitivity to environmental pollutants, and this will be discussed in Chapter Six. It is by understanding and developing that knowledge that lichens may prove to be reliable indicators of the causes of weathering. To this end, lichen surveys were commissioned for each of the case study sites, and the species compositions were compared, where possible, with the species compositions recorded in surveys carried out in the past. An analysis of any significant differences between groups of species might indicate changes in the concentration, or type of air pollutants, and this may have implications for weathering.

Flora as part of cultural significance of ruins

Cultural significance is defined in the Burra Charter as: '...aesthetic, historic, scientific or social value for past, present or future generations.' (Australia ICOMOS 1999). An answer to this question will emerge from the answers to the previous three questions. This is because those answers will reveal the extent to which those four values, stated in the charter, can be attributed to flora, in addition to the cultural significance of the standing remains of the monuments under consideration. Flora may, therefore, add further layers of value to the layers already recognised; consequently, all the research methods which have been described will be used in order to provide an answer to this question.

Selection of sites

In the selection process, there were initially 77 sites under consideration for case studies. These were narrowed down to seven, on the grounds of accessibility, ownership, extent of standing remains, extent of flora and condition of stonework. From these seven, four were finally selected. The criteria were:

- They should be within easy travelling distance from York;
- at least one should be a property in guardianship;
- at least one should be in private ownership, and should not have been subjected to recent reconstruction, consolidation or major conservation;
- at lest one should have an abundant lichen flora;
- at least one should have extensive stone decay in the presence of flora;
- there should be a diversity of stone types either within, or between, the different sites.

These were the general criteria, but an account of how the selected case study sites fit within the general criteria can be found at the beginning of each case study, in Chapter Six.

OUTLINE OF CHAPTERS

Chapter Two: The Cultural Context

This chapter traces the changing values which have been placed on ruins in the past. It also examines how those values are still changing and investigates the possible consequence for their conservation.

Chapter Three: Literature Review

This chapter examines what is known about the causes of the weathering of stone, and investigates how the weathering processes attributable to plants, including indirect processes, might fit in an overall model of stone weathering.

Chapter Four: Laboratory test methods and their development

This chapter identifies the laboratory methods which are available to determine the physical properties and weathering characteristics of stone, and how those methods can be adapted to the requirements of this research. This chapter also describes the development of new test procedures to determine the indirect influence of plants on weathering processes.

Chapter Five: Results and Analysis Methods

This chapter presents the results of the laboratory tests, and analysis of the data. An assessment is made of the likely impact of plants on stone types with differing physical properties and weathering characteristics.

Chapter Six: Case Studies

In this chapter the fieldwork methods are described, the results presented and analysed, and the results of the analyses are discussed in relation to the results of the laboratory tests.

Chapter Seven: Conclusions

Appendices

The supporting documentation, generated principally by laboratory work, fieldwork and data analysis, is beyond the scope of the main chapters of this thesis, and is contained within the ten appendices which follow Chapter Seven.

1 The pilot tests of the laboratory methods: methods; data; results
2 Physical properties tests: data; results; analysis
3 Simulated weathering tests: data; results; analysis
4.1 Saturation and drying tests: data
4.2 Saturation and drying tests: graphs
4.3 Saturation and drying tests: analysis
5 Saturation and drying tests: analysis of uncontrolled variables
6 Saturation and drying tests: analysis of significant results
7 Duncombe Park Temples: data; graphs; analysis
8 Lichen surveys: methods; species lists
9 Illustrations
10 Development of a risk assessment model

The Glossary of technical terms

Bibliography

CHAPTER TWO

THE CULTURAL CONTEXT

INTRODUCTION

This research is set against a background of changes to the way ruins are managed in Britain. This chapter investigates the nature of those changes, and the reasons why they are occurring. The reasons are not, however, to be found solely in the recent past, but it is necessary to trace changing perceptions, and the shifting values which have been placed on ruins over the past 500 years to understand fully what is happening now.

The origins of Ruins

What are now ruins were once buildings, but buildings become ruins for many reasons. These reasons might include the consequences of political or social change, changes in use-requirements, structural inadequacy, fire, wilful destruction, or financial misfortune.

Many types of building, religious, secular, military, domestic, industrial and commercial, have, historically, become ruins. It is, however, only certain types of buildings which have been valued in their ruined condition. Two types of buildings are under consideration here, because between them they provide much of the stock of managed ruins in England today. These buildings are medieval abbeys and monasteries and castles of the medieval period and later.

There is one principal reasons why the abbeys and monestaries of England became ruins and that is political. The Dissolution of the Monasteries by Henry VIII in the early 1530s, and its aftermath, is an event which is well documented, particularly by Briggs (1952, pp.16-30). As a consequence, the monastic houses were forced to surrender their lands and property to the Crown. Their lands were usually sold, often for favourable sums, to the nobility. Their properties were either converted to other uses or, more usually, rendered unusable by partial destruction, or by partial dismantling for materials for new buildings elsewhere. By 1540 most of the monastic houses in England were in ruins (Briggs 1952).

Castles, however, became ruins for several reasons. It is often assumed that this was because of improvements in artillery in the fifteenth century, but many were simply abandoned because they were obsolete, or no longer considered as desirable places in which to live. Some were, however, turned to other purposes, or modernised (Briggs 1952, p.40-41). In any event, by the fifteenth century, most battles were fought in open country, and the castle as a place of refuge during long sieges was, by then, out of date; nevertheless, many castles had still retained a defensive function into the fifteenth century, but their defences were easily breached by cannon fire. Those which were captured during the English Civil Wars were subsequently pillaged for materials at the end of the Wars, which ensured that they were no longer of use either offensively, or defensively (Briggs 1952, pp40-41).

There is one further reason why castles became ruins, and that is not because their defences proved inadequate under siege, but because they were never completed. Some castles, or more correctly, fortified houses, may have been started either just before, or even during the first Civil War, and as workmen were called away to take up arms, work was suspended. Because of the duration of the wars, work on some never recommenced (Brook 1904).

Mention was made in Chapter One that temples in designed landscapes are also to be included in a definition of ruins. They are, however, ruins of a quite different kind to abbeys and castles. They were not abandoned for any of the reasons so far described, but gradually slipped out of use, largely as a result of changing social values and the financial constrictions suffered by many country house estates since the Edwardian era. They were not slighted, or pillaged for materials, but have been left gently to decay, but are still valued as an integral part of those designed landscapes.

PAST VALUES

Buildings which originate from the medieval period, or from the middle ages, and which subsequently became ruins, can be considered to have passed through several phases since they were built. Chitty (1987) identified those phases as: a building as architectural design and construction; a building with a useful working life; a building abandoned and despoiled; a period as a ruin; a ruin with picturesque value; a ruin with historical value; a ruin as a object for preservation (Chitty 1987, p.44). One additional phase can be added, and that is a ruin with botanical value, because in the late eighteenth and early nineteenth centuries, they were valued for the abundance and variety of the plants for which they provided habitat. These, then, can be considered to be the phases of the life of ruins up until the 1930s, by which time most of the ruins in guardianship in England had been consolidated, and made accessible to the public. Then their value was principally as historical evidence.

There are, however, two further phases to add, which have been apparent at least since the end of the Second World War. It is evident that for much of the latter half of the twentieth century, there had been increasing disquiet over the way in which ruins were managed and presented. The passing of the Picturesque, and of the Romantic was regretted by many, and it is argued, therefore, that ruins have also been valued as reminders of past, un-attainable, values. It is only the recent recognition that historic sites, including ruins, have unique nature conservation value, which has, to some extent, mitigated against that feeling of lost values, and more will be said about these two aspects later in this chapter.

Materials and reuse value

The destruction of monastic houses after the Dissolution is well documented. Thomas Cromwell and his agents systematically stripped the interiors of their precious artefacts and works of art, which were then sold. Large parts of many abbeys and monasteries were dismantled or demolished in order to salvage materials, particularly lead from roofs, timber, and stone, and the bells (Briggs 1952, pp. 16-30).. Once the roof covering and structure had been removed, the wall-tops and internal surfaces were left exposed to the elements, and the processes of weathering and decay began. Many religious houses were situated in rural areas. There, the demand for salvaged materials was limited, and they were not plundered to the same extend as those in urban situations, but were converted to other uses such as cow-sheds, cart-sheds, or piggeries (Briggs 1952, p.24).

Castles fared a little better, despite the policy of Fairfax and Oliver Cromwell, during the Civil Wars, to slight castles in England and Wales. That policy involved their intentional destruction by blowing up keeps, curtain walls and bastions (Briggs 1952, pp.73). Despite this policy, they faired better than religious houses because many were left with a large part of the structure undamaged, due to their often massive construction. Some castles, such as Arundel and Alnwick, were subsequently restored, but many were finally abandoned by their owners and subsequently fell further into ruin due to pillage of their stone (Briggs 1952, pp.72-74).

No value

Once the retrievable building materials had been taken from the recently abandoned abbeys, monasteries and castles, they were considered to be of no further value. The reasons why they were not completely destroyed is not clear, but mention has already been made that demand for stone in rural areas might be supposed to be less than in towns and cities. Compare, for example, the extensive surviving remains of Rievaulx Abbey, or Fountains Abbey, with that of St Mary's Abbey in York, where little more than the wall of the north aisle of the nave of the abbey church, and part of the central crossing survive above ground level. What is clear, though, is that these remains lay abandoned for at least 150 years, before they once again were considered to be of value, but this time the value was entirely different.

Picturesque value

Thompson believes that for at least 100 years after the Dissolution, the ruins of religious houses were too close to the catastrophe of destruction and current events at that time to be viewed dispassionately, and it was only in the mid-to late-seventeenth century that they could be viewed in a more detached way (Thompson

1981, p.14). Ousby (1990) suggests that ruined abbeys, particularly by the early 1700s, when the neo-classical had become fashionable, came to symbolise what Clark described as the '...fantastical and licentious...' (Clark 1962, p.15), but also the freeing of England from the horrors of a Catholic past. Similarly, the surviving castles and manor houses were reminders of the ties of feudalism (Ousby 1990, pp.104-105). But by the early part of the eighteenth century the ruins of abbeys, monasteries, and of castles, began to take on a new value as picturesque objects in a landscape.

The picturesque movement had its roots in eighteenth century aesthetic theory, which began in Italy. It was painters such as Nicholas Poussain, Claude Lorraine, Salvator Rosa and Carracci and, later in Britain, Constable and Turner who painted with a new way of 'seeing'. The idea of the Picturesque, as it came to be known, was brought to Britain by travellers returning from The Grand Tour in the eighteenth century, and this idea was a way of seeing buildings and landscapes as if they were paintings: from the Italian *Pittoresco* – after the manner of the painters. This way of seeing buildings and landscapes was in vogue from between about 1730 to 1830 (Hussey 1927), and was not restricted to painting. It was a genre which also embraced poetry, prose, architecture, and landscape design. This was not only the era of Gainsborough, Constable and Turner, but also of artists such as John Abbot White, Samuel Prout, Cotman and, particularly William Richardson, whose water-colours and engravings of ruins, produced around 1840 for the book *The Ruined Abbeys of Yorkshire* (Richardson and Churton 1843), have immortalised a way of seeing ruins as an integral part of the landscape. It was also the era of Humphrey Repton and 'Capability' Brown, and landscape 'improvements', of Edmund Burke and William Gilpin. The writers of the time whose works influenced the direction of the movement include: Burke (1757); Gilpin (1782; 1794; 1796); Knight (1795); Price (1810). The most scholarly accounts and analyses of the movement are those of Hussey (1927), Hipple (1957) and more recently Ousby (1990).

A review of the Picturesque in Britain would not be complete without mentioning the works of novelists such as Ann Radcliffe, Jane Austen, and that quintessential English romantic poet, William Wordsworth (Radcliffe 1794; Austen 1818; Wordsorth 1810). All of these artists and writers have conditioned the way in which we perceive the relationship between ruins and the natural environment, and there is a strong argument to support the view that there is implicit in the Picturesque a perception which is now deeply embedded in our culture.

An important aspect of the Picturesque, as Barrell observed, is that it was a *genre* which was concerned with the appearance of objects to the entire exclusion of their use or function (Barrell 1992, p.98) – they are purely part of a composition. 'The picturesque eye is a polaroid lens, which eliminates all sentimentality and moral reflection.' (Barrell 1992, p.104), and therefore figures are what they do and objects are what they are. It follows, therefore, that the incorporation of images of ruins into Picturesque scenes was only possible because they fulfilled the requirements of the *genre* as defined in the writings of it proponents, particularly of Burke and Gilpin.

From the 1720s, landscape gardeners began to incorporate neo-gothic temples or ruins into their designs, and by the 1770s the neo-classical was seen as less fashionable; '...gothic would be exalted from a novel, agreeable, plaything to the very embodiment of architectural purity.' (Ousby 1990, p.106). By the end of the eighteenth century, many of England's ruined abbeys and castles had been incorporated as picturesque objects into designed landscapes. These include the ruins of Fountains Abbey which was incorporated into the design for Studley Royal Park by William Aislaby. The ruins of Harewood Castle were incorporated into the design for the pleasure grounds of the landscape of Harewood House, and the ruins of Rievaulx Abbey which were used as a picturesque object to be viewed from the designed landscape of Rievaulx Terrace, part of the Duncombe Park Estate.

Botanical value

There is no doubt that the Picturesque, and the Romantic movement which followed it, led botanists of the late-eighteenth and early-nineteenth century to turn their attentions to ruins. This happened long after the ground-breaking work of Linnaeus, who developed the first system for the classification of plants (Linnaeus 1753), and it was long after Robert Brown's 'natural' system of plant classification was proposed. It was also after Charles Darwin had written his *Origin of Species*, and so the foundations of modern botany and biology had already been laid. The botanists under consideration were, then, interested not just in the botanical aspect of ruins, but in the study of natural history as a broad cultural aim.

Gilmour (1944) suggests that the publication in 1789 of Gilbert White's *The Natural History of Selborne* (White 1788-89) was evidence of that broad cultural aim, and that many amateur societies were established during that period. Allen (1976) suggests that it was the acceptance of the Linnaean system in Britain which helped to create the Romantic movement faster than might otherwise have happened (Allen 1976, p.53).

By the early nineteenth century the amateur societies included many groups concerned with field botany, established with the aim of recording the plants of a particular locality (Gilmour 1944, p.41-42), and the passage from Francis, quoted at the beginning of Chapter One, suggests that botany was a fashionable hobby, especially for young ladies. Thomas and Wells (1998) (subsequently published in Grenville 1999, pp149-162) make the point that in the nineteenth century, ruins were key places in which to record animals, and plants, and it is not difficult to understand why this was the case. It is only a short step, intellectually, from the Picturesque ruin in a landscape, to the same ruin as a Romantic location in which to study the flora and fauna, as well as the geology and archaeology of that location, and that step was taken in only a few decades.

Historical value

The Picturesque, Romanticism, The Gothic Revival, William Morris, the Arts and Crafts, and archaeology, have all played their part in moulding our attitude towards ruins, each movement overlaying what went before (Thompson 1981, p.95), and so the transition between romantic ruin and managed monument was not a sudden one. It was, rather, the culmination of an interest in ruins, particularly Gothic, which had begun even at the time William Gilpin was popularising the Grand Tour. It was also a result of changes in architectural taste, described by Kenneth Clark as the transition from the 'picturesque phase' to the 'ethical phase' of the Gothic Revival, dominated by the work of Pugin and Gilbert Scott and the emerging concept of ecclesiology (Clark 1928, p.120). The cornerstones of British archaeology were being laid by Sir Richard Colt Hoare, William Carrington and William Cox, who made inventories, surveys and excavations in Wiltshire at the end of the eighteenth century. Colt Hoare documented the deterioration of many ruined sites (Chitty 1987, p.47) which, ultimately, led to restorations by James Essex and James Wyatt, in the late nineteenth century. It was only later that these restorations, in turn, received criticism from Ruskin and Morris, and in 1877 the SPAB was founded in order to try to put an end to such radical interventions. It was gradually accepted that repair, and not restoration, should be the accepted way of preserving ruins, particularly Gothic ruins.

In 1882 the first Ancient Monuments Act was passed (Anon 1882). This legislation effectively heralded the end of the romance between buildings and nature, a relationship which had lasted for almost two hundred years. Following the taking into care by the Government of monuments which had received statutory protection under the developing legislation, there then began a series of 'rescues' of those ruins.

PAST POLICIES

The philosophy behind those 'rescues' was based on the premise that ancient monuments should be valued for both their fabric and as an historical record.

There was no place for *romantic* notions about the past and, therefore, 'dead' monuments should appear 'dead', both physically and symbolically. The objectives were to arrest decay and to preserve the masonry in the condition in which it was found. This has, to a large extent, been the philosophy which has persisted in Britain since that first programme of 'rescues' was begun by the Office of Works and its successors, in the early decades of the twentieth century.

Interpretation, presentation and intelligibility of monuments, for the benefit of both scholars and the public, were matters which had to be addressed, along with the attendant matters of accessibility and public safety. The result was that many of the ancient monuments in Britain were stripped of their vegetation, their sites excavated to reveal the ground plan, their masonry consolidated, and their sites made neat and tidy so as to present an intelligible 'whole' to the public – to a great extent, that is the situation which remains today.

As a result of centuries of neglect, monuments under the jurisdiction of Sir Charles Peers, the Chief Inspector of Ancient Monuments, were stripped of their vegetation to reveal the fabric, and to enable repairs to be made to damaged masonry, resulting from neglect. Frank Baines, principal architect in The Office of Works in the early twentieth century, wrote a series of instructions for foremen in charge of works of preservation. These appeared as an appendix to the *Report of the Inspector of Ancient Monuments*, for the year ending 31 March 1913. He advised that ivy roots remaining at the foot of walls, after the remainder had been removed from the masonry, should be dug out, or killed by the application of sulphuric acid (HMSO 1914, p.104). There was clearly the intention that ivy-clad masonry, once beloved of the Romantics, would be banished for ever.

In the early years of the twentieth century, honesty, truthfulness and above all 'evidence' were therefore important considerations in the preservation of ruins (Thompson 1981, p.20), and these rescues effectively saw the end of the romantic ruin. The ancient monument in a setting of mown turf was created, where evidence of vegetation was not allowed to obscure, either physically or metaphorically, the historical narrative of the monument.

The managed monument

The implications of those policies were many. Thompson recalls '...both the preservation and display of the masonry require it to be free from the later accretions of vegetable growth.' (Thompson 1981, p.22). Those accretions of vegetation which concealed the stonework, and which were a deterrent to its preservation, or to the understanding of the original construction, had to be removed, along with accretions of structure or fallen debris. Debris was removed from wall bases so that the original ground plan could be revealed, and any treatment to walls was only to be undertaken after the removal of vegetation. '...what is displayed on the site are the authentic remains of the period to which they purport to belong.' (Thompson 1981, p.27).

On the matter of display, Thompson notes that many ruins were part of urban parks and that flowers formed a rival distraction to be frowned upon. Similarly, in a rural setting, trees within the ruin were acceptable, but trees on the ruin were not. There was also a certain incongruity between gardens, which imply activity, and ruins (Thompson 1981, p.63). The lawns, which provided the setting, were often more impressive than the ruin, and have come to symbolise the English obsession with order, tidiness, and efficient maintenance. But despite its disadvantages, grass was seen as low maintenance, allowed exposure of low walls and was dry and soft underfoot – its main disadvantage was that it did not stand wear and tear, but nevertheless, it looked good with stone (Thompson 1981, p. 30).

Thompson further describes what can only be referred to as the obsession with the monument, at the expense of all other layers of value or meaning. He notes that the surroundings affect the impression of the monument, which can be enhanced by the demolition of later obstructions, or the restoration of original buildings immediately adjacent. Later additions, particularly later landscaping, as at Fountains Abbey and Rievaulx Abbey is, he claims, entirely misleading as to the real medieval appearance of those sites, and gives visitors the wrong impression of their original aspect, although he acknowledges, perhaps with hindsight, that these later additions are important in their own right (Thompson 1981, p.33).

RECENT PERCEPTIONS

There are two threads of argument which follow from the way in which ruins were, and still are to a large extent, managed. One concerns the appearance of the monument, the visual perceptions and whether what has been done to them is acceptable; the second concerns how the practical aspects of maintaining them in their present state are perceived.

Visual perceptions

In the examination of the first of these threads, it is evident that although the establishment of mown lawns around ruins was supposed to provide them with an anonymous setting which gave them prominence, this policy has caused problems. It has been extended to so many of Britain's monuments that is has become a standardised approach and, whilst it *may* assist in the understanding of a monument, it has resulted in a certain 'sameness' which has had a detrimental effect on the *genius loci* of many sites. This matter is one of concern, and the whole matter of a monument, in relation to its setting, is one which was first addressed by the Venice Charter of 1966. Indeed, it is quite clear that these monuments have not been handed on by those responsible for their rescue '...in the full richness of their authenticity.' (ICOMOS 1966), because so much of the ruins and their sites were altered as a result of those rescue policies.

Many writers have made the observation that the treatment of ruins, to make them legible as historical documents – although whether that was achieved is a matter of some debate – leaves much to be desired from other points of view. 'Our ruined abbeys and churches are, as a rule, only too well tidied up and cleared, losing in the process who can say how much of the mystery and nostalgic awe.' (Macaulay 1977, p.131). Macaulay recalls the intentional creation, in 1836, of a ruin by the destruction of an ancient fortified manor, to create a picturesque object to be viewed from a new house built higher up a hillside. The creator of this ruin, Mr Hussey,

> '...achieved his picturesque object; from the first it must have been beautiful; today, creeper-grown and the colour of lichen, standing with the grey and rust-coloured barbicaned castle tower against a steep wilderness of quarry flowers behind, and at its foot the Lilly moat reflecting sky, trees, tower and ruined mansion, today makes an exquisite picture.'
>
> (Macaulay 1977, p.224).

Conserving ruins can be seen as not just about the 'stones', but also about the 'spirit' of the place. It could be claimed that it should involve the gentle integration of the structure into the natural environment, which allows ruins to regain their clothing of flora. That is something which has, to a large extent, been excluded from many conservation projects until recently; the visible links with the past have been lost, but at the same time, the body of evidence which could guide the way for a closer integration with nature has not been thoroughly consulted, has not been accessible, or worst of all, is lost or utterly destroyed.

Of Carew Castle in Pembrokeshire, Felmingham and Graham wrote: 'We should point out that it is something of a rarity today to find ruined castles still wearing their green cloak.', and 'It is hoped that this castle will remain in its present ownership that allows ivy, and flowers, and lichens to remain whilst skilfully avoiding their worst depredations.' (Felmingham and Graham 1972, p.30-31). In describing Baconsthorpe Castle, in Norfolk, they compare the castle, photographed in 1946, showing it as a copse of trees and undergrowth in a field, with its prospect after restoration a few years later. They note that the wildlife which had abounded in the area of the castle when it was a jungle had disappeared, except for the odd few birds –

> '...one almost feels that, although it is a good thing that the decay has been stopped, the appearance of the castle, clothed in ivy and twisted trees, had a more romantic and appealing air about it than the clean naked lines of the spruced-up ruin on its smooth green lawns with which we have since become increasingly familiar.' (Felmingham and Graham 1972, pp.36-37)

Mostafavi and Leatherbarrow observed that buildings take on the qualities of the places in which they are situated, their colours and surface textures being modified by, and in turn, modifying those of the surrounding landscape (Mostafavi and Leatherbarrow 1993, p.72). This is a key aspect of weathering over time, and one which has been largely overlooked in the context of the management of ruins, for most of the twentieth century. The interrelation between buildings and ruins, and place, and the role of plants in that interrelation is not to be underestimated, because both the colour and texture of much of our built heritage, particularly in rural areas, and more particularly of ruins, is due to plants. The variable of time, which plants represent, was not a consideration in those early rescues.

Those perceptions, evoking multiple layers of meaning and hierarchies of values, all have overtones of Romanticism. Isaiah Berlin maintained that Romanticism overturned a strand of western thought which had existed for over two-thousand years. That strand was that there is virtue in knowledge, and what the Romantics achieved was not knowledge, but the creation of values (Berlin 1999, p.118-119). Those early twentieth century rescues were certainly carried out in the search for knowledge, but it is still debatable whether they resulted in new values with any lasting appeal. Bate claimed that the appeal of the Romantics was in their alternative, holistic vision of nature, which included buildings and ruins in landscapes; they were, in effect, the first ecologists (Bate 1991, p.57). That observation now has an even greater relevance to the present than it did when it was written, only twelve years ago, and the reasons why that is so will become apparent before the end of this chapter.

Practical perceptions

The second of these threads concerns practical aspects of conservation, and the ambivalent attitude towards plants on buildings and ruins, since the 1920s. Powys, for example, claimed that lichens and mosses must draw some nourishment from the stone, and may even secrete harmful acids, '...but they do these things to such a small extent that their powers of damage may be ignored.' (Powys 1929, 1995 reprint, p.70). Powys goes on to point out that mosses may cause damage because they hold moisture, which may help weathering by frost, but lichens and mosses do so little harm, and '...add colour and quality which few fail to admire...', and concludes that these plants can be preserved. He notes that the destructive effect of the grey and yellow species is more than counterbalanced by the protection they give the stone, and should be left alone (Powys 1929, 1995 reprint, p.71).

Even in the 1970s, the ambivalent attitude towards algae, mosses and lichens on buildings continued and is evident from the advice of the Building Research Establishment in *BRE, Digest 139* (Building Research Station 1972). They recognise that the appearance of lichens and mosses on walls and roofs can be 'mellow and pleasing', but they also point out that acid secretions can be damaging, and mosses in particular can, when on roofs, interfere with proper drainage; nevertheless, the suggestion was to encourage mosses and lichens on repaired surfaces, by the application of a wash of cow dung and water, or human urine and skimmed milk. This, it was claimed, would ensure that the repair, or insertion, would eventually take on the same colour and species cover as the existing surfaces, and avoid any harsh contrast. This advice was, however, omitted from the 1977 reprint and the later edition of this Digest (Building Research Establishment 1977; 1992). The only options which were included in the later edition were of taking no action, or the option of removal of plants, if desired, by either scraping, wire brushing, or by the application of toxic chemical washes to kill them and prevent further colonisation.

It is clear that plants on buildings and ruins add layers of meaning, and that even up until the end of the 1970s there was indecision, even within the Building Research Establishment, as to whether plants should be encouraged, or discouraged. The treatment of ruins in much of the twentieth century has concentrated on their value as evidence, both archaeological and historical. This has been achieved largely at the expense of any other levels of meaning or value which might be attached to them. The ruin, '...frozen in time, for fear of the future.' (Stanford 2000) neatly summarises the approach to their presentation which, until relatively recently, has remained largely unquestioned amongst those responsible for their management.

THE CURRENT TRENDS

The question as to whether ruins should continue to be conserved and presented in the same way as most have, for much of the twentieth century, is still in debate. It would appear that there are currently four options available for their future: continue as in the past; put ruins to beneficial use; allow limited and controlled encroachment of the natural environment; allow ruins to return to ruin. Clearly, the last option would receive little support from the mainstream conservation lobby, although it can be argued that with the ever-growing numbers of historic buildings and ancient monuments and, more recently, historic environments, in private ownership, trusteeship or guardianship, a time may come when the financial burden becomes such that a dwindling supply of public money has to be spread ever more thinly. Buildings in use already receive preferential treatment to ruins, and under increasingly stringent financial circumstances may, eventually, receive progressively less financial support for their maintenance. The second option would appear to be unacceptable because it may involve excessive levels of intervention. It was, however, an option which was recently debated at the SPAB, the proceedings of which were reported by Mary Anderson, with an introduction by Matthew Slocombe (Slocombe and Anderson 1998).

Conservation or reconstruction?

The concept of rebuilding ruins is not new. The Church of Dore Abbey, formerly a Cistercian abbey in Herefordshire, largely destroyed after the Dissolution, was restored in the 1630s by Viscount Scudamore, great-great-grandson of the abbey's purchaser in 1537 (Stanford 2001). The monastic buildings, however, remained in ruins. Before the first Ancient Monuments Act in 1882, the prospect for the future of ruins was seen in a very polarised way; they could be further neglected and allowed to disappear, or they could be restored and brought back into use. In the late nineteenth, and early twentieth centuries, there had been great debate about the reconstruction, or restoration of many ruins, both ecclesiastical and secular, including St Germain's Cathedral, Isle of Man in 1879, Glastonbury Abbey in 1907 and Holyrood Abbey, also in 1907 (Slocombe and Anderson 1998). Since then, the subject of restoration and reconstruction has been a sensitive issue but, nevertheless, proposals were considered in 1948 for works at Fountains Abbey, now part of a World Heritage site, but the view of the SPAB at that time was that considering the condition of the ruin, and its location, any attempt at rehabilitation would require so much reconstruction that the architectural and historical value of the building would be impaired (Slocombe and Anderson 1998).

Since then, attitudes have changed and there are cases, from the last decade of the twentieth century, where the principle of the reuse of ruins has been accepted, including the medieval West Dereham Abbey, Norfolk, and the seventeenth century mansion of Ruperra Castle in Gwent (Slocombe and Anderson 1998). The consensus of the SPAB discussion group which considered these matters in 1998 seems to be that several important aspects require consideration: the relative importance of the ruin and its setting; the quality of work proposed; the level of intervention; whether the proposals comprised reconstruction, or merely additions. In any event, each ruin should be considered on its own merits, and so the formulation of any sort of cohesive approach to the subject of ruins and how they should be treated is somewhat elusive (Slocombe and Anderson 1998).

In Europe, however, the situation is different. There are many instances where ruins, resulting from a variety of causes, including wars, have been reconstructed for beneficial occupation. An eminent conservator from Croatia whilst on a visit to Harewood Castle prior to the start of a major programme of consolidation work, anticipated its reconstruction. The presumption was that if it was to survive further, after many centuries of neglect, it must be rebuilt and put to some beneficial use. It is, however, not just ruins which were caused by conflicts or political upheavals in past centuries which have been reconstructed. The most recent, and perhaps the most controversial is the work, now well advanced, to rebuild the ruins of the Frauenkirche in Dresden, but it seems doubtful that reconstruction of ruins in Britain could ever be conceived on that scale; nevertheless, ruins managed as historical evidence are a relatively recent phenomenon, and have existed as such for only a fragment of the time since their original building.

The ecological imperative

In 1963, a piece of research was published which, in the present context can be considered to be ground-breaking. It was published, not by a body concerned with historic building conservation, but by The Royal Society for Nature Conservation. That research, by Raistrick and Gilbert, although not strictly speaking academic in intent, achieved something very rare at that time. Not only did it trace the history of a building, Malham Tarn House, in the Yorkshire Dales National Park, but it also set out to record and identify the type of stone used in its construction, their weathering forms, and the flora for which the building provided habitat. This piece of research predates, by thirty years, the establishment by joint collaboration between English Heritage and English Nature, of a database to record the fauna and flora of historic buildings and sites in guardianship. The work of Raistrick and Gilbert is the first attempt to understand the inter-relationships between a building, the materials from which it is constructed, its flora and the wider environment, and many decades elapsed before anything approaching the same degree of recording and analysis was conducted on monuments in Britain.

There has been debate for some time as to whether historic sites should be 'green' (English Heritage 2000), and it has recently been recognised that most ruins in guardianship *are* in an artificial state of existence, resulting from those rescues in the early part of the twentieth century. There is a certain paradox about monuments which are 'frozen in time', because that particular moment of time was artificially created at the time of conservation. Coppack highlights a further paradox, and that is that buildings naturally exist in only two conditions: as roofed, buildings-in-use, or as ruins which will gradually and inevitably be covered by plants of varying genera and species (Coppack 1999). To hold vegetation at bay, in the context of a ruin is, therefore, to deny a natural state of existence.

It was not until the last ten years of the twentieth century that attitudes towards the conservation of ruins in England began to change. There was an increasing awareness of the relationship between conservation of the built and the natural environments, and of the nature conservation value of historic sites, not just as settings for historic buildings, but of the nature conservation value of the plants on those buildings as well.

Change during those ten years was not a result of an emotional response to ruins devoid of vegetation, nor as a response to either of the paradoxes already highlighted. It was for more pragmatic reasons. The United Nations Conference on Environmental Development, held in 1992, and the subsequent UK Biodiversity Action Plan (Department of the Environment 1994) were the catalysts of change, because thereafter there was a growing realisation that many historic sites had ecological value, as well as historic value.

Almost as if the resolutions of the Rio Summit had been anticipated, Thompson had been commissioned by English Heritage to evaluate the wildlife potential of standing remains (Thompson 1990; 1991; 1992). This was followed by further commissions to investigate the acquisition and management of data for nature conservation at historic sites (Harding 1993), and to establish the principle of using turf to protect the tops of ruined walls (Laycock 1994). Although some English Heritage properties in the north of England were surveyed for their ecological value as early as the 1980s, at many sites the wildlife and botanical value is still to be determined (Thomas and Wells 1997, Appendix 2), and that has also remained the case at some sites in private ownership, until botanical surveys were carried out as part of this research.

Of English Heritage properties, forty-three percent comprise castles, forts, abbeys, priories, churches and other ecclesiastical buildings (Thomas and Wells 1997). Thomas and Wells also make the point that of all English Heritage properties, ruined walls and inland rocks provide the single most abundant habitat for wildlife and plants. This includes habitat for rare, or protected species, including two species of lichens at Rievaulx Abbey and the lichens on the megaliths of Stonehenge (Thomas and Wells 1998).

The publication in 1995 of *Managing Ancient Monuments: an integrated approach* (Berry *et al.* 1995) was, perhaps, the first publication to demonstrate how the conservation of the built and the natural environment could work together, and in 1997 English Heritage produced an internal advice note specifically on the conservation of wall flora (English Heritage 1997a). During this same period the conservation by English Heritage of Wigmore Castle in Shropshire provided a dramatic demonstration of how a vegetation-clad ruin could be conserved as a vegetation-clad ruin (Chitty and Baker 1999).

English Heritage stated the case for wall-dwelling plants, and recognised the importance of true wall-dwelling species because of their adaptation to endure the extremes of temperature and drought which a wall environment provides (Thomas and Wells 1997). More importantly, perhaps, they recognised that walls can provide habitat for species which are scarce or absent in the surrounding countryside. This may be due to a combination of factors which might include stone type, weathering pattern, water run-off pattern, acidity or alkalinity, aspect or orientation, which are absent on natural rock outcrops in the area. Indeed, natural rock outcrops in the area may be absent.

The ecological significance of plants on walls can only be assessed by survey, which would enable the species present and the relative abundances to be determined; whether they are common, rare, or endangered in the context of their local, regional and national distribution, and how commonly any particular combination has previously been encountered. This information will determine how they, and the monument should be conserved (Thomas and Wells 1997); however, should it be considered undesirable to conserve plants on standing remains, English Heritage's *Landscape Advice Note 6* provides a list of appropriate chemical treatments to control vascular, and non-vascular plants, including mosses and lichens (English Heritage 1997b).

There are certain aspects of monument conservation, which have been in use since the 1920s, which have recently been questioned. That questioning is a result of the recognition that sites have ecological value, and the consequent trend towards 'green' monuments. For example, English Heritage have now recognised that the use of hard cement capping to the tops of ruined walls in order to shed water has, over the years, resulted in discoloration and decay to wall faces. The alternative is the use of softer lime mortars, and this has proved to be less damaging to the building fabric, but is susceptible to colonisation by particular types of plants because it is more porous and less durable that cement mortars (Emerick 2000). As a result of limited research work the conclusion was reached that the resultant plant mat on the tops of walls has a beneficial conservation effect, because of its capacity to absorb rainwater, and to allow plant roots to absorb water from the stone. If the plant mat does act in that way, then the consequences of its capacity to hold water in contact with the stone for long periods of time would appear to have been overlooked; nevertheless, this approach is now unwritten policy within English Heritage, and has been applied to properties in care, including the World Heritage site of Fountains Abbey, as well as properties still in private ownership.

The reasons for using soft-cappings and the active use of vegetation are that it is believed to be beneficial for the conservation of the monument and acceptable for its own aesthetic (Emerick 2000). The management of ivy, however, is still viewed as potentially problematic, since removal at ground level can cause problems at higher levels due to the unsupported weight of the plant. The consensus would appear to be, therefore, that ivy can be tolerated, but it must be trimmed at regular intervals.

The biggest single problem with the policies which are being developed and adopted, particularly by English Heritage, is that the potential risks and benefits involved for historic masonry have not been particularly well researched, and it is always assumed that any detrimental effects due to plants will be on a scale which is relatively well understood. For example, it is always assumed that the effects of ivy will be on a macro-scale, involving masonry structures as a whole, whilst the effects of mosses and lichens will normally be on a micro-scale, that is, on the surface, or part of the surface of individual stones. There is, however, the possibility that all forms of plant life on ruins have an influence on weathering beyond that which is normally perceived. To ignore, or fail to recognise, the implications of that may put historic fabric at risk. This is a fundamental strand of the argument upon which much of this research is based, and it is one which will receive further consideration in Chapter Three.

Green ruins

Not all ruins were taken into guardianship and received the Department of Works treatment. Many are still in private ownership, and valued for that, and thus they are managed and presented differently. Jervaulx Abbey, in North Yorkshire, is particularly noteworthy. Its informal setting and abundance of flowering plants, lichens and even ivy, make visiting this site a very different experience to that of visiting the more formal settings of many ruins in guardianship. The ruins of Jervaulx Abbey can only be maintained in their present state by the adoption of a very different management regime to that which is generally adopted on other sites. There are other sites, however, where just such regimes have recently been adopted, at Wigmore Castle for example, but this has not yet been implemented on ruins which were previously under the Department of Works or the later Ministry of Public Buildings and Works regimes.

The ruins of Wigmore Castle, in Herefordshire, are unique in several respects. The castle dates from the thirteenth and fourteenth century, and is one of the chain of castles which defended the border between England and Wales. Like many castles in England, it was either destroyed during, or dismantled after, the Civil Wars, but unlike most, it remained in ruins, undisturbed, for at least four hundred years. For much of the twentieth century, concern had been expressed about its condition, and in 1995 it was taken into English Heritage Guardianship (Channer 2001). Since then it has undergone an extensive programme of conservation which has, to a large extent, retained much of the vegetation on its walls, with the addition of new planting. The ecological value of the site has, therefore, been respected, and some of the criticisms of the way ruins are presented, expressed by many, has been addressed (Stanford 2000).

The rebuilding of the abbey church at Dore Abbey has already been mentioned, but the sacristy, all that remains of the monastic buildings, has only recently received attention. Plans for its conservation were only initiated by a partial collapse in 1997, but the policy which was adopted was to preserve the ruin as a 'green' ruin. Stanford notes, in the reporting of the conservation work in the *SPAB News*, that the process of stripping ivy reveals the stonework for detailed recording, and this is the method usually adopted; however, without it walls loose much of their charm. Recording can often be carried out without its removal, and the retention of plants on ragged, ruined, masonry gives a sense of the ruin still existing within time (Stanford 2001).

The approach adopted to the conservation of ruins, of which Jervaulx Abbey, and more recently Wigmore Castle and Dore Abbey are examples, is still rare. Even rarer, perhaps, are the few ruins in private ownership which have escaped any form of conservation. Within those ruins lies evidence of two critical types. The first is historical evidence and that will, undoubtedly, be the first to be retrieved. The second type of evidence, of vital importance if the trend towards 'green' monuments continues, is that provided by the flora of these ruins, and the ways in which it had caused weathering.

In the past, the process of preserving historical evidence of ruins had undoubtedly been at the expense of the botanical evidence. The single-minded preservation of the remaining historic fabric of long-destroyed abbeys and castles had, inadvertently, destroyed the evidence of the many ways in which the natural environment, particularly vegetation, affected, not just the stability of ruins, but also the weathering of their stones. What remains of that evidence is largely anecdotal, and if the same degree of scholarship had been expended on that aspect of ruins, as had been expended on understanding the historical and archaeological evidence of the fabric of many of the ruined abbeys and castles of England now in guardianship, then there would be available a soundly-based body of knowledge to help inform the current decision-making on heritage management issues relating to 'green' ruins. There is no doubt that there is a trend to value historic properties not only for the history to which they give testament, but also for the wildlife, including plants, for which they provide habitat. This research, then, takes a small step towards rediscovering what some of that lost botanical evidence might have been.

The next chapter will examine what is known about the mechanisms which cause weathering of stone, and will also investigate what *is* known about the risks to masonry posed by the presence of plants.

SUMMARY

During a period of more that 400 years, the imperceptible changes which the ruins of Britain underwent by natural processes have symbolised many things to many people. In the late nineteenth, and early twentieth centuries, many of those ruins came into public ownership, and were consolidated and made accessible. They were valued as historical evidence, and that is how they were, and still are, presented to the public. No other layers of meaning are permissible, and that has been a cause for comment, debate, and criticism for nearly sixty years.

There is, however, a trend to conserve ruins as ‘green’ ruins, and this is based upon an increasing awareness of the ecological importance of historic sites. This trend is gathering momentum without the benefit of appropriate research, and much of what might have been useful from the past has been destroyed at the expense of preserving the historical evidence; furthermore, the systematic recording of relevant evidence of damage, or weathering by plants, on extant ruins which have not been conserved is largely absent from the conservation agenda. The key question is: to what extent is our heritage being put at risk from direct or indirect weathering by plants?

CHAPTER THREE

LITERATURE REVIEW

INTRODUCTION AND SCOPE

This chapter, in two parts, investigates the current state of knowledge of the processes involved in the weathering of stone. Part one considers the literature concerning the weathering of stone in the absence of plants. Part two discusses the types of plants under consideration in this research, and investigates how the literature deals with their role in the weathering process.

The literature on the weathering of stone is extensive, and a comprehensive review of what has been written in these two areas of study would be impracticable. The content of this chapter is therefore, of necessity, selective, and serves to highlight key aspects which are relevant to this research.

PART 1 – THE WEATHERING OF STONE

Stone, in the walls of buildings or ruins, is in an alien environment; its natural environment is in the earth's crust. The moment stone is exposed to the atmosphere, the natural processes of weathering, begin. Weathering and other processes cause alteration to stone, which is eventually converted to soil (Allaby 1998, p.305). The rate at which these processes take place is partly dependent upon the mineralogy and structure of the stone, and partly upon geographical location and climate. When stone is used for building, the rate of weathering is also influenced by the position and detail of the stone elements, their aspect and orientation and their juxtaposition with other materials.

The process of weathering cannot be reversed. The objectives of the conservation of historic buildings constructed of stone are, therefore, to arrest or at least slow, the weathering processes or to replace with new material those parts which have weathered to a degree where they are no longer able to fulfil their original function. These functions are mainly structural functions or water-shedding functions, but often include decorative functions such as carved details, without which the original stylistic 'narrative' of a building becomes obscure.

DEFINITIONS

The term, *weathering*, has been used in the introductory section, but many other terms are also commonly used in this context. Other terms commonly used might include: *decay*, *distress*, *degradation*, or *deterioration*. These are all general terms, but it is important to the understanding of the mechanisms involved in weathering that a more specific common language is employed. It is important, therefore, for what follows to define precisely what they mean.

The dictionary definition of *weathering* is, simply, 'the action of the weather on materials etc. exposed to it' (Thompson 1995). There is, however, more to *weathering* than simple exposure to the weather; furthermore, there is more to weathering than just defining the word in this simple manner, as will be demonstrated.

Weathering has also been defined as the natural process of alteration (Viles, in Baer and Snethlage 1997 p.96). The process of *alteration* implies a change in the properties of the material, be it chemical or mineral composition, or porosity. *Deterioration* implies alteration of a material by damage factors leading to distress and decay (Viles, in Baer and Snethlage 1997). Confusion in terminology may arise because weathering can be considered at several different levels, from the micro-structure of stone, to a whole building. Terms which are intended for one specific context are sometimes used to describe a phenomenon in a different context. Viles helps clarify the terminology by suggesting specific terms to be used in specific contexts;

> *Deterioration* occurs on a scale of less than ten millimetres;
> *distress* occurs on a scale of between one centimetre, and one meter;
> *decay* occurs on the whole-building scale.

These three terms can be considered to represent different degrees of *weathering*.

The foregoing definitions were presented to the Dahlem Workshop as a suggestion for a preliminary classification system for terminology, because 'The crisis over definitions and terminology in stone deterioration studies is a severe handicap for scientific progress...' (Viles in: Baer and Snethlage 1997 p. 109). Viles went on to point out that because research into the weathering of stone is carried out at an international level, the problem of terminology also needs to be addressed at an international level.

To summarise, *weathering* can be considered to be the process of alteration of stone, which implies changes in the properties of the stone. *Deterioration* is caused by damage factors leading to degradation, *distress*, and *decay*. These are the components of weathering, and these are the terms, and their meanings, which will be used in the remainder of this thesis.

Stone used in the construction of buildings is a small piece cut from the rock which makes up the various geological strata, whether igneous, metamorphic or sedimentary, of different ages, which comprise the earth's crust. Rock can be defined as an aggregate of minerals (Lapidus 1990), which are generally understood to be naturally occurring inorganic substances of unique chemical composition. They typically have crystalline structures whose characteristics of hardness, lustre, colour, cleavage, fracture and relative density are used as means of identification (Allaby 1998). It is the mineralogy of rock, and hence of stone, which is one of a number of key factors which determine the degree to which it weathers when exposed to various weathering agents.

REGIONAL GEOLOGY AND STONE TYPES

The broad geological divisions of Britain were mentioned in Chapter One, but this research is concerned with the geology and building stones of two distinct geographical areas. The first is the area comprising the Howardian Hills, the Hambleton Hills, the North Yorkshire Moors and the Vale of Pickering. These lie to the north of York where the underlying geology is the Jurassic.

By contrast, the second area under consideration is the eastern part of Wharfedale, to the north-west of Leeds, where the underlying geology is the Carboniferous.

The Carboniferous system

The Carboniferous system has extensive coverage in the north of England, extending from Richmond in the north, to Derby in the South. Its sandstones '...are not the most beautiful of the English varieties, but for strength and durability they are the best.' (Clifton-Taylor 1987, p.132). It has two subsystems: the Dinantian, comprising the lower and older rocks, and the Silesian, the upper and younger rocks. From the Namurain Series, which is the bottom Series of the Silesian, come the Sandstones and Gritstones, which have been used extensively in the past for building in the both Yorkshire and beyond. These Gritstones, generically described as Millstone Grit, are the stones from which Harewood Castle was built. More detail of the local stratigraphy of the Gritstones will follow in Chapter Six, and a detailed description of the Carboniferous system in Yorkshire can be found in Rayner and Hemingway (Ramsbottom *et al.*, in: Rayner and Hemingway 1974, pp.45-114).

The Jurassic system

The Jurassic succession of sedimentary rocks in North Yorkshire forms three broad divisions: the Lower, the Middle and the Upper Jurassic. Of these, the Middle and Upper Jurassic are pertinent to this research and range from hard, dense, limestones and oolitic limestones, to fine-grained calcareous, and siliceous sandstones.

The Middle Jurassic rocks have been used for many historic buildings in this region. They include the Dogger, worked in the Terrington area, four kilometre west of Castle Howard and used in the construction of Sheriff Hutton Castle (Smith, in Rayner and Hemingway 1974 p.364). The Kellaways Rocks were quarried at Hackness, about twenty kilometres north-east of Pickering, and at Levisham, eight kilometres north of Pickering. This same rock, quarried further west, was also used in the construction of parts of Rievaulx Abbey.

Perhaps the most important of the Jurassic successions is the Upper Jurassic, because it has provided a source for several types of stones which have been used extensively for building in the north-east of the County, including Pickering and Helmsley Castles, the Temples at Duncombe Park, Slingsby Castle and parts of Rievaulx Abbey. The Middle Calcarious Grit, of the Upper Jurassic, was quarried in the Helmsley area and used most notably perhaps, in the building of Ampleforth College. The Coral Rag, which includes Hindenley Limestone, is still quarried at Hovingham (Smith, in Rayner and Hemingway 1974, p.364). The scale of past quarrying can be seen by examination of disused quarry sites at Helmsley and Pickering, and the innumerable smaller quarry sites around Rievaulx and Duncombe Park, and these will receive further mention in Chapter Six. A full account of the Jurassic in North Yorkshire can be found in Rayner and Hemingway (Hemingway, in Rayner and Hemingway 1974, pp.161-223).

AN OVERVIEW OF WEATHERING MECHANISMS

Many authors have described from various points of view the mechanisms of stone weathering. They are often divided into physical weathering, and chemical weathering, or by stone type, or by weathering form. Powys, for example considers weathering under the headings of organic, mechanical and chemical (Powys 1929). Schaffer, considers them under the headings of chemical, physical, salts, and living organisms and also weathering due to inherent materials defects, errors in choice of materials and poor craftsmanship (Schaffer 1950). Félix, in the compilation of the papers from the Lausanne conference, included two sections; one covered physical and chemical weathering, the other air pollution and weathering (Félix 1985). But Honeyborne, in Ashurst and Dimes (1998), made a distinction solely between deterioration of stone due to salt crystallisation, attack by acidic gasses in the air, and by frost action. Feilden (1996), discussed causes of decay under the headings of ‘Climatic ...’ and ‘Manmade ...’, while Price (1996) reviewed weathering mechanisms under the headings of pollution, salts and biodeterioration.

Organisation of material

There is no doubt that the ways in which reviews are organised reflects the way research is currently considered, that is, usually on a discipline-by-discipline basis. This has the unfortunate effect that it tends to obscure the broader picture of how mechanisms interact with each other. In order to help overcome this problem, and to provide a foundation for what follows in this research, weathering mechanisms will be reviewed in this chapter from a different perspective, and that is from one which considers the mechanisms in order of increasing complexity. By adopting this perspective it will be demonstrated that weathering by plants is not just another weathering mechanism, acting in isolation, but that any direct or indirect weathering of stone by plants adds further levels of complexity to an already complex series of interactions between mechanisms.

The starting point will be the effects of heating and cooling. Then effects due to water will be considered, first as liquid and vapour, then as solid. Water will then be considered as a means of transport of substances for which it can be a solute. And finally, the concept of *complex weathering* will be introduced.

Thermal cycles

The simplest from of weathering could be considered to be that due to cyclical changes in temperature of stone and temperature gradients within stone, due to insolation. Snethlage and Wendler suggests that expansion and contraction of stone due to thermal effects alone is a reversible process, but there must inevitably come a point when the internal structure of the stone becomes permanently disrupted, the atomic bonds between molecules become broken and the thermal expansion of the stone becomes permanent (Snethlage and Wendler 1997). It is easy to see why this phenomenon might be overlooked as a cause of stone decay, because most materials expand on heating and contract on cooling. There is, generally, no expectation that materials, after heating and expanding, will remain in their expanded condition after cooling. This is a phenomenon which appears to be peculiar to porous, non-homogeneous, materials such as stone.

Zezza, however, showed by experiment with carbonate stones that there is a direct relationship between temperature fluctuations which a stone will withstand and the inter-granular, or inter-crystalline bonds within the stone. He showed that temperature fluctuations in the range –40 to +60 degrees Celsius are sufficient to disrupt the equilibrium of the inter-molecular bonds in the types of marble which were studied (Zezza *et al.* in: Rodrigues *et al.* 1992). Zezza and his fellow researchers suggest that this temperature range is one to which stone in historic structures is often subjected, although perhaps not in Britain.

Mineral solubilities

Stone can comprise a variety of minerals. Limestones comprise principally calcium carbonate, or a combination of calcium and magnesium carbonate. Some sandstones are composed of grains of silica, cemented together by silica, or a variety of other mineral cements, including calcium carbonate, metallic carbonates such as ferric carbonate, or metallic oxides such as ferric oxides. Some types of stone have complex mineral structures, such as feldspars, which can be composed of calcium, sodium, or potassium-aluminium-silicate. The common perception might be that the majority of these minerals are insoluble; nevertheless, they are all, to a greater or lesser degree, soluble in water.

Drever (1994), writing from a geochemical perspective, highlights the earlier work of Stumm and Wieland (1990), and uses their data to illustrate the relative solubilities of some common rock-forming minerals. Table 3.1 is based on that of Drever and shows relative mineral solubilities in terms of lifetime-years of a one millimetre sphere of pure crystal in pure water at pH5, at twenty-five degrees centigrade. The mineral groups and chemical formulae were extracted from Sorrel and Sandstrom (1977) and added to Table 3.1, below.

Mineral	Mineral group	Chemical formula	Lifetime-years
Quartz	silica	SiO_2	34,000,000
Muscovite	mica	$KAl_2(Si_3Al)O_{10}(OH)_2$	690,000
Biotite	mica	$K(Fe,Mg)_2(Si_3Al)O_{10}(OH)_2$	600,000
Orthoclase	feldspar	$KAlSi_3O_8$	440,000
Albite	plagioclase feldspar	$NaAlSi_3O_8$	210,000
Anorthite	plagioclase feldspar	$CaAl_2Si_2O_8$	190,000
Diopside	pyroxene	$CaMgSi_2O_8$	6,700
Forsterite	olivine	Mg_2SiO_4	3,100
Dolomite	calcite	$CaMg(CO_3)_2$	1.75
Calcite	calcite	$CaCO_3$	0.6

Table 3.1 Solubilities of rock-forming minerals (Based on Drever 1994 p.28)

A useful addition to this table would have been the sulphate gypsum ($CaSO_4{\cdot}2H_2O$), the production of which, during the weathering of some stone types, is a significant component of complex weathering and which will be considered later in this chapter. There are, however, ways of relating the solubility of gypsum to that of calcite by reference to other published material. For example, Mottershead and Lucas (2000) quote the solubility of gypsum rock as 2.4g/l, at 20 degrees centigrade, but without comparable figures for other minerals this does not provide an answer.

Howe (1910), using data from Hirschwald (1908), calculated the annual loss of surface of prepared samples of stone, but Winkler tabulated the relative solubilities of various minerals (Winkler 1994, p.191). Table 3.2, which follows, illustrates the relationship between solubilities of quartz, calcite, dolomite, siderite and gypsum, in water at 20°C.

Mineral	Chemical formula	Solubility, parts per million
Quartz	SiO_2	5
Siderite	$FeCO_3$	10-25
Dolomite	$CaMg(CO_3)_2$	21
Calcite	$CaCO_3$	40-85
Gypsum	$CaSO_4{\cdot}2H_2O$	2400

Table 3.2 Solubilities of rock-forming minerals – 2 (Based on Winkler, 1984 p.191)

By using the average of the upper and lower values given for Calcite, in table 3.2, it can be calculated that the lifetime of a one millimetre sphere of Gypsum in pure water is likely to be about six days.

Stone is rarely, if ever, exposed to *pure* water as a potential mineral solvent. Most stone-forming minerals become increasingly soluble as the pH of the water reduces; whereas silicate minerals become more soluble as pH levels increase above pH5. Drever showed that solubilities rise exponentially as pH rises above pH5 (Drever, in: Krumbein *et al.* 1994, p.30). Silicate minerals, including feldspars, as Table 3.1 above shows, are insignificantly soluble in water at pH5, but since dissolution takes place at the grain boundaries, any small loss of cementing material may lead to a disproportionate loss of grains. Silicate stones which are bedded and pointed in lime mortars can be vulnerable because high levels of high pH moisture can result from run-off from the much more soluble carbonates in the mortar (Drever, in: Krumbein *et al.* 1994, p.30). In carbonate-cemented stones, the problem of dissolution of cement becomes much more serious because, based on Drever's account, it could be predicted that as calcite cement is taken into solution, the pH of the solution rises, and becomes an even more aggressive solvent.

Drever points out, however, that in stone which is cemented by carbonates such as calcite, micrite or dolomite, the dissolution rate increases as the pH decreases, and the porosity and pore structure of some types of calcite-cemented stones can affect the rate of dissolution. Moisture can be held within the pore spaces for relatively long periods of time and if the rainwater is acidic, as when rainwater has taken atmospheric sulphur dioxide into solution, the resultant loss of cement can cause rapid disintegration of the stone (Drever, in Krumbein *et al.* 1994, p.34).

In limestones the susceptibility to dissolution of calcite is slightly different. The structure of limestones may be due more to the processes which occur after sedimentation than to the composition of the original sediment itself. Drever includes in these subsequent processes: porosity reduction due to carbonate cement precipitation; pressure-solution causing dislocation of grains in areas of high stress contact points between grains; and precipitation of carbonate in areas of low stress (Drever, in: Krumbein *et al.* 1994 p.34). The resultant rock may be virtually impermeable, with calcite grains 'welded' together, in which case dissolution by water will be largely a surface phenomenon rather than an in-depth cause of weathering as is the case with calcite-cemented sandstones and, therefore, the durability will be significantly greater.

Moisture cycles

Dissolution of the cementing minerals in stone is not the only way in which the action of water can cause weathering. In porous stones the moisture content of the stone is rarely static. Moisture will evaporate from the surface in dry weather and be absorbed by the stone in wet weather. Sources of moisture might include: direct wetting by rain; moisture absorbed from the ground; moisture absorbed from the air, including both mist and fog and from condensation deposited when the surface temperature of the stone falls below the dew point of the surrounding air.

Snethlage and Wendler (1997) investigated, by computer simulation, the cyclical process of wetting and drying, particularly in relation to sandstones, in order to explain certain decay phenomena and to stimulate further research. Their starting point was the well-established principle that all porous systems exhibit hygric dilation and contraction due to relative humidity changes within the pore structure, and hydric dilation and contraction due to changes brought about by the volume of water absorbed (Snethlage and Wendler, in: Baer and Snethlage 1997, p.9). In order for weathering to take place, the grains of which the stone is composed have to be displaced in some way. They point out that typical moisture movements in sandstone can be expected in the region of 500 microns per metre. These movements have been shown to be reversible during laboratory tests of ten wetting and drying cycles; however, over the life of stone in a building, subjected to thousands of such cycles, material fatigue-failure and irreversible displacement of grains is to be expected. This is a consequence of the non-elastic nature of stone. Snethlage concludes that '...wetting and drying... obviously causes the displacement of grains relative to each other and contribute to the loosening of the grain structure.' (Snethlage and Wendler, in: Baer and Snethlage 1997, p.11).

Frost action

Water behaves in various anomalous ways. One of the anomalies is that its density increases as it cools, but reaches a maximum at four degrees centigrade. On further reduction in temperature, its density as it freezes then begins to fall (Clugston, 1998). The significance of this, for the weathering of stone, is that water below zero degrees centigrade, in the form of ice, has a lower density than the liquid water above zero degrees. Since the mass of water remains the same it must, therefore, have a higher volume, since density equals mass per unit volume. In fact, when unit volume of water freezes, its volume increases by seven percent (Ashurst and Dimes, 1990). This increase in volume is the common perception of the underlying mechanism of damage to stone by freeze-thaw cycles, but it is misleading.

Several writers have investigated the implications of this change in volume of water as it freezes in relation to different types of stone with different pore sizes and structures. Bell, for example, identified a critical pore size in relation to damage by freezing water. He maintained that sandstones are more or less resistant to frost because their pore sizes are generally above the critical 0.005mm diameter (Bell, in: Rodrigues *et al.* 1992, p.878). Bell maintained that pores above this diameter allow the drainage of water ahead of any advancing ice front within the pore structure. Bell acknowledges, however, that persistently wet surfaces are always vulnerable to damage by freeze-thaw cycles. Drever on the other hand maintains that quartz-cemented sandstones with high porosity may disintegrate as a result of freezing water (Drever in: Krumbein *et al.* 1994). It should be noted however that large pore size does not always imply high porosity. So what are the key characteristics of stone which make it vulnerable to weathering by freeze-thaw-cycles?

Honeyborne and Harris had identified the relationship between pore size and distribution, and the durability of some limestones (Honeyborne and Harris 1958), but Everett provided the explanation of the mechanism by which water freezing in the pores of stone causes weathering (Everett 1961). Everett's starting point was the recognition that frost damage has no necessary connection with the expansion which occurs when water freezes. He pointed out that even within the scientific community this is a relatively unknown fact (Everett 1961, p.1541), and similar effects can equally be produced by organic liquids which contract when they freeze; however, he acknowledges that in building materials '...there are conditions of freezing under which this expansion can contribute to the damage.'

Everett went on to point out that it has been known, at least since the early part of the nineteenth century that as water freezes in a saturated porous material, the ice crystals grow in the larger pore spaces, withdrawing water from finer, adjacent, pores. The growth of crystals in the smaller pores will be limited by the pore size. Everett then set out to explain why the growth of crystals in the larger pores is not similarly restricted by the pore size. If it was, no damage would occur, but instead the crystals would continue to grow against the constraint provided by the pore walls, resulting in disruption to the pore structure (Everett 1961, p.1542).

Everett's explanation of the thermodynamics of this process is beyond the scope of this review, but there are several key factors which arise, relating to pore size and structure, which influence the ability of ice crystals to grow and the ability of particular stone types to resist the pressures exerted by that growth. The first of these is that frost damage is associated with structures which have coarse pores, separated from each other by microporous regions; structures which are composed of pores of uniform size tend to be resistant to frost damage. Everett states 'The excess pressure which can build up in a coarse pore of radius R, connected to a supply of water ... by a capillary of radius r is proportional to $(1/r-1/R)$.' (Everett 1961, p.1546). From this equation it can be seen that if r equals R, then the result of the equation will be zero, but as r decreases below the value of R, or the value of R increases above r, then the result of the equation increases, and so, therefore, will the excess pressure in the coarse pores.

Two things can be deduced from the above equation. If a stone has a pore structure comprising pores of a similar size, there will be no ice crystal growth and no potential for the development of excess pressure in the pore structure. There will, however, be an optimum relationship between the size of the small pores and the large pores, which must be interconnected, which enables maximum crystal growth and maximum damage potential.

Everett's model was developed principally to explain and predict frost heave in soils, but he acknowledges that it is equally applicable to porous building materials, including stone. He showed that it is possible to calculate both the critical pore sizes and the forces which will be generated in the pore structure by the growing ice crystals. If this force is related to the tensile strength of the stone, then its likely resistance to damage by freeze-thaw cycles can be predicted.

Stones with poor resistance to freeze-thaw cycles are characterised by a large proportion of pores of diameter 0.001 to 0.005mm, 'The pressure required to propagate ice through pores of this size lie in the range of 6 to 1.2 kg cm^{-2}' (Everett 1961, p.1548), but the factors governing the pressure build-up in a large pore depends on the size of the largest capillary leading out of it. This would suggest that weathering by freeze-thaw cycles can never be a surface phenomenon, since large pores which are open to atmospheric pressure will always allow the exit of growing ice crystals. Such damage must therefore always originate from within the structure of the stone, indeed it is theoretically possible that microcracks in limestone can act in the same way as the fine pore structure does; furthermore, an initially vulnerable stone may acquire resistance due to the enlargement of its small pores by other weathering mechanisms, thus reducing the availability of capillary water required to propagate ice crystal growth. Sandstones generally, because of their relatively coarser pore structure, develop much lower pressures, which can be as much as ten times smaller than in vulnerable limestones during ice crystal growth (Everett 1961, p.1548).

It is, therefore, the detailed relationship between the small capillary structures and the regions of larger pore size in as well as the overall pore size distribution of the stone which determines its resistance to freeze-thaw cycles (Everett 1961, p.1548).

Soluble salts

Of all the weathering mechanisms which have been studied in the past, the role of salts, and the growth of their crystals in the pore spaces of stone, seems to be the one studied more than most. Price maintained that weathering by soluble salts is '...the most important of all the causes of stone decay.' (Price 1994)

A *salt* is the generic name for the product of a chemical reaction between an acid and a base. A base is defined as a substance which reacts with an acid to form a salt and water only. The acid-base reaction can also be considered to be one in which an alkali, a water-soluble base, is neutralised (Daintith 2000). Examples of salts are: sodium chloride – a product of the reaction of sodium hydroxide and hydrochloric acid; sodium sulphate – a product of the reaction between sodium hydroxide and sulphuric acid; potassium nitrate – a product of the reaction between potassium hydroxide and nitric acid. In each of these three salts, the metal hydroxide is the base and the acids are hydrochloric, sulphuric and nitric respectively.

Sources of salts

Snethlage and Wendler pointed out that water within the pore structure of stone will invariably be contaminated with salts of varying types, and in varying concentrations (Snethlage and Wendler, in: Baer and Snethlage, 1997). The geophysical sources of these salts were examined in some detail by Goudie and Viles (1997), but Schaffer generalises the sources as:

- salts already in the stone, although these are not usually a problem because they tend to be leached out by rainwater;
- salts derived from the weathering of the material, as a result of reactions between stone, rainwater and atmospheric pollutants;
- salts derived from external sources such as Portland cement mortars, or from the soil, from the air, or from sea-spray.

(Schaffer 1950, pp.60-61)

Types of salts

About 70 different salts have been associated with the weathering of natural rock formations, and over twenty-five different salts have been found associated with efflorescences on walls at major monuments world-wide (Goudie and Viles 1997, pp.72-73). Goudie and Viles highlight the fact that calcium sulphate is the salt most commonly associated with efflorescense on building stones. Calcium sulphate is produced by the reaction between carbonate stones and atmospheric sulphur dioxide, and will be discussed more fully in the sub-section concerning *complex weathering.*

Mechanisms of weathering by soluble salts

The prerequisite for salt weathering is not just the presence of salts but also the cyclical presence of water. Large and frequent cycles of temperature and humidity alter the state of salts, strong evaporation aids the crystallisation of salts and high ground-water levels and prevailing winds provide a source of salts (Goudie and Viles 1997, p.90). Sources of water for salt-induced weathering include dew, fog, rain and groundwater (Goudie and Viles 1997, p.79-86).

Weathering is induced by chemical or physical changes in the salt. Chemical changes might include silica mobilisation under alkaline conditions, etching of calcite under acid conditions, or gypsum/silicate replacement. Physical changes might include crystallisation, hydration, thermal expansion, and the important deliquescent properties of hygroscopic salts, whereby atmospheric moisture is absorbed and can then be retained in the stone (Goudie and Viles 1997, p.123).

Crystallisation pressures

Several researchers have attempted to explain the mechanism by which the growth of crystals of salts in the pores of stone cause weathering. Goudie and Viles highlight the work of Fitzner and Snethlage (see Fitzner and Snethlage 1982) who, in turn, refer to the earlier work of Everett (Everett 1961). Fitzner and Snethlage identify the similarity between the thermodynamics of ice crystal growth, described by Everett, and the growth of crystals of salts within the confines of the pore system of stone (Goudie and Viles 1997, p.127); however,

> 'The presence of crystallising soluble salts does not invariably cause decay, because salt crystallisation can be either disruptive, or cause cementation, depending upon the pore structure of the material and the crystallisation pressures that develop with particular pore size distributions.'
>
> (Goudie and Viles 1997, p. 130)

Price points out that some researchers have, using thermodynamic considerations, calculated the crystallisation pressures which can develop as salts grow from a supersaturated solution. These have been shown to far exceed the tensile strength of many stone types, but Price expresses doubt as to whether the conditions necessary to develop these pressures can ever be achieved in reality (Price 1996, p.9). The precise mechanism whereby crystallisation pressures cause weathering would appear, therefore, to be uncertain.

Hydration pressures

Many salts can exist in two states. Calcium sulphate, for example, exists as anhydrite ($CaSO_4$) and more commonly as the dihydrite gypsum ($CaSO_4 \cdot 2H_2O$). Similarly, sodium sulphate can exist as the anhydrous threnardite (Na_2SO_4) and as the decahydrate mirabilite ($Na_2SO_4 \cdot 10H_2O$) (Daintith 2000). Schaffer notes that when an anhydrous salt changes to the hydrated form, there is an increase in volume (Schaffer 1950), and Winkler points out that this change of state occurs not only with a change in relative humidity, but can also occur with a change in temperature (Winkler 1994, p. 169). Goudie and Viles acknowledge that although volume changes of up to 300% can occur when certain salts hydrate, the mechanism by which damage occurs is not clear, because often anhydrous salts form from solutions in the pore structure, and therefore there should, theoretically, be space available for them to expand back (Goudie and Viles 1997, p.131). In order for an anhydrous form of a salt to hydrate, not only does there need to be moisture available, but the critical transition temperature needs to be reached. The likelihood of salts in stone hydrating would therefore appear to depend upon the magnitude of the diurnal temperature cycles and upon relative humidity fluctuations.

Snethlage and Wendler's 'salty system'

Snethlage and Wendler's weathering model, discussed in the foregoing section on moisture cycles, considered water in the context of both hydric, and hygric expansion, or to use their term 'dilation'. They went on to consider these phenomena in a salt-contaminated system. By reference to the earlier work of Wendler and Rückert-Thümling, they compared the dilation of stone samples in water, and in sodium sulphate solution, when subjected to repeated wetting and drying cycles. They found that the samples in water expanded during wetting, and contracted during drying; however, the samples in the salt solution contracted during wetting and expanded during drying, but the expansion on drying was not wholly reversible, being cumulative from cycle to cycle (Snethlage and Wendler, in: Baer and Snethlage 1997, p. 12; see also Wendler and Rückert-Thümling 1993).

The explanation for this unexpected behaviour was that during wetting, dense hydration shells form between the grains of the stone, which become denser as the electrolytes become stronger and so the stone contracts. The expansion during drying could, however, have two possible explanations. It could be by the crystallisation of salts in the coarser pores, as proposed by Everett, or it could be due to the formation of a salt films which adhere tightly to the grains of the stone, and push them apart while they are growing. They go on to point out that this system is self-intensifying, because the more salts there are within the stone, the stronger the contractions will be at constant moisture content; and at constant salt content the absorption of water will cause a decrease of salinity and the system will expand. They conclude by stating that this is all that is required to explain the weathering action of soluble salts, and 'The idea of crystallisation and hydration pressures should therefore still be questioned, and further research carried out to verify the existence of those processes as damage factors' (Snethlage and Wendler, in: Baer and Snethlage 1997, p.13-15).

Moisture distribution

Moisture gradients within stone are an important consideration in determining where weathering effects take place. Snethlage and Wendler have shown that during wetting and drying cycles, there are well-defined moisture distributions in porous materials, which are dependent upon the properties of the material and on the drying conditions (Snethlage and Wendler 1997, p.15). They showed that during drying, salts migrate to the part of the pore system which is still wet, not necessarily the surface, and there they increase the concentration of the pore liquid and precipitate when all the water has evaporated. The zone of weathering is, therefore, the zone of maximum salt precipitation, which is the zone of maximum moisture content. It may also be assumed that in the absence of salts, the zone of maximum moisture content will also be the zone of maximum disruption to the stone structure due to differential hydric dilation.

Snethlage and Wendler go on to point out that dependent upon the position of the zone of maximum moisture content in a salt-contaminated stone, different weathering forms will be evident. If the zone is at the surface, loss of surface grains, or sanding-off will be evident. If the zone is one or two millimetres below the surface, a thin scale will form; if the zone is deeper, scales of one or two centimetres thick will form (Snethlage and Wendler 1997, p.17-18).

It should be pointed out that work of Snethlage and Wendler was in relation to sandstone, and they acknowledge that limestone may not respond in the same way, because their weathering rates are dependent upon the softer, water-soluble matrix which after dissolution leaves the more durable components standing proud. Their model may, therefore, only be applicable to limestones, such as calcareous sandstones and oolitic limestones, whose pore structures and weathering characteristics are similar to sandstones (Snethlage and Wendler 1997, p.22).

It is clear from the foregoing selected material that there is still debate about the precise mechanisms of weathering by salts. What *is* clear is that there is a difference in the risk posed by weathering due to the action of soluble salts compared to that by freeze/thaw cycles. That is because in Britain, freeze/thaw effects are likely to be seasonal, whereas the effects of salts are likely to be persistent, thus the risk is significantly greater.

Complex weathering

There is rarely, if ever, one decay mechanism acting in isolation. Although that is certainly the perception which may be obtained from the literature, and as Viles (1997) pointed out it is a naive analysis which tries to separates weathering into the neat packages of chemical, physical and biological influences, because of the overlaps and 'synergisms' involved in the processes. This view is also echoed by Snethlage and Wendler, and it has been shown in the preceding sections of this chapter how their model of weathering was developed to explain the interactions of multiple variables (Snethlage and Wendler 1997).

As soon as there is water involved in the decay process, the potential combination of decay mechanisms becomes increasingly complex and in Britain water is invariably involved in the weathering of stone. Goudie and Viles (1997) pointed out that gaining an understanding of the co-associations between decay mechanisms is an area of research which is relatively un-tapped.

The next two subsections, therefore, describe what is known about sequences of events which lead to weathering and weathering effects which might act concurrently.

Weathering implications of sulphur dioxide

The burning of fossil fuels produces many compounds, the most important of which, for the weathering of stone, are sulphur dioxide, carbon dioxide, and particulates. The production of particulates was significantly reduced when the clean air acts of 1956 and 1968 passed onto the Statute Book (HMSO 1956; 1968). These two acts also led to reduced sulphur dioxide and carbon dioxide emissions from domestic and urban industrial sources, and now the most important source of these two pollutants is coal-burning power stations (Cooke and Gibbs 1993). The current level of sulphur dioxide emissions is 776,000 tonnes, from a total of 1,187,000 tonnes from all sources, and 38,463,000 tonnes for carbon dioxide, expressed as weight of carbon emitted, from a total of 145,129,000 tonnes. Both sets of figures are for 1999, the last year for which figures are available (Department of Environment Food and Rural Affairs 2002a).

Schaffer pointed out that even carbon dioxide, dissolved in rainwater, has the capacity to cause weathering to sandstones in which the grains are cemented by calcium carbonate (Schaffer 1950, p.25). This is because calcium carbonate is more soluble in a solution of carbon dioxide than it is in pure water. Schaffer also explained the process by which sulphur dioxide can cause weathering of stone. Sulphur dioxide dissolves readily in water to form sulphurous acid which, on contact with calcareous stone, dissolves the calcium carbonate to form the relatively insoluble calcium sulphite. Calcium sulphite can then combine with oxygen in the air to form calcium sulphate, which is much more soluble in water, and crystallises to gypsum (Schaffer 1950, p.27), although gaseous sulphur dioxide can have a direct effect on carbonate stones (Serra and Starace 1978).

Another possible route to the formation of gypsum, described by Schaffer, is by the reaction between sulphur dioxide and oxygen, to form sulphur trioxide which, when combined with water, forms sulphuric acid. This then reacts with calcium carbonate in stone, to form calcium sulphate. It has more recently been recognised that there can also be a direct reaction between moist stone and gaseous sulphur dioxide, to produce gypsum (Cooke and Gibbs 1993, p.7).

Goudie and Viles highlight the two routes by which sulphur dioxide can be converted to sulphuric acid. The first route is by reaction between gaseous sulphur dioxide and atmospheric oxygen or ozone, to form sulphur trioxide, which then dissolves in rainwater. The second route is similar but with sulphur dioxide in aqueous form. The outcome for carbonate stones is, however, the same – the dissolution of the calcium carbonate to form calcium sulphate, carbon dioxide and water (Goudie and Viles 1997, p.149).

Thus, the formation of gypsum is a by-product of the weathering of carbonate stones by acid rain, but the weathering process does not stop there. On dense, hard, calcareous stones which are exposed to direct rainfall, the gypsum may subsequently be washed away by rainwater, but in more sheltered situations, particularly on softer, more porous calcareous stones, the calcium sulphate can cause a hard surface skin to develop (Schaffer 1950, p.28). Price (1996) highlights the work of Schiavon, who investigated the growth of gypsum crusts, and discovered that the crust growth is both inwards, into the stone, and outwards (see Schiavon 1992). The consequences of this are that differential thermal movements between stone and crust can cause disruption to both the crust and to the stone, resulting in blistering and exfoliation. In more porous stones the gypsum can enter the pore structure, where it can re-crystallise (Drever, in Krumbein *et al* 1994), or differential thermal expansion between the gypsum and the stone can also cause weathering. Gypsum formation can be seen, therefore, as both a consequence and a cause of the weathering of stone (Goudie and Viles 1997, p. 14).

As well as theoretical modelling, and the laboratory study of the processes involved, there have also been many site-based studies of the effects of air pollution on stone weathering. The work of Cooke and Gibbs (1993) has already been mentioned, and other studies include Butlin *et al*, (1992), and particularly Brimblecombe (1991), who studied the history of air pollution at historic sites and whose work was highlighted by Price (Price 1996).

The processes described so far have been mechanisms acting sequentially, which result in weathering. The following sub-sections consider weathering mechanisms which can occur concurrently.

Salts and frost

It has already been shown that water in the pore structure of stone is never likely to be pure water, and so frost action will inevitably involve the freezing of salt-contaminated water.

Two aspects to the weathering by frost and salts have been identified by researchers in the past. One is the effect which lowered temperatures have on salt solution within pore structures. The other is the effect which salt solutions have on stone as they freeze. It might be expected, from common experience, that solutions of salt would freeze at lower temperatures than water and so some degree of protection against weathering by frost would be afforded. Goudie and Viles, however, point out that some rocks disintegrate more rapidly when they are frozen after soaking in salt solution, but the severity of action is dependent upon the type of salt present and the concentration (Goudie and Viles 1997, p.158). It has been shown by laboratory tests that chalk which has been wetted by seawater is subsequently particularly vulnerable to weathering by frost (Goudie and Viles 1997, p.160; see also Jerwood, Robinson and Williams 1990a and 1990b). Goudie and Viles referring to the work of Williams and Robinson (1981) highlight several possible reasons why the severity of weathering of certain stone types by a combination of frost and some types of salt is greater than produced by either mechanism acting alone. These include:

- Surface sealing by salts, inhibiting water extrusion as it freezes;
- combined growth of salt and ice crystals may be greater than either acting alone;
- potential for greater saturation levels due to the hygroscopic nature of some salts;
- low concentrations of dissolved salts might increase the rate at which water moves to ice crystals on freezing, increasing crystallisation pressures;
- if, however, the freezing rate of a dilute solution is slower than pure water, the resultant ice crystals will be larger, because they have more time to grow, and hence they will be more effective at causing disintegration of stone.

Goudie and Viles point out that these hypotheses lack experimental verification, and Williams and Robinson conclude by suggesting that a single theory of frost and salts is probably not achievable because of the number of variables which require consideration (Goudie and Viles 1997, p.158-160; see also: Williams and Robinson 1981).

Air pollution, salts and plants

Abd el Hady and Krzywoblocka-Laurov investgated the weathering of the masonry of the Roman Theatre and Qaite Bay's Citadel in Alexandria, which highlights important considerations in complex weathering. Weathering was found to be due to a combination of salts which acted by crystallisation and by hydration pressures in a marine environment under the influence of atmospheric sulphur dioxide from local industry and in the presence of biological growths (El Hady and Krzywoblocka-Laurov, in: Félix 1995). They concluded that the weathering was caused by a combination of dissolution of the stone by sea water, the action of calcium sulphate, magnesium sulphate and sodium chloride from sea-spray and the oxidising effect of both sea-spray and rainfall on industrial airborne pollutants to produce sulphuric acid. This then reacted with the limestone to produce yet more calcium sulphate. They also observed that 'A good deal of limestone decay in Roman Theatre and Qaite Bay's Citadel has been caused by several varieties of fungi and algae growing on the damp surface of the stone...', and that they '...are capable of decomposing the stone by the acidic, soluble products they produce.' (El Hady and Krzywoblocka-Laurov, in: Félix 1995, pp.307-312)

SUMMARY

It can be seen from the foregoing, that many of the mechanisms involved in the weathering of stone are not yet fully understood. It is not surprising, therefore that the way in which mechanisms interact with each other is even less well understood. The example of the multiple weathering mechanisms acting in combination, identified and described by El Hady and Krzywoblocka-Laurov is relative rare in the literature, and the development of a 'model' of complex weathering still seems to be somewhat elusive.

Part two of this chapter will investigate what is known about the weathering effects of the types of plants which are under consideration in this research.

PART 2 – THE BOTANICAL COMPONENT

INTRODUCTION

Most texts on the conservation of stone have a section, no matter how brief or superficial, which describes the mechanisms whereby plants cause weathering. The intention here is to examine in some detail what those mechanisms are, to determine the extent to which they take place independently of those discussed in Part One of this chapter and the extent to which they can be seen as components of complex weathering.

DEFINITIONS

The terms *flora*, *plants*, *lichens* and *mosses* were defined in Chapter One, but it is worth reiterating that the term *plant* is used here as a generic term and not as a definition. This applies particularly to lichens, because to describe them as *plants* is taxonomically incorrect; nevertheless, that word is used in this research as a convenient collective term, to describe all the organisms under consideration. There are, however, other terms which will be used in this and subsequent sections which need defining. These are principally in connection with plant habit, or form, and are used to describe mosses, lichens and climbing plants.

Plant habit

Two basic plant forms are relevant: endoliths and epiliths.

Endoliths

Endolithic plants are those which live within the pore structure of stone and include photosynthetic bacteria, algae and some species of lichens.

Epiliths

Epiliths are plants which grow on, or are attached to, rocks or stones and those which are relevant here are lichens and mosses.

It should be explained, perhaps, that the terms endolith and epiliths are both general terms to describe plants which have similar growth forms or habitat, but in no way do these terms correspond to any taxonomic classification. Indeed, many plants can be classified in more than one of the above groupings, despite their taxonomic rank. These two terms are therefore convenient ways of distinguishing plants which have certain similarities in where and how they grow, irrespective of their appearance, structure or physiology.

Plant processes

It is not the intention to describe in detail all the processes involved in the germination, growth and reproduction of plants; that has been done many times, most notably by Stryer (1995), Salisbury and Ross (1992) and James (1973). There are, however, four key processes which require consideration because they are instrumental in the capacity of plants to cause weathering of stone.

Photosynthesis

Green plants manufacture carbohydrate by photosynthesis, whereby sunlight acting on chlorophyll converts atmospheric carbon dioxide, in the presence of water, to carbohydrate oxygen and water. The process can be summarised by the following equation:

$$CO_2 + 2H_2O \xrightarrow{\text{light}} \underset{\text{carbohydrate}}{(CH_2O)} + O_2 + 2H_2O$$

Respiration

Respiration is the process whereby the oxidation of the carbohydrates produced by photosynthesis produces energy. This is achieved in plants by respiring atmospheric oxygen to produce energy, carbon dioxide and water. The process can be summarised by the following equation:

$$\underset{\text{glucose}}{C_6H_{12}O_6} + 6O_2 \Rightarrow 6CO_2 + 6H_2O + \text{energy.}$$

Transpiration

Transpiration is the force whereby water and minerals are taken up by plant roots, and organic compounds are translocated throughout the plant. The water, in vapour form, is continually lost to the atmosphere through the leaves.

Mineral assimilation

Plants require several minerals for the manufacture of molecules upon which they depend. Of those minerals, calcium is most relevant to this research, because calcium ions are components of several metabolic substances, organic and inorganic, intra- and extra-cellular, which are implicated in the weathering of stone.

WEATHERING MECHANISMS

Algae

Algae, although not the primary organisms under consideration in this research are, nevertheless, important to one of the case studies considered in Chapter Six. Their ability to cause weathering of stone has long been recognised and the most recent research in Britain was carried out for Historic Scotland, in the context of disfigurement of sandstone buildings (Cameron, Urquart, Wakefield and Young 1997; Anon 1995; Andrews, Young and Tonge 1994). Although Cameron *et al.* were concerned with other forms of botanical growths including algae, they identified the key processes of weathering which algae can induce. These include the encouragement of water retention on the stone surface, dissolution of minerals by acidic secretions, and pressure effects of mucilage and algal growth within cracks, and within the pore structure of stone.

More significantly, perhaps, Walter-Lévy and Straus (1954) found that several types of plants, including algae, produced extra-cellular organic and inorganic compounds. The most significant of these for stone weathering is the production of extra-cellular gypsum. This suggests that in addition to the weathering processes summarised by Andrews *et al.* the complex weathering initiated by algae could be significantly greater than any of the mechanisms which they identified.

Lewin and Charola (1981) also found that algae growing on the surface of stone samples submerged in water produced crystalline deposits which, on analysis, showed the characteristics of orientated gypsum. By reference to their earlier work in 1978, they recalled that re-crystallisation of gypsum, due to periodic wetting and drying cycles of stone, is notorious as a source of decay (see Lewin and Charola 1978).

However, during the restoration of a villa in Salamanca, Spain, Grondona *et al* (1997) observed an unexpected phenomenon concerning a local sandstone, and botanical growths including algae. They observed that two well-defined naturally-developed layers occurred on the sandstone surface. These were identified as an outer, hard, crust principally comprising quartz and gypsum and an inner microbial mat comprising a fungus, a cyanobaterium and a green alga, with accumulations of different extra-cellular metabolites. After analysis, they concluded that the outer crust was formed by the crystallisation of salts mobilised by a nearby underground water source. They also concluded that the microbial mat was binding this hard outer crust to the surface of the stone, protecting the stone from further weathering. This conclusion was confirmed when they compared the condition of the stone surface where this phenomenon occurred with adjacent, highly weathered stone where this phenomenon was absent. This bio-preservation effect was only able to function because the stone was always at a high constant moisture content, providing stable micro-environmental conditions for the botanical mat, which also prevented moisture-induced movements between the outer crust and the stone and within the stone itself. It was also noted that the association between the three botanical components of the mat, although not a lichen, were living in a state of obligate mutualism which had not previously been reported.

These findings raise the question as to whether this biopreservation effect could exist on historic buildings in Britain. Theoretically, there is no reason why this should not be so, provided that water is available in sufficient quantities to achieve suitable stable micro-climatic conditions and the stone is of appropriate mineralogical composition and porosity. Grondona *et al.* note that despite the semi-arid Spanish summers, this phenomenon has been observed on several occasions (see De la Torre *et al.* 1991), but it is not clear from their account to what extent the combination of high local levels of moisture and high summer temperatures favour the growth of the organisms described, compared with the conditions which are normally encountered in the more temperate climate of Britain.

Lichens

> '...wherever they fasten their tiny fangs, the process of disintegration commences; and though carried out slowly and imperceptibly, though ages may elapse before any apparent effects have been produced, except the increase of individuals and the more shaggy and picturesque appearance of the rocks, yet the object of that steady, ceaseless labour will one day be accomplished; and is humiliating to the pride of man to find, that apparently as solid as the rock of which each individual stone had been hewn, and as hard as the famous Roman cement which had resisted the utmost efforts of Goth and Vandal, must yield in the end to the slow but persevering assaults of the most diminutive and contemptible vegetables, and be brought back again by these apparently feeble agents to the bosom of nature, out of which he had reared them with such labour and skill.'
>
> (Macmillan 1861, pp89-90)

Although those words were written by Macmillan in the mid-nineteenth century, it had been recognised at least 100 years earlier that lichens cause weathering of stone. Smith, writing in 1921, referred to Linnaeus who observed that lichens had the role of breaking down hard rock and preparing a soil on which more highly developed species could grow (see Linnaeus 1753). Linnaeus observed that the first colonisers of stone are crustose lichens which, as they die, leave organic matter on the stone surface. This enables foliose species of lichens to thrive and their rhizines to penetrate fissures and cracks in the stone surface where weathering is initiated. As these species die, the humus increases, enabling mosses to begin colonisation. As the mosses die, humus accumulations increase further and a herb layer can become established, and so the succession of genera and species continues.

Since Linnaeus, many writers have made similar observations, including Francis, in 1842, quoted at the beginning of Chapter One, but more recently specific research has been carried out into the nature of the weathering mechanisms involved in different species and the effect on various types of stone, but it is only possible to highlight a fragment of that body of research here.

Before considering the specific mechanisms whereby lichens cause weathering to stone, it is worth highlighting some of the factors which determine which species colonise which types of stone, because that has a bearing on the type and severity of weathering. As well as aspect, orientation, exposure, patterns of water run-off surface roughness and levels of nitrification, there is one other key factor which influences lichen colonisation and that is the mineralogy of the stone. Lichens are known to be sensitive to the pH of the surfaces which they colonise, and that is a function of the mineral content of the stone. Stone can be considered to be either acid or alkaline, depending upon whether the surface pH is below or above pH7 (Gilbert 2000, pp95-97). Saxicolous lichens (those which normally colonise rock or stone) can be broadly grouped into those which prefer to colonise acid stone and those which prefer to colonise alkaline stone. The critical pH value which separates those two broad groups of species has been found to be between pH6 and pH7 (Gilbert 2000, p.96). The determining mineralogical factor in the pH of stone, from the geologist's point of view, is the silica content. Acid rocks, those with low pH, include quartzites, gritsones, granite and slate, while neutral stones include dolomite and ironstones. Alkali rocks, those with high pH, include chalk, limestone, marble and evaporites. But from a botanist's point of view there are other mineralogical factors which influence species composition, such as the presence of metallic ions which might be toxic to some species or inhibit nutrient availability, but Gilbert acknowledges that these are relatively unexplored areas of research (Gilbert 2000, p 96). The buffering effect of alkali rocks to the effects of atmospheric pollutants is another mineralogical influence which determines species composition, and this will be discussed further in Chapter Six. Each rock type has a tendency, all other factors being equal, to attract particular groups of lichen species, and it is the intimate relationship between the mineralogy of the stone, be it quartzitic, neutral or calcitic, and the species present, be they endolithic or epilithic, crustose or foliose, for example, which determine the type and severity of direct weathering which takes place.

There were many publications on lichenology during the late-nineteenth and early-twentieth centuries, of which Smith (1921) is considered to be one of the most significant; however, the most important observations on lichen weathering in that period were those of Bachman, who was one of the first to investigate in detail the relationship between lichens and their substrata (Bachman 1890; see also Bachman 1892; 1904; 1915).

In the 1970s, three key texts on lichens were published (Ahmadjian and Hale 1973; Brown *et al.* 1976; Seaward 1977). These texts covered all aspects of lichenology and between them could be considered to represent the sum total of knowledge in that field at that time. The contribution to Ahmadjian and Hale by Syers and Iskandar is, perhaps, the most significant in this context. They consolidated the knowledge on lichen-induced weathering of stone and categorised the main mechanisms as biological and bio-chemical (Syers and Iskandar, in: Ahmadjian and Hale 1973, pp.225-248).

Biological weathering is caused by rhizine penetration of mineral crystals and stresses induced into the stone surface by the expansion and contraction of lichen thalli during wetting and drying. Biochemical weathering is caused by a variety of chemical compounds which are produced by lichens, the most significant of which are carbon dioxide, oxalic acid, and lichen acids.

Biological weathering

Many species of lichen depend on root-like, filamentateous, fungal hyphae or, dependant upon species, root-like rhizines, for their method of attachment to the substratum. Several researchers have observed that these rhizines often penetrate small cracks in stone, where the pressures exerted can gradually widen the crack and aided by the 'ratchet effect' caused by the inclusion of small grains of stone in the crack, can eventually lead to loss of material. Bachman observed that the hyphae can also penetrate mineral crystals, irrespective of lines of weakness in the crystal, or its cleavage planes (Bachman 1890). So disruption to the structure of stone can occur at an intra-crystalline as well as an extra-crystalline level.

Unlike vascular plants, lichens cannot control their water content in response to environmental changes; nevertheless, they are resistant to drought. During periods of rain, or high humidity, water is absorbed by capillary attraction into the lichen thallus, or absorbed directly from the substratum by the hyphae. During periods of drought, the stored water in the thallus is gradually assimilated, and the lichen eventually reaches a state of desiccation, where metabolic processes cease. When water again becomes available the thallus re-hydrates, often over a period of only a few minutes, and metabolic processes resume. The weight of water which lichens are capable of absorbing, for crustose species, can be up to 300% of the dry weight of the thallus. A full account of lichen physiology can be found in many of the texts on lichenology, particularly those by Baron (1999, pp.41-49) (from which the foregoing is drawn), Hale (1983) and Smith (1921, pp.209-245).

The consequences of the ability of lichens to resist drought and then to re-hydrate after wetting are two-fold. The endolithic species of lichen, such as *Verrucaria* spp. are completely immersed within the pore structure of the stone to a depth of several millimetres, often with only the fruits visible above the surface. When these species re-hydrate, the resultant expansive forces exerted by the immersed thallus can cause disruption to the structure of the stone. Epilithic crustose species, which are closely adpressed to the stone surface and tightly attached by their rhizines, can also cause disruption to the stone surface during drying and re-saturation. These processes involve detachment of particles of stone, removal of a thin film of stone, or tearing of the lichen thallus from the stone, detaching small fragments of stone in the process (Syers and Iskandar 1973, p.228; see also: Fry 1924).

McCarroll and Viles (1995) made the observation that although it is generally accepted that lichens cause weathering to stone, the critical factor is whether they do so at a faster rate than to stone without lichen cover, under similar environmental conditions. They investigated the weathering effects of *Lecidea auriculata* on the boulders of glacial moraine ridges of known date in southern Norway. *Lecidea auriculata* is principally an upland species in Britain and occurs rarely on Dartmoor and the northern Pennines, but more frequently in the Grampian Mountains of Scotland (Dobson 2000, p.205). The species is endolithic in habit, and its mode of weathering may, therefore, be similar to that of other more commonly occurring endolithic species of Britain.

By using scanning electron microscopy, McCarroll and Viles examined samples taken from boulders with lichen colonisation. They found that the lichens exploited weakness in the surface of the rocks and as they grew into them caused flakes of rock to become detached in the process. As the lichen grew, so these detached flakes were incorporated into the thallus and eventually came to the surface, probably to be expelled (McCarroll and Viles 1995, pp.199-206). They found that over time, the number of boulders affected increased and this corresponded to a decreasing surface hardness, detected by means of a Schmidt-hammer test. They were able to determine by laboratory tests the degree of weathering, and found that the mean rate of surface recession was 0.0012mm per year. This was in the order of twenty-five to fifty times that of rocks without lichen cover (McCarroll and Viles 1995, pp.199-206).

They also made one further observation which is relevant to this research. They noted that other researchers have argued that rocks which have a semi-permanent cover of snow are likely to suffer enhanced physical and chemical weathering due to the constant supply of moisture but they concluded that the action of *Lecidea auriculata* probably resulted in greater weathering rates on the dry, exposed boulders which they colonised, compared to the un-colonised boulders in damp, shaded hollows where snow accumulates (McCarroll and Viles 1995, p. 205).

Bio-chemical weathering

There are three principal components to bio-chemical weathering by lichens. These are effects due to carbon dioxide, oxalic acid and lichen substances. The significance of carbon dioxide, a product of lichen respiration, is that it is soluble in water to produce carbonic acid. This can then react to dissolve carbonates in stone, although it is not clear how significant this is as a weathering mechanism. Syers and Iskandar (1973) maintain that it is less significant that oxalic acid, which occurs on the hyphae and the surface of the upper cortex. Oxalic acid, one of many extra-cellular metabolic products of lichens is virtually insoluble in water and so its potential to act as a weathering agent in solution, Syers and Iskandar maintain, is also likely to be negligible.

There are said to be over 350 extra-cellular metabolic substances unique to lichens, but the chemical structure of many of them has not yet been determined They include the common Usnic acid, and esters, depsides and depsidones (Baron 1999, p.44). They are excreted from the hyphae, and some are responsible for the colour of the thallus, but otherwise their precise function is not yet fully understood. The substances which *are* understood, some of which are discussed by Hale (1983), are considered to be important to stone weathering because they have the ability to form metal complexes by the process of chelation. This is a reaction between an organic compound and a metal ion, and Syers and Iskandar note that significant amounts of calcium, iron, magnesium and aluminium can be complexed by lichen substances, with the result that the substratum on which they grow can undergo mineralogical changes sufficient to cause local disintegration, resulting in pits. Such pits, formed by many endolithic lichens are, perhaps, most noticeable in lighter-coloured species such as *Verrucaria baldensis*, where the dark, often empty, pits which contained the perithecya, which are the flask-shaped fruiting bodies, contrast sharply with the creamy-grey of the thallus.

Differential thermal stresses

Viles and Pentecost (1994), as well as acknowledging the work Syers and Iskandar, make further important observations for potential weathering action by lichens. They noted that one of the areas of study which has received little scientific attention is the thermal effects of difference in coloration between lichen and stone. Lichens often only partially cover stone, or they may form a mosaic of several different species of different colours which may also differ from the colour of the stone. The implication of this is that there will be differential absorption of insolation between species and between lichens and stone. Dark coloured lichens, such as *Verrucaria nigrescens* will produce higher surface temperatures than, for example, the ivory-white *Pertusaria lactea.* The consequence is that there may be thermal hot and cold spots over the stone surface, which may induce thermal stresses into the stone. Thus the potential for disruption to the internal structure of stone noted by Zezza (1992) may be greater between areas with and without lichens, than in areas of un-colonised stone.

The potential for bio-preservation of stone

Despite the above findings, recent research has suggested that there are circumstances under which lichens can protect stone surfaces from weathering. Mottershead and Lucas (2000), for example, investigated the way in which lichens inhibited the dissolution of a soluble rock in Malaga province, Spain. They observed that on gypsum rock, the lichens *Aspicillia calcarea,* common in Britain and *Diploschistes diacapsis* occurred on slight mounds on the rock surface. These mounds were, on average, 52.1mm wide, and 8.4mm high. They observed that on many of the mounds the centre of the lichen had died, resulting in the formation of an orbicular pit. They concluded that the general surface of the rock had been dissolved by rainwater, leaving the areas of lichen-colonised un-weathered rock standing proud of the surrounding weathered surface. As the centre of the lichen died, as is frequent with many species, the rock was re-exposed to weathering and hence the formation of pits (Mottershead and Lucas 2000, pp.601-609). The result was a series of conical, cratered mounds, the gradient of which was a function of the rate of lichen growth and the rate of lowering of the surrounding rock surface.

Whether the observations of Mottershead and Lucas are applicable to other species of lichens on less soluble types of rock is questionable. In any event, with a soft, porous rock such as gypsum, dissolution during episodes of inundation by water, especially if it is slightly acidic, might be expected to be more than just a surface phenomenon. This then raises the question as to how unique the observations of Mottershead and Lucas were, or whether it is a widely observed phenomenon on this type of rock either with, or without lichen colonisation.

One further piece of research in which it was believed lichens were providing a degree of protection to stone was that carried out by Viles and Pentecost (1994). They investigate the role of epilithic crustose lichens in the weathering of a quartzitic sandstone in the Cedarberg Mountains, in South Africa. Rock formations in these mountains had an unique weathering form, and the objective was to determine the extent to which the lichen flora was responsible for this. They observed, by scanning electron microscope examination of samples, that there was evidence of etching of the quartz grains, and dissolution of the quartz cement between the grains. But they concluded that the lichen flora was acting on a micro-scale on a very thin surface zone and was not linked to the macro-scale weathering form. The lichens may, therefore, be providing an overall protective cover, but just a few hundredths of a micron thick (Viles and Pentecost, in: Robinson and Williams 1994, pp.99-116).

From the investigation which Viles and Pentecost undertook, there is further evidence of the potential for lichens to provide protection to stone. Yet their work does not shed any light on the way lichen processes interact with other weathering mechanisms; they do not explain how, if not influenced by lichens, the unique weathering forms they observed were produced. But they do make some important observations which have implications for complex weathering. They pointed out that the combined effects of endolithic and epilithic lichens acting together is an area which requires study and equally relevant to this research, they observe that it is also important to understand the role of lichens at different scales, since '...geomorphological systems are part of a nested hierarchy, and processes dominant at one scale may take on a very different role at other scales.' (Viles and Pentecost 1994, p.113).

Lichen colonisation may, therefore, have an insignificant micro-scale weathering effect, but has the capacity to influence the severity of macro-scale weathering mechanisms.

Bryophytes

Of the Bryophytes, mosses are perhaps the best known and most significant in terms of masonry decay. They have a primitive root system, leaves and stems, and like lichens, can resist drought. A consequence of the inadequacy of their root system for assimilating water is that some are able to absorb water directly into the leaves (Doyle 1970). They are able to survive drought as a result of their ability to conserve moisture by preventing evaporation from the leaves, and this is achieved in some species by curling them tightly in a spiral to reduce their surface area. When water becomes available again, the leaves uncurl, where water in contact with them is absorbed by capillary attraction, as needed (Watson 1972). The perceived consequences for the decay of stone is that mosses can hold considerable volumes of water in direct contact with the stone surface for relatively long periods of time. This may result in the dissolution of calcite in calcareous stones, the mobilisation of soluble salts and the enhancement of the potential for frost damage.

There is one further consideration and that is the fact that many mosses are species of damp places (Jahns 1983). Because of their primitive root system they require an almost permanent supply of moisture, and this can be provided by stone which is in a permanently damp environment. Under these circumstances it is the stone which is supplying the moisture to the moss and not the converse.

A stonemason once made the observation that mosses cause damage to stone. The evidence was that if they are removed, a small depression in the stone often remains (Spree, pers com. 1997). Equally it could be argued that the moss was there because there was a depression in the stone, which accumulated humus and retained water, providing the perfect micro-environmental conditions for germination and growth of the moss. It is, in fact the root environment of mosses where the greatest potential for weathering occurs, because bacteriological activity in the root environment and the action of soil organic acids are well-recognised phenomena in mineral weathering processes (Drever and Vance 1994; Pitman and Lewan 1994). Only after a detailed investigation into the mineralogy and weathering characteristics of a particular stone type, with an understanding of the habitat preferences of different moss species, is it possible to assess which came first: the moss, or the depression in the stone.

Vascular flowering plants

Vascular flowering plants are a secondary consideration in this research. This is not because they are unimportant, but because they normally root in mortar joints which, arguably, are a sacrificial part of any masonry structure; therefore any weathering due to bacterial, or soil organic acid action in the root environment of the plants will normally act on the mortar, not on the stone. Feilden, however points out that the presence of plants growing in mortar joints is usually an indication that the joints are in poor condition and require maintenance (Feilden 1996, p.131). Notwithstanding Feilden's comment, the ecological significance of wall flora has long been recognised and it is worth mentioning the two key texts of Segal (1969) and Darlington (1981), as well as the many local floras which include Risbeth (1948), Woodel and Rossiter (1959) and Payne (1990) and the more recent work of Gilbert (1992) commissioned by English Nature, in which the ecological significance of obligate wall-dwelling species was highlighted.

SUMMARY

The main weathering effects of the two groups of plants under consideration can be summarised under the following headings:

Chemical effects

- Dissolution of the minerals or cementing agent by water produced by plants during photosynthesis, respiration or transpiration;
- dissolution of the minerals or cementing agent by water held against the stone;
- dissolution of the minerals or cementing agent by organic metabolic products;
- dissociation of minerals in the stone by organic acids.

Chemo-physical effects

- Preconditioning and soil development on the stone surface which encourages colonisation by higher plants.

Physical effects – direct

- Disruption to the internal structure of the stone due to growth of micro-flora;
- differential thermal absorption due to plant cover, and resultant alteration to the thermal stress distributions within stone;
- induction of surface shear stresses due to shrinkage/swelling of plants, notably those of algae and endolithic crustose lichens;
- effects on pore structure and moisture movements within the stone.

If active weathering is taking place it is indeed, as Macmillan observed, being '...carried out slowly and imperceptibly...', but the key question for this research is to what extent do the three plant groups under consideration, by their influence on other weathering mechanisms, contribute towards complex weathering; what are their macro-scale effects? That is the aspect of weathering by plants which will be investigated and discussed in the following two chapters, the results of which will further be considered in the case studies in Chapter Six.

CHAPTER FOUR

LABORATORY TEST METHODS AND THEIR DEVELOPMENT

INTRODUCTION

> 'So while it is tempting, and true, to say that your non-significant results in an experiment may point to the need for a larger-scale study, it is actually the significant results from the well-designed relatively small-scale studies that are going to pick up the more important 'robust' experimental findings'
>
> (Robson 1994, p.37)

This quotation, written in the context of research in the field of psychology, but nevertheless relevant here, highlights an important factor. Relatively small-scale studies, if they are properly designed and the results analysed in an appropriate way, are likely to reveal important findings. The laboratory investigation carried out as part of this research has been on a relatively small number of samples, many of which have been subjected to more than one test.

The previous Chapter investigated how an analysis of the literature on the causes of the weathering of stone might lead to the development of a model of complex weathering. This chapter will describe the ways in which some of the components of that model can be tested, particularly the component which involves lichens and mosses. So this chapter provides the link between the development of the model and the case studies in which the practical aspects of some of the components of the model are examined in more detail.

It is important to understand how different types of stone will react when exposed to particular weathering agents. The influence of the key properties of mineralogy, porosity, and pore size distribution were explored in the previous chapter, and this chapter investigates how those properties can be determined. In addition, a method was developed whereby the macro-scale weathering by lichens and mosses could be investigated by analysing their influence on moisture movements in and out of stone, already mentioned in Chapter One.

Aims and Objectives

The aims of this chapter are:

- To identify and apply the tests to determine the key physical properties of the stones from the case study sites;
- to identify and apply tests which will simulate weathering on those stones;
- to develop test methods which will enable the plant component of the weathering model to be investigated;

The objective is:

- To generate data from those key tests which, after analysis, will indicate the degree to which the plant component of complex weathering influences other weathering processes.

This Chapter describes the test methods and the sample preparation, but the matter of the sampling strategy will be discussed in the Chapter Six, following the investigation of the local geology of each case study site.

Structure

This chapter is divided into six sections:

- The identification of tests which can be carried out on samples of stone;
- the application of specific tests, or the application of modified tests, to a trial batch of samples;
- the application of specific tests to samples from the case study sites;
- the development of a test sequence to enable a comparative analysis to be made of water absorption and evaporation from stone, including stone with botanical growths;
- the development of a technique to isolate one surface of a test cube, subsequently to be subjected to simulated weathering tests;
- the development of a test method to determine the resistance of stone to the action of soluble salts, having botanical growths on one face.

Key aspects of the laboratory test methods

The laboratory test methods fall into three groups: tests to determine the relevant physical properties of the samples; tests to simulate weathering processes on the samples as indicators of durability; diagnostic tests to determine the causes of weathering. The steps in the development of the methods to investigate stone properties and durability are:

1. Identify key tests;
2. identify sample sources, and prepare samples;
3. preliminary implementation of tests;
4. assess suitability of tests;
5. if test is suitable, go to '12' below;
6. if test is unsuitable, go to '7' below;
7. modify tests;
8. apply modified tests;
9. assess modified tests;
10. if modified test method is unsuitable, go to '7' above;
11. if modified test method is suitable, go to '12' below;
12. develop test sequences;
13. apply tests, or modified test methods, to the case study samples, following the test sequence;
14. analyse results – this is dealt with in Chapter Five.

The criteria to be used in assessing the suitability of a test are:

the test must be repeatable;
it must be reliable;
it must be achievable without the use of expensive, or elaborate equipment;
it must provide analysable data which relates to the stated objectives of the test.

It may be that a test method – even after several attempts to modify it – is still unsuitable. Under these circumstances the test must be discarded and the consequences of not being able to apply that particular test assessed.

TESTS TO DETERMINE THE PHYSICAL PROPERTIES OF STONE

The following key tests have been identified:

Test to determine porosity;
test to determine pore size distribution;
tests to determine mineralogy.

Test to determine porosity

Before this test is described, it is worth mentioning that there are two types of porosity measurement which can be made on a stone sample. These measurements can be of open porosity, or of total porosity. Each requires a different experimental procedure. The total porosity relates to the total volume of air spaces, or pores, within a given sample of stone, including those which are not connected to the external surface of the sample. Open porosity, on the other hand, is the total volume of pores which are connected with the external surface of the sample (Borrelli 1999a). For the purposes of this research, only open porosity is relevant because as Borrelli points out, although closed pores affect the density of a sample and its thermal properties, they have influence on neither permeability nor transport of liquids within stone (Borrelli 1999a, p.3). It is permeability, and the pore structure as highways for liquid transport from the outside to the inside, and from inside to outside, which are key properties in the context of weathering mechanisms, and of the influence of lichens and mosses on weathering.

There are several versions of a test procedure to measure open porosity. British Standard *BS EN 1936: 1999* (British Standards Institution 1999b) requires dried weighed samples to be placed in a vacuum chamber, the air to be evacuated and water to be gradually introduced so as to fill the evacuated pores. The reduced pressure in the vacuum chamber is held for twenty-four hours, and then the hydrostatic weight of the samples is measured. The open porosity is calculated by inserting the measured values in the equations given. A similar procedure was earlier described by Ross and Butlin (1989).

Borrelli (1999a pp.10-11) also describes a procedure which, with modifications, was adopted in this research. The procedure described by Borrelli, while not requiring elaborate or expensive equipment, requires samples of a specific size and shape. The procedure has four stages: initial drying of the sample; saturation of the sample; determination of the apparent volume of the sample; calculation of open porosity.

The only variation from Borrelli's method was the way in which the apparent volume of the sample was measured. Borrelli's method of achieving this was to immerse the saturated sample in a graduated cylinder of water and note the rise of the water in the cylinder. A more accurate method, adopted here, is that described by Teutonico (1988) where the saturated sample was weighed suspended in water. This gave the hydrostatic weight of the sample, which, from Archimedes' principle, is numerically equal to the apparent volume.

Tests were conducted on three trial batches of samples, designated Porosity Test 1, 2 and 3. The results and analysis of these form part of Appendix 1. The main test, Porosity Test 4, was conducted on 40mm test cubes, the data from which is included in Appendix 4.1, the results of which are discussed in Chapter Five.

Tests to determine pore size distribution

There are several methods by which the pore size distribution can be measured. These can be by direct, or by indirect measurement.

Direct methods of measurement include assessment by means of examination of thin sections of the sample viewed under an optical microscope. This method enables the percentage of voids within the stone to be expressed as a percentage of the total surface area under examination. This method is described in a little more detail by Borrelli (1999a, p.7). One drawback to this method is that a number of thin sections need to be cut and examined from various layers and at various angles from the sample, in order to obtain a statistically viable set of results. This is a time-consuming process. A further drawback is that there is a limitation on the size of pores which can be measured, because this is a function of the resolution of the optical microscope.

Another direct test method described by Borrelli is by the use of the scanning electron microscope which can produce a three-dimensional image of the pore structure, giving otherwise unobtainable information about pore shape, size and distribution.

Indirect methods include the measurement of water absorption by capillarity. Borrelli (1999a) outlines this method and it was adopted in this research in a modified form. The results obtained are an important indicator of rates of absorption of water by stone because the rate of absorption by capillary action is inversely proportion to the pore size. The smaller the pores, the faster the rate of absorption.

The method adopted was to place standard 40mm test cubes on capillary matting in a petri dish. The capillary matting was raised off the floor of the dish by stone off-cuts about 5mm thick, so as to form a 'moat' around the perimeter of the dish. Water was added to the dish such that the water level was below the upper surface of the matting. Thus the only contact between sample and water was via the matting; no part of the stone surface was in direct contact with the water surface. The sample test cubes were oven-dried to constant mass at 50°C and then placed on the capillary matting.

The height of water rise was measured at hourly intervals for eight hours and then after twenty-four hours. Some samples absorbed water rapidly and for these the time taken for the water to reach the top of the cube was recorded. The height of the water rise was measured from the base of the cube, at each corner and along a vertical line drawn from the mid point on each vertical face. The results were tabulated and graphs plotted of time against the height of water rise. The tables and graphs are included in Appendix 2.

While the results of this test give a good indication of the relative pore sizes for a rang of samples, they do not provide an indication of the actual pore sizes. But Gauri and Bandyopadhyay provide us with the mathematical formulae from which the mean pore radii of the small pores can be calculated (Gauri and Bandyopadhyay 1999, p.84-87). This mathematical method has not been pursued in this research because there is a much simpler method whereby the pore size distribution can be determined and that method is by the use of a mercury porosimeter.

The principle of this method is that mercury is forced under increasing pressure into the pores of the sample. From a knowledge of the pressure exerted, the surface tension of mercury, the contact angle between the mercury and the solid, the pore radius can be then be calculated (Gauri and Bandyopadhyay 1999). The data generated by the porosimetry tests conducted on samples from the case study sites are included in Appendix 2 along with the histograms which were plotted from the data.

Saturation and drying Tests

In addition to the tests described above, it became apparent that a further test, not always described in the literature but included in Borrelli (1999a, pp.12-16), but in a different form to that presented here, could give valuable information about the performance of different stone types. The time for a sample to saturate and the time for it subsequently to dry to its original weight could provide information indicative of performance under the action of frost, salts, or acid rain, independent of those specific simulated weathering tests. This is because it provides an indication of how long weathering agents remain in the pore structure of the stone, compared to the time they take to accumulate. The test was performed on three preliminary batches of samples in order to develop the method, before its application to samples from the case study sites.

Method

The daily weights of the samples were recorded from the constant weight, oven-dry state, up to saturation when further immersion did not lead to any further increase in weight. Then, the daily weights were recorded while the samples dried out at room temperature until the weight became constant. Graphs were plotted from the results, and the shape of the graphs were used for comparative analysis between samples of the same stone and between samples of different stone types. Certain inferences can be drawn, relating to likely weathering performance of the sample when considered along with porosity and capillary rise time and with climatic data. These aspects will be discussed in the next chapter. The results from the three preliminary batches of samples, Saturation and Drying Test 1, 2 and 3, are included in Appendix 1. The data from the main test, Saturation and Drying Test 4, is included in Appendix 4 part 1 and the time-series graphs form part of Appendix 4 part 2. The data analysis is included in Appendix 4 part 3.

It should be noted that during the drying phase of this test there were three uncontrolled variables: the air temperature; the relative humidity; and the atmospheric pressure. These variables were recorded each day, at the time the samples were weighed and are included in Appendix 5, and are also considered in the analysis of the data in Chapter Five.

Tests to determine mineralogy

There are several test methods available to determine the mineralogy of stone. The streak test uses an unglazed porcelain plate along which the mineral, or stone, is drawn to make a streak on the plate. The colour of the streak is characteristic of the mineral present. The flame test subjects the sample to the hottest part of the gas flame. The subsequent colour of the flame is indicative of the mineral present (Sorrell and Sandström 1977).

The test method which gives the most detailed information is the use of thin sections, for examination with a petrological, optical microscope. This method relies on the characteristic refraction colours of minerals when the sample is reduced to a standard thickness of 30 microns, illuminated with polarised light and viewed through a polarising filter, 'crossed' at ninety degrees to the filter through which the sample is illuminated. A method of slide preparation is described by Adams, Mackenzie and Guilford, (1984, pp.97-98) and that, in a modified form, was used to prepare a number of slides from the case study sites, but with limited success.

The hydrochloric acid test is among the simplest of tests and can quickly give an indication of the presence of calcium carbonate in a sample, because this will be dissolved by the acid. Dilute hydrochloric acid – not more than 15% solution – is used and applied to the sample one drop at a time from a dropper-bottle. Effervescence on the surface of the sample indicated the presence of calcium carbonate – there is no reaction with quartz and feldspars, and dolomite will be dissolved only if the acid is warmed. This test was used principally as a spot test to distinguish carbonate stones from siliceous stone. The general application of the test to the samples from the case study sites was not undertaken as the principal mineralogical aspect was to distinguish the carbonate-cemented sandstones from the siliceous, because of the implications for weathering. This level of differentiation is equally well revealed by the test to determine the resistance to acid rain, described in the following section and so a separate hydrochloric acid test was unnecessary.

TESTS TO SIMULATE WEATHERING PROCESSES

The following key tests have been identified:

Test to determine resistance to freeze/thaw cycles;
test to determine resistance to the effects of soluble salts;
test to determine resistance to acid rain.

Test to determine the resistance to freeze/thaw cycles

It could be argued that there is no need for a test to determine the resistance of stone to freezing and thawing cycles, because a test to determine the resistance to the effects of soluble salts will yield the same information; both depend for their weathering effect on the growth of crystals within the pores structure. Price (1978) points out that the salts tests was developed in 1828 in order to be able to assess the resistance of stone to frost damage. Ross and Butlin (1989), although considering the suitability of stone for use in different exposure zones on a building, rely on a salts test and do not include a freeze/thaw test in their methods for determining durability. The Building Research Establishment have, however, subsequently acknowledged that now, with less polluted atmospheres, a need for two separate test has become apparent (Building Research Establishment 1997, p.6).

The simplest method of determining the resistance to freezing and thawing cycles is the one outlined in *BRE Digest 420*, 1997 (Building Research Establishment 1997). This involves placing samples of stone in a tray of water outdoors and exposing them to natural frost. The disadvantage with this method is that it may take several years before any significant results are obtained. This BRE Digest also reviewed the EN standard test method, and while sample dimensions and freezing temperatures vary in the final version of the EN test, the essential steps are the same.

The essential steps in European Standard test method *prEN 12371: 1996* (British Standards Institution 1996) include the preparation of five samples from a homogeneous batch of stone. The samples are to be 70 x 70 x 240mm, with a temperature probe inserted into the centre of one of the samples. The samples are to be dried to constant mass at 70°C. The samples are immersed, to constant mass, in water at 20°C, after which the hydrostatic weight is measured, along with the longitudinal resonant frequency. The samples are then placed vertically in a freezing tank. Each freezing and thawing cycles consists of freezing in air for six hours, followed by six hours thawing in water. The assessment of the action of freezing and thawing are made after the thawing part of the cycle, by visual inspection, measurement of apparent volume to detect loss of material, and measurement of longitudinal resonant frequency, to detect the development of micro-cracks in the sample. After each measurement the samples are turned over in the vertical plane. The test is repeated for a maximum of two hundred and forty cycles.

The above method is both elaborate and time consuming, requiring large numbers of large samples of stone. While it may be feasible in a commercial situation to obtain and prepare samples of this number and conduct the test over a protracted period of time, it was not considered practical in the context of a single-handed research project, where the largest amount of data had to be obtained from the minimum number of samples in the shortest possible time.

The key parameters of this test were concluded to be: preparation of standard size samples; saturation of the samples in water; freezing the samples for a given time; thawing the samples for a given time; determination of a method of assessing the effect of the test.

A more pragmatic approach to this test would be to use standard 40 x 40 x 40mm test cubes. The cubes could also, first, be used for the physical properties test and so be multiple-use test cubes. The saturation of the samples in water does not pose a problem, but the only readily available 'freezing tank' was either a domestic freezer or the freezer compartment of a domestic refrigerator. In order to decide which to use, the rate of freezing had to be considered.

Everett's investigation into the thermodynamics of frost action (Everett 1961), discussed in the previous chapter, showed that damage by frost is caused primarily by growth of ice crystals within the large pores, by withdrawal of water from the small pores. Goudie (1976), in a different context, has shown that the size of crystals which grow is dependent upon the length of time in which they are allowed to grow; therefore, a long growth time will produce a greater degree of weathering, and this will be determined by the time the saturated samples take to freeze. Fast freezing results in smaller crystals, and a greater number of cycles would be required to produce measurable weathering. Slow freezing, on the other hand, produces larger crystals and fewer cycles would be required to produce measurable weathering.

Two methods were adopted to determine the likely freezing rates of the samples in the two freezer options. These methods were: the monitoring of the temperature of a given weight of water as it was cooled from a known temperature to freezing point in each freezer; and the measurement of the core temperature of a sample of stone, measured by an embedded temperature sensor, as it was cooled from room temperature to the temperature of the freezer, or to some reference temperature. A sample of 15ml of water, in the freezer compartment of a refrigerator took 25 minutes to cool from 24.7°C to –0.6°C. The same volume of water at the same starting temperature took only ten minutes to fall to 0.0°C in a domestic freezer and so the former was used for the test. The difference in these two times can be attributed to the lower temperature in the domestic freezer.

The method of determining the degree of weathering need be nothing more complicated than a combination of visual observation of the samples and recording their weights after each cycle, although it is acknowledged that recording the resonant frequency of the sample after each cycle would give an indication of changes within the sample which are not visible to the naked eye.

The length of the cycles and the total duration of the test then needed to be determined. There would be obvious logistical advantages in a cycle with a duration of twenty-four hours, and for the trial of this test on ten, 25mm, test cubes it was decided that soaking for twelve hours and freezing overnight, for twelve hours would be a convenient starting point. The samples were weighed every tenth cycle and there was initially no limit set on the total number of cycles until the performance of the trial batch of samples could be assessed. In fact the trial batch ran for 130 cycles; the two further, smaller batches, of three 25mm cubes, and four 40mm cubes, ran for 120 and sixty cycles respectively. The results of these trials, Freeze/Thaw Test 1, 2 and 3, are included in Appendix 1.

Twenty-six samples from the case study sites were tested, Freeze/Thaw Test 4, using 40mm test cubes, and the same method described above was used except that because of constraints of time, the samples were tested over a maximum of 100 cycles, or until the sample had lost material such that its weight had fallen below five percent of its starting weight. The data and analyses are included in Appendix 3, and the results are discussed in the next chapter.

Test to determine the resistance to the effects of soluble salts

Mention has already been made of the development of a test method using soluble salts to provide a rapid indication of the resistance of stone to weathering by frost. In the absence of a British Standard test method specifically to determine the resistance of stone to the effects of soluble salts, the Building Research Establishment, in 1989, developed their own method, which was widely adopted and considered to be the most appropriate to the British climate, of the many methods then in use. A detailed description of this test can be found in Ross and Butlin (1989, p.3), but an outline is given here.

The test method used sodium sulphate as the salt, and 40mm test cubes. The cubes were dried to constant mass in an oven, placed in a desiccator to cool and then weighed. They were then immersed in sodium sulphate solution for two hours, then placed in a pre-heated, humid oven and dried for sixteen hours. After removal from the oven the samples were allowed to cool, then weighed and the cycle repeated for a total of fifteen cycles.

It is worth noting that Ross and Butlin state 'The main use of the crystallisation test in Britain is for testing limestone, but it can be of limited use for sandstone.' Price on the other hand maintained that sandstones are rarely susceptible to frost damage; nevertheless, a salts test can give a good indication of the resistance of a particular sandstone to the effects of salt crystallisation (Price 1978, p.2). Notwithstanding this apparent disagreement, a salts test was used on all the samples from the case study sites, both limestones and sandstones.

Price (1978) investigated the influence of certain variables on the performance of the salts test following the production of anomalous results in inter-laboratory tests initiated by the RILEM 25 PEM Working Group. After examination of the differences in the test methods used, Price identified the critical variables as: solution concentration, solution temperature, and rate of drying. The influences can be summarised, in general terms, all other variables remaining equal, as follows:

- Higher solution concentrations result in a greater weathering effect;
- lower solution temperatures result in a greater weathering effect; at temperatures over 30°C there was negligible weight loss of samples after twenty cycles;
- higher drying temperatures tend to increase the weathering effects; stones with fine pores tend to dry more slowly that stones with large pores; furthermore, incomplete drying results in incomplete crystallisation of the salt, which then blocks the pores and inhibits uptake of solution during the next soaking cycle (Price, 1978).

Price concluded that although it was essential to control these critical parameters during tests, failure to do so would be unlikely to affect the overall ranking of the samples at the end of the test. It was only when samples did not dry to constant mass after each cycle that anomalous results occurred.

Since the work of Price, and the development of the BRE salts test method, there has been published an European Standard salts test method: *BS EN 12370:1999* (British Standards Institution 1999a). Only a brief summary of the test method will be given here, because an investigation into its precise mode of action will be carried out later in this chapter.

The procedure follows closely the BRE method, but the European Standard method requires that:

The samples are wet cut by diamond cutting wheel;
the specific gravity of the solution should be checked;
the temperature of the solution during soaking should be maintained at 20°C;
the oven temperature should be brought up to 105°C in not less that ten hours and not more than fifteen hours.

The points of departure of the method adopted in this research were, due to restrictions imposed by equipment, more closely based on the BRE method than the BS EN method, but as Price has pointed out, provided that there is consistency throughout a series of tests, variations in the method would not be expected to change the ranking of the samples at the end of the test (Price, 1978).

The method adopted was as follows:
Test cubes of size 40mm were dry cut by diamond cutting wheel. The cubes were washed to remove excess dust and dried to constant mass in a fan-assisted drying oven, at 50°C. The samples were allowed to cool to room temperature and weighed. They were then placed in individual 120ml glass beakers, and 60ml of 14% sodium sulphate decahydrate solution was added to each beaker. The beakers were covered to reduce evaporation and the samples left to soak for twenty-four hours – Borrelli also gives twenty-four hours as the soaking time (Borrelli 1999b, P.13). They were then taken out of the beakers and allowed to drain for thirty minutes before being placed on a wire rack in a drying oven at 50°C, for twenty four hours. The oven was pre-heated, with a petri dish containing 150ml of water placed on the floor of the oven. By running a parallel dummy test during the trials it was established that the samples would dry to constant mass at this temperature in twenty-four hours. The dummy test involved the same procedure as the main test, except that the sample was immersed in water instead of sodium sulphate solution. The samples were removed from the oven, allowed to cool for thirty minutes in a desiccator and weighed. The cycle was repeated for twenty cycles, or until the samples had lost material such that their weight fell below 5% of the weight recorded after the first cycle, or until they became so friable that they could no longer be handled. The resultant weights were tabulated and time-series graphs drawn to indicate the comparative rate at which material was lost from each sample during the test. Two trials of this test were carried out, the results of which are included in Appendix 1. The data for the main test, Salts Test 3, is included in Appendix 3, along with the time-series graphs which were plotted from the data and the analyses. The results are discussed in the following chapter.

Test to determine resistance to acid rain

Ross and Butlin (1989) identify a test to determine the resistance of a sample to the effects of acid rain as one of their key tests of stone durability. The test procedure involves soaking 50 x 50 x 15mm test prisms in 20% sulphuric acid for ten days. If, they maintain, a more rigorous test is required, 40% sulphuric acid may be used.

In the trials of this test, samples of size 40 x 40 x 15mm were dried in an oven at 50°C to constant mass, and then weighed. They were placed in individual 120ml beakers and 60ml of 20% sulphuric acid was added. The beakers were covered and placed in a mechanically-ventilated cupboard for ten days. Subsequently they were drained and washed in running water. Highly-deteriorated samples were transferred to 500ml beakers and filled with tap water. Water was decanted after any sediment had settled and the decanting process repeated every few hours over a period of two days. The residue was then filtered. The samples and residues were dried to constant mass, as at the start of the test. The results were tabulated, a bar charts of weight losses, or gains, were plotted. In addition the extent of weathering of the samples was described and set out in a table so that each sample could be given a 'destruction score', on a scale of 0 to 5: 0 represents no change to mass nor volume; and 5 represents complete disintegration of the sample.

Nine samples were tested in the trial of this test and the results appear in Appendix 1.

After the trial, samples from the case study sites were tested with 10% and with 5% sulphuric acid. 20% sulphuric acid had proved too harsh for some of the carbonate-cemented Jurassic sandstones. Fourteen samples were tested, and a further fourteen samples with lichens on one face were also tested.

The results were analysed in the same way as in the trial and both results and analysis are included in the next chapter. The data from this test are included in Appendix 3.

Ross and Butlin (1989) maintain that this test is only suitable to be carried out on sandstone because the reaction between carbonate stones and sulphuric acid produces calcium sulphate. It is thought that this forms a protective crust on the surface of the sample, hindering any further reaction with the acid. Notwithstanding this, it was decided to include carbonate stones in this test to try to verify or disprove this theory.

DIAGNOSTIC TESTS

The diagnostic tests which have been used are the microchemical tests to detect the presence of soluble salts in a sample. Borrelli (1999b) describes a series of tests to detect soluble sulphates, chlorides and nitrates (Borrelli 1999b, pp. 14-19). Only the test for the presence of soluble sulphates was used.

Test for the presence of soluble sulphates

The test method adopted follows closely that described by Borrelli. The samples were ground to a fine homogeneous powder, and not more than 0.1g was put in a test tube to which was added about 5ml of de-ionised water. Each sample was split into five, for five tests on each sample. For each test, one simultaneous test was carried out on approximately 1ml of de-ionised water so as to compare these 'blank' results with the results obtained with the sample. After the insoluble residue had settle to the bottom of the test tube one or two drops of Hydrochloric acid of 2 mole strength and one or two drops of 10% solution of barium chloride were added. Borrelli points out that before the reagents are added, the solution must be clear – if not it should be filtered. The appearance of white crystals of barium sulphate, insoluble in nitric acid, indicate the presence of sulphates. The walls of the test tubes were stroked with a glass rod to help the nucleation of the crystals and therefore the formation of the precipitate. The results, either positive or negative, were noted, appear in Appendix 7 and are discussed in Chapter Six.

TEST SEQUENCE AND SAMPLE GROUPS

Introduction

In order to be able to determine the influence of lichens and mosses on stone, a sequence of tests had to be devised so that performance of samples both with and without lichens and mosses could be compared.

Stage 1

The first stage in the test sequence was to determine the physical properties and weathering characteristics of the stones of the case study sites. This was achieved by the application of the key tests already outlined, including Saturation and Drying Test 4, to standard test cubes cut from stone from the case study quarry sites.

Stage 2

Stage two was to seal five of the faces of the Stage 1 samples and to repeat the saturation and drying test.

Stage 3

Stage three of the sequence was to repeat the saturation and drying test on stone samples with lichens and mosses on one face, being 16.7% of the available surface area, representing partial cover by those two plant groups.

Stage 4

The fourth stage of the sequence was to isolate all but one face of the test cubes with lichens and mosses. This would represent 100% plant cover by those two plant groups.

As a result of those four stages of the test sequence, the samples could then be arranged into two groups: those with lichens and mosses, and those without. The following table shows the relationship between the test stages, the resultant sample groups and the pairs of groups which would subsequently be analysed. It should be noted, however, that groups 1, 2 and 3 comprise the trial samples and are not included in the analysis in Chapter Five.

Test sequence stage	Sample group	Paired-groups analysis
Stage 1: tests on standard cubes	4	groups 4 & 6
Stage 2: tests on cubes with five sealed faces	5	
Stage 3: tests on cubes with lichens and mosses on one face	6	
Stage 4: tests on cubes with lichens and mosses on one face and five sealed faces	7	groups 5 & 7

Table 4.1 Relationship between test stages and sample groups

In addition to the above, a salts test was to be applied to samples at Stages 2 and 4. Because of the peculiar nature of the samples used in those stages of the sequence, an alternative to the standard salts test needed to be developed. The processes involved are described later in this chapter under the heading of *Alternative salts test method.*

ENCAPSULATION OF SAMPLES

Introduction

This section describes the development of a laboratory method to enable moisture movement and simulated weathering tests to be investigated in stone test cubes, but in a manner whereby the mode of action of the test will be through living plant material growing on one surface of the test cube. The results of both saturation and drying and weathering tests can then be compared to the results of the same tests carried out on samples of the same stone, but without plant tissue. The sealant must therefore exclude water and the weathering agents from all faces of the test cubes, except for the surface under test. This can be achieved by encapsulation of the remaining five surfaces of the test cubes.

Aims and objectives

Aim

To find a sealant material which can be used on stone test cubes to seal five of the faces, and satisfy the following parameters:

- Readily available product;
- must be easy to apply consistently to stone;
- must be waterproof;
- must bond with the stone surface;
- must not contaminate the pore structure of the stone
- must withstand 33% sodium sulphate solution at 32°C;
- must be flexible under test conditions so as to accommodate temperature and moisture-induced dimensional changes of the test cubes;
- must withstand repeated handling during the test procedures.

Objectives

- To apply the sealant to five surfaces of previously tested sample cubes;
- to repeat the tests;
- to compare the results.

Method

The method of selection of the sealant involved a simple saturation and drying test, in water, of stone test cubes completely encapsulated in a variety of possible sealants. Eight 30mm cubes of stone were cut, to a tolerance of ±1mm, from a single sample obtained from the Penny Piece quarry near Rievaulx Abbey. This particular stone was selected because it has a high porosity, an 'open' surface texture, and because of a perceived difficulty in sealing such a surface due to the potential absorption of liquid sealants before they have time to cure.

Before the application of sealants, the test cubes were dried in an oven at 50°C to constant weight, then allowed to cool to room temperature in a desiccator. Six potential sealants were tested, as listed below, along with the reason for their selection, and the method of application.

- ***Waterproof PVA adhesive:*** used in the construction industry as an adhesive, additive to plasters and as a porous-surface sealant; claimed by the manufacturer to be water-proof; application by two full brush coats, undiluted.
- ***High-performance acrylic sealant:*** used in the electronics industry to seal printed circuit boards, and claimed to be resistant to both acids and alkalis, to withstand high temperatures, and retain its flexibility; application by three aerosol coats.
- ***Hammerite paint:*** primarily used on ferrous-metal surfaces, but composed of micro-flakes of glass and claimed to be waterproof; application by two full brush coats.
- ***Silicone sealant:*** used in the construction industry as a general-purpose waterproof sealant, compatible with porous building materials; applied by mastic-gun, and smoothed by metal spatula to approximately 0.5mm thick.
- ***Polymeric sealant:*** claimed by the manufactures to be a more 'advanced' sealant than Silicone; packaged in a tube with nozzle; applied direct from the tube and smoothed with a metal spatula to approximately 0.5mm thick.

- ***Concrete floor paint:*** used in the construction industry as a surface coating to concrete floors and claimed to be resistant to weak acids and alkalis; application by three brush coats.

After the sealants had cured, the test involved the measurement of the rate of water absolution of the samples and the subsequent rate of drying compared to un-treated samples. The cubes were re-weighed, submerged in a tray of water, and re-weighed at twenty-four hour intervals, for fourteen days. The samples were then allowed to dry at room temperature and weighed at twenty-four hour intervals for a period of eight days or until they achieved their original weight. During the drying part of the test the relative humidity and air temperature were measured. Time-series graphs were plotted of the sample weights.

The saturation and drying curves for the samples were compared with a 'standard' saturation and drying curve for the same stone, established in previous tests by the writer. The criteria for the success or failure of the sealant was the degree of divergence from the 'standard' curve. The maximum divergence – a horizontal straight line – would indicate the ideal sealant which neither gained nor lost weight during the test; however, a small weight gain, in the order of a few tenths of a gram would be acceptable provided that this gain occurred within the first forty-eight hours of the immersion part of the test and was lost within a similar period during the drying phase of the test. Such a situation might suggest water absorption by the sealant rather than the stone, but the sealant would not allow water to reach the stone. The worst case would be a sealant which permitted water absorption at a similar rate to the reference cube and followed the pattern of the wetting part of the 'standard' wetting and drying curve, but which subsequently prevented drying at the same rate as the reference cube. This would indicate a highly porous sealant which would subsequently entrap water within the sample.

The cubes were tested in two batches. Each batch consisted of three cubes, each encapsulated by a different sealant and one reference cube with no encapsulation.

Results:

The graphs plotting sample weight against time for the two batches of four samples per batch, are shown below.

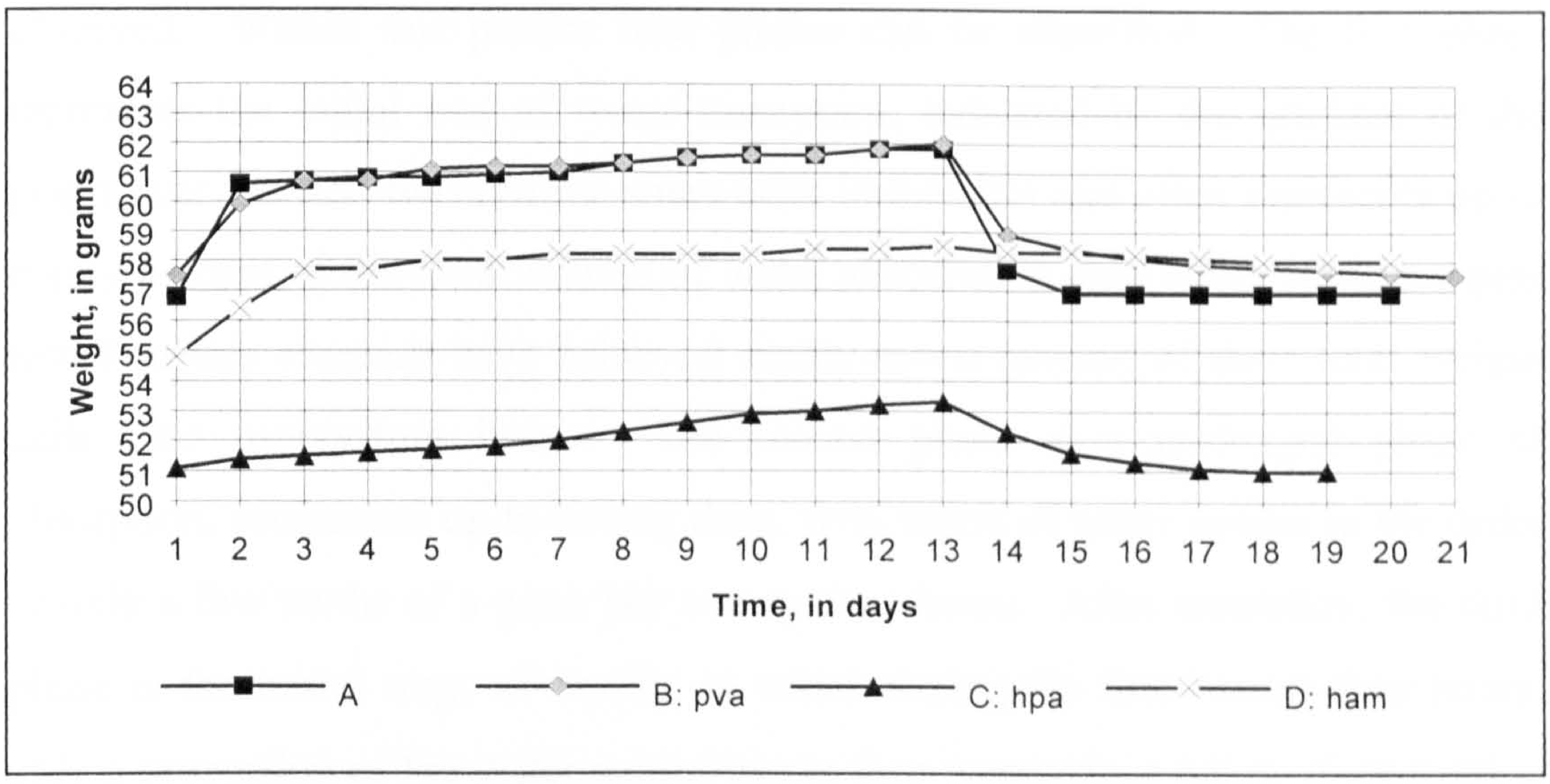


Figure 4.1 Encapsulation materials test: saturation and drying curves for batch 1

The letters in the legend have the following meanings:
A: the reference cube; B: waterproof PVA; C: high performance acrylic; D: Hammerite metal paint

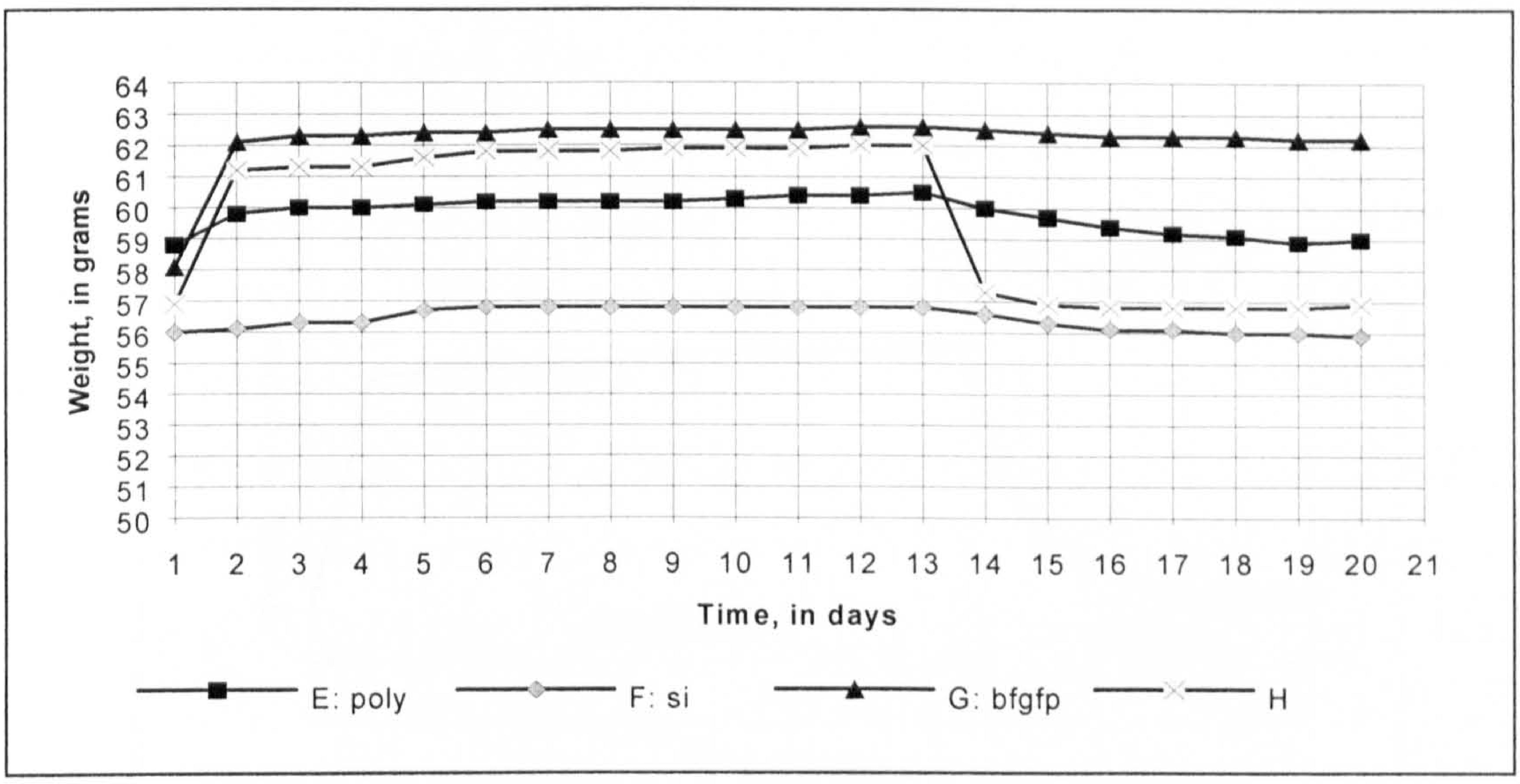


Figure 4.2 Encapsulation materials test: saturation and drying curve for batch 2

The letters in the legend have the following meanings:
E - Polymeric sealant; F - Silicone sealant; G - Concrete floor paint; H - Reference cube

Discussion

Mention has already been made of the 'standard' saturation and drying curve, in which a distinct pattern of water absorption and subsequent water loss has been observed. Within this pattern four phases can be identified. The first phase represents the initial rate of water-absorption, indicated by the gradient of the graph over the first twenty-four hours after immersion and often represents up to eighty percent of the final volume of water absorbed at saturation; some samples tested in this research have achieved eighty-seven percent of their total weight gain after twenty-four hours. The second phase is a prolonged phase of absorption, sometimes up to twenty days, with levels of water uptake in the order of only a few tenths of a gram per twenty-four hours. After saturation, the third phase is the initial stage of drying, in which during the first twenty-four hours, only a proportion of the water gained in the first twenty-four hours of immersion is lost by evaporation. The fourth phase is the more prolonged loss of the remaining water until the sample reaches its original equilibrium weight at the ambient relative humidity. The results of this test were analysed by comparing them to these four phases of saturation and drying curves of the reference cubes:

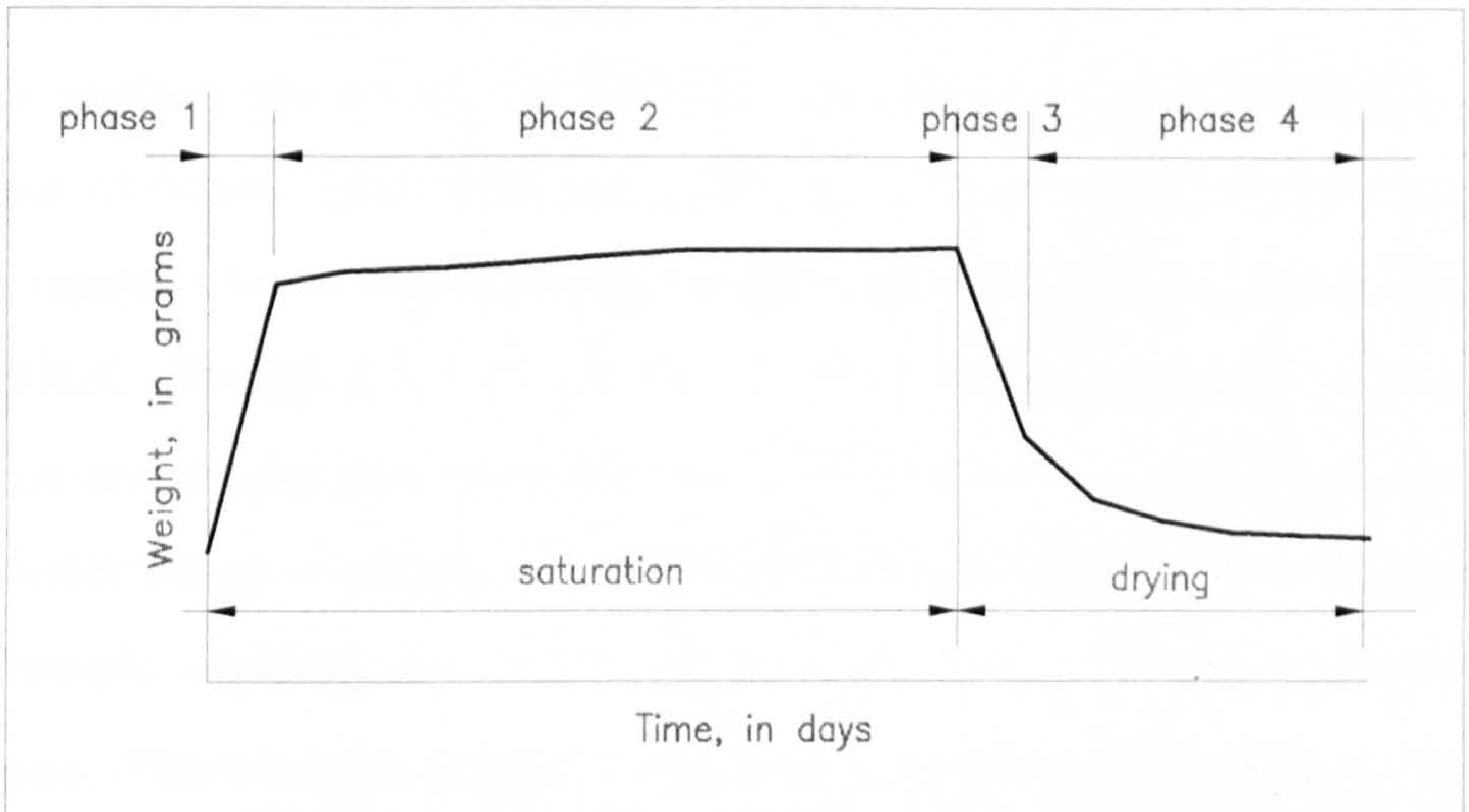


Figure 4.3 The four phases of a typical saturation and drying curve

The performance of all eight cubes tested is analysed below, in order of performance – worst performers first.

Reference cubes: The graph of weight gain and subsequent loss in the reference cubes closely matched the 'standard' curve, as was expected.

PVA sealant: the graph is a close match to the 'standard' curve, except that the initial rate of absorption, and subsequent evaporation is slower. This sealant was unsuitable.

Hammerite: absorbed to the same extent as the reference samples, but subsequently entrapped the absorbed water, failing to release it during the drying phase. This sealant was unsuitable.

Concrete floor paint: absorbed to the same extent as the reference samples, but subsequently entrapped the absorbed water, failing to release it during the drying phase. This sealant was unsuitable.

Acrylic sealant: only absorbed two-thirds of the amount of water of the reference cubes and compared with the 'standard' curve, the gradients for all phases were much flatter. The sample dried to its original weight, but it permitted too much water absorption.

Polymeric sealant: had a very flat initial rate of water uptake, but steadily absorbed a total of over two grams. This represents over 14% of the dry cube weight, but nevertheless it returned to its original weight on drying. Despite the amount of water absorbed, it performed better than most.

Silicone sealant: had a very flat initial rate of absorption and absorbed less than one gram of water. This represents 1.6% of the dry weight of the cube. The sample returned to its original weight at the end of the drying part of the cycle. This sealant, although it did not produce the ideal horizontal straight line graph of saturation and drying, performed the best of those tested. To enable its suitability to be further tested, a sample of this sealant was placed in a freezer compartment of a domestic refrigerator at –15°C for ten days, and its elasticity checked on a daily basis. There was no change to its elastic properties under this test. A further sample of the sealant was place in a sealed container of 14% sodium sulphate solution for ten days. There was no detectable change to its elastic properties under these conditions.

SATURATION AND DRYING TESTS ON SAMPLES FROM THE CASE STUDY SITES: SAMPLE PREPARATION AND TEST PROCEDURE

The method adopted to determine the saturation and drying times of a trial batch of test cubes has already been described. This section adopts the same basic method, but with refinements to suit the four sample groups described earlier. The sample preparation, test procedure and key parameters for the samples of each group are described below.

Group 4 samples

Standard samples

Number of samples: 32

Stone samples were cut into 40mm cubes, to an accuracy of ±1mm, using a diamond tile-cutting blade in a stand-mounted angle grinder. The test cubes were washed to remove surface dust, and then dried to constant mass at 50°C in a fan-assisted drying oven. The samples were then allowed to cool in a desiccator for one hour, and weighed, to a precision of 0.1 grams.

The samples were immersed in an open dish of water for twenty-four hours. The dish accommodated about 30 samples, with a space of twenty-five millimetre between samples, and was sufficiently deep to provide a water cover over the top surface of the samples of at least twenty millimetres. After twenty-four hours immersion, the cubes were removed from the dish and the surfaces of the cubes were carefully blotted with a paper towel to remove surface moisture. The samples were re-weighed and then re-immersed in water. The cycle of immersion, blotting dry and weighing was repeated every twenty-four hours until the samples were saturated. Saturation was deemed to have occurred when at least three consecutive weights were equal, or when five consecutive weights fluctuated by no more than 0.1gram. The samples were placed on a tray to dry at room temperature and their weights recorded at twenty-four hour intervals until they had returned to their original weight, or at least three successive weights were equal or five successive weights varied by no more than 0.1 grams.

In parallel with the air-drying and recording of daily weights of the samples, three further parameters were recorded: The air temperature in the laboratory; the relative humidity in the laboratory and the weight of water in an open petri dish. The importance of these three additional parameters will be discussed fully in the analysis of the results of these tests, in the next chapter. The data for these three parameters is included in Appendix 5.

The weights of the samples, the relative humidity, the air temperature and the weight of water in the petri dish were all measured at the same time, plus or minus 30 minutes, each day.

Group 5 samples

Test cubes with five sealed faces

Number of samples: 15

This group was the last to be prepared and tested, as the samples were the same as those in Group 7, but with plant material removed. This was done to ensure maximum homogeneity between the samples in these two groups, which would aid the subsequent analysis of the data. The samples in this group are, then, the same samples as Group 7, but with the mosses and lichens removed.

The moss cover could easily be peeled from the surface of samples and the surface gently scrubbed with a fine bristle-brush to remove surface debris and rootlets. Four of these mats of moss, after removal, were subjected to an independent saturation and drying test, the results of which will be discussed in the next chapter. Lichen cover could not be removed by this method but had to be carefully scraped off the surface, or, on the harder calcareous stones, removed by the very careful use of a small diamond grinding wheel. It was important, in the preservation of homogeneity, that the absolute minimum amount of stone material be removed, whilst ensuring that lichen tissue was removed from the surface pores of the samples. There was no possibility of using any of the removed lichen tissue for further tests, so a separate saturation and drying test was performed on six samples of lichens collected from various locations. The results will be discussed in the next chapter.

The test procedure was then the same as for the Group 4 samples.

Group 6 samples

Test cubes with plants on one face

Number of samples: 24

The method of preparation of samples was as for the Group 4 samples, but the subsequent test procedure had two important variations:

- The samples were not oven-dried to constant weight before the start of the test because that would have destroyed the plant cover. Instead, the samples were allowed to dry at room temperature for fourteen days;
- after each soaking phase of the test, and before each weighing, the samples were shaken gently for a few seconds to remove excess moisture from the surface with the plant cover. These surface were not blotted to remove excess moisture, but since they were invariably irregular it can be argued that after initial surplus water has been shaken off, the remaining moisture held by surface tension will be the same on each occasion; any fluctuation in sample weight could then be attributed to water gains or losses from the sample.

Group 7 samples

Test cubes with five sealed faces and plants on the sixth face

Number of samples: 15

The preparation of the samples in this group was the same as for the samples for Group 4, but with two additional operations:

- Preparation of edges and corners;
- the application of the silicone sealant to five of the faces.

After the cubes had been cut, the sharp edges and corners were removed with a small diamond file to a radius of approximately 1.5mm, so as to ensure even coverage of the silicone sealant. The sealant was applied to five faces of the cubes by mastic gun in beads, about five per face, and then spread evenly with a spatula, taking extra care to ensure that the edges and corners had adequate cover. After about ten minutes the sealant was smoothed with a moistened spatula, then left for a few hours until the cubes could be handled. They were then inspected and any thin or missing areas of sealant were spot-filled and smoothed. The cubes were then left to cure for forty-eight hours.

The test method was then the same as for the Group 6 samples.

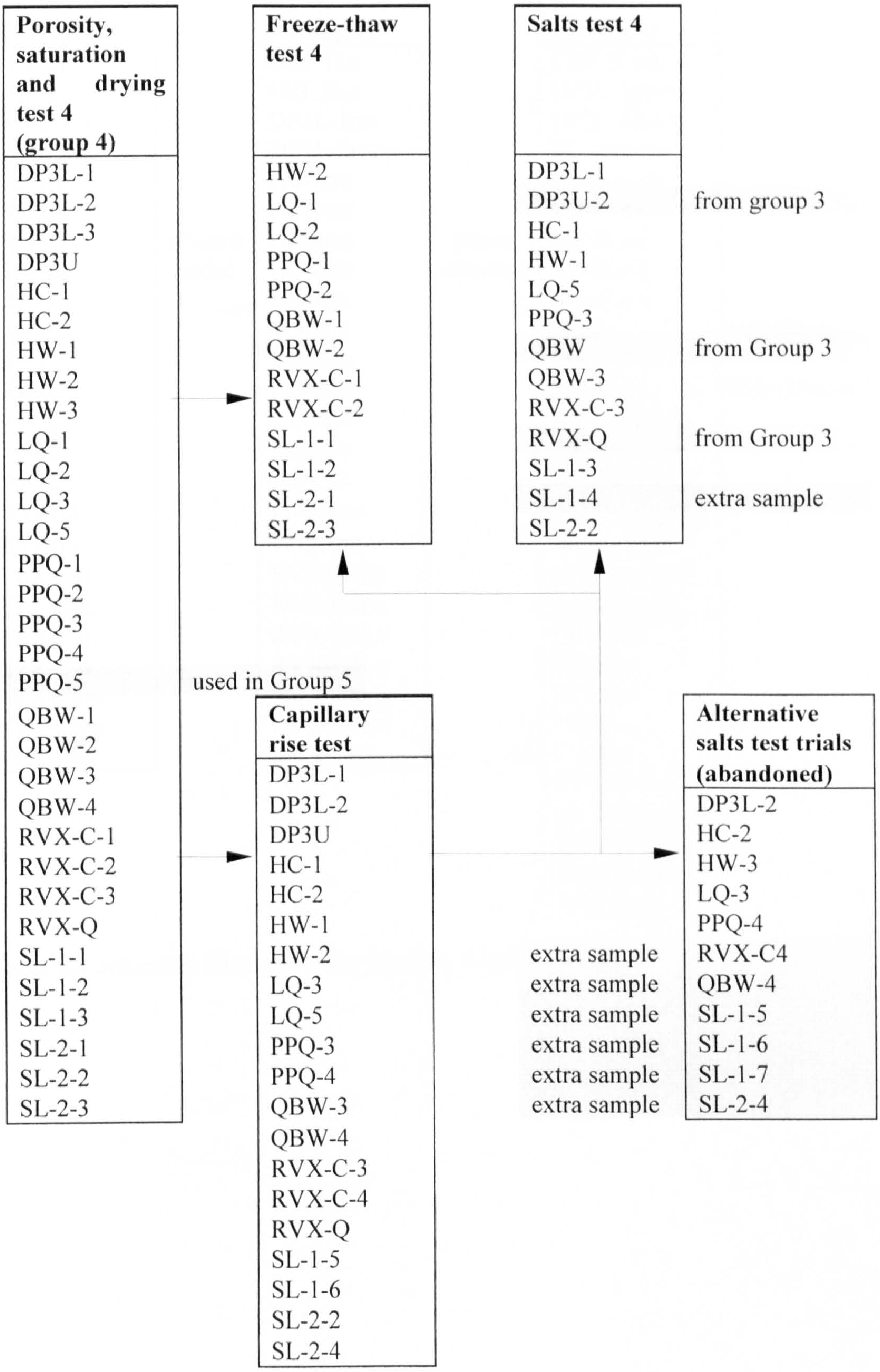
The data from this series of tests was tabulated and is included in 4 part 1 and the time series graphs which were plotted from the data appear in Appendix 4 part 2. The analysis of the data generated appears in Appendix 4 part 3 and is discussed in the next chapter.

On the following two pages are flow-charts, which show the relationship between the samples in each of the four sample groups and allows the identification of samples which have been used for more than one test and those which have been re-used to preserve homogeneity between pairs of groups. The sample references have the following meanings:

Sample reference	**Source**	**Stone type**
DP3L	Duncombe Park	Jurassic Sandstone
DP3U	Duncombe Park	Jurassic Sandstone
HC	Harewood Castle	Carboniferous Gritstone
HW	Rievaulx, Hollins Wood	Jurassic Oolitic Limestone
LQ	Rievaulx, Laskill Quarry	Jurassic Sandstone
PPQ	Rievaulx, Penny Piece Quarry	Jurassic Sandstone
QBW	Rievaulx, Quarry Bank Wood	Jurassic Sandstone
RVX-C	Rievaulx Abbey Church Quarry	Jurassic Sandstone
RVX-Q	Rievaulx Bank Quarry	Jurassic Oolitic Limestone
SL-1	Slingsby Castle	Jurassic Sandstone
SL-2	Slingsby Castle	Jurassic Oolitic Limestone

Table 4.2 Laboratory test samples: references, sources and stone types

KEYS TO TESTS AND SAMPLE GROUPS



Porosity, saturation and drying test 4 (group 4)	
DP3L-1	
DP3L-2	
DP3L-3	
DP3U	
HC-1	
HC-2	
HW-1	
HW-2	
HW-3	
LQ-1	
LQ-2	
LQ-3	
LQ-5	
PPQ-1	
PPQ-2	
PPQ-3	
PPQ-4	
PPQ-5	used in Group 5
QBW-1	
QBW-2	
QBW-3	
QBW-4	
RVX-C-1	
RVX-C-2	
RVX-C-3	
RVX-Q	
SL-1-1	
SL-1-2	
SL-1-3	
SL-2-1	
SL-2-2	
SL-2-3	

Freeze-thaw test 4
HW-2
LQ-1
LQ-2
PPQ-1
PPQ-2
QBW-1
QBW-2
RVX-C-1
RVX-C-2
SL-1-1
SL-1-2
SL-2-1
SL-2-3

Salts test 4	
DP3L-1	
DP3U-2	from group 3
HC-1	
HW-1	
LQ-5	
PPQ-3	
QBW	from Group 3
QBW-3	
RVX-C-3	
RVX-Q	from Group 3
SL-1-3	
SL-1-4	extra sample
SL-2-2	

Capillary rise test
DP3L-1
DP3L-2
DP3U
HC-1
HC-2
HW-1
HW-2
LQ-3
LQ-5
PPQ-3
PPQ-4
QBW-3
QBW-4
RVX-C-3
RVX-C-4
RVX-Q
SL-1-5
SL-1-6
SL-2-2
SL-2-4

	Alternative salts test trials (abandoned)
	DP3L-2
	HC-2
	HW-3
	LQ-3
	PPQ-4
extra sample	RVX-C4
extra sample	QBW-4
extra sample	SL-1-5
extra sample	SL-1-6
extra sample	SL-1-7
extra sample	SL-2-4

Table 4.3 Freeze/thaw, salts, capillary rise tests and Group 4 samples

Saturation and drying test 6 (Group 6)
CRF 1L
CRF 2L
DP3L-1m
DP3L-2m
HC-1m
HC-2m
HC-3m
HC-4m
LQ-1L
LQ-2L
LQ-3L
LQ-4L
LQ-5L
LQ-6L
LQ-7L
PPQ-1m
PPQ-2m
RVX-C1L
RVX-C2L
RVX-C3L
RVX-C4L
RVX-C5m
RVX-C6m
RVX-Qm

silicone added →

Saturation and drying test 7 (Group 7)
CRF 1Ls
CRF 2Ls
DP3L-1ms
DP3L-2ms
HC-1ms
HC-2ms
HC-3ms
HC-4ms
LQ-1Ls
LQ-2Ls
LQ-3Ls
LQ-4Ls
LQ-5Ls
LQ-6Ls
LQ-7Ls
PPQ-1ms
PPQ-2ms
RVX-C1Ls
RVX-C2Ls
RVX-C3Ls
RVX-C4Ls
RVX-C5ms
RVX-C6ms
RVX-Qms

plants removed →

Saturation and drying test 5 (Group 5)	
CRF 2Ls-L	
DP3L-1ms-m	
DP3L-2ms-m	
HC-1ms-m	
HC-2ms-m	
LQ-1Ls-L	
LQ-2Ls-L	
LQ-3Ls-L	
LQ-4Ls-L	
LQ-4s	spare sample
LQ-5Ls-L	
PPQ-5s	from Group 4
RVX-C2Ls-L	
RVX-C3Ls-L	
RVX-C5ms-m	

→

Alternative salts test (not carried out)
CRF-1Ls
HC-3ms
HC-4ms
LQ-6Ls
LQ-7Ls
RVX-C1Ls
RVX-C2Ls
RVX-C4Ls
RVX-C-6ms
RVX-Qms

Table 4.4 Saturation and drying test: Group 5, 6 and 7 samples

ALTERNATIVE SALTS TEST METHOD

Introduction

The European Standard test method for determining the resistance of stone to salt crystallisation, *BS EN 12370: 1999*, is a cyclical test (British Standards Institution 1999a). One part of the cycle involves drying the samples in an oven for up to thirty-one hours at a temperature of 105°C for sixteen of those thirty-one hours. The type of plant tissue under investigation in this research, principally lichens and mosses, is unlikely to survive many of the fifteen cycles required by this test. For that reason an alternative test procedure was required.

Aims and objectives

- The aim of this section is to develop a laboratory test method to simulate salt-induced weathering on samples of stone colonised by living plant material.

- The objectives are to apply the test to a trial batch of samples;
- to compare its performance with that of the standard test;
- to apply the new test to stone samples from the case-study sites.

Existing test method

British Standard *BS EN 12370: 1999* (British Standards Institution 1999a) relies on the evaporation of water from a solution of sodium sulphate in which sample cubes of stone had previously been soaked for two hours. After soaking, the samples are placed in an oven, and at high, although unspecified, relative humidity the oven temperature is raised to 105 degrees centigrade in not less than ten hours. The relative humidity is allowed to fall and the temperature is maintained at 105 degrees for a further sixteen hours. The samples are removed and allowed to cool to room temperature before being weighed. The cycle is then repeated.

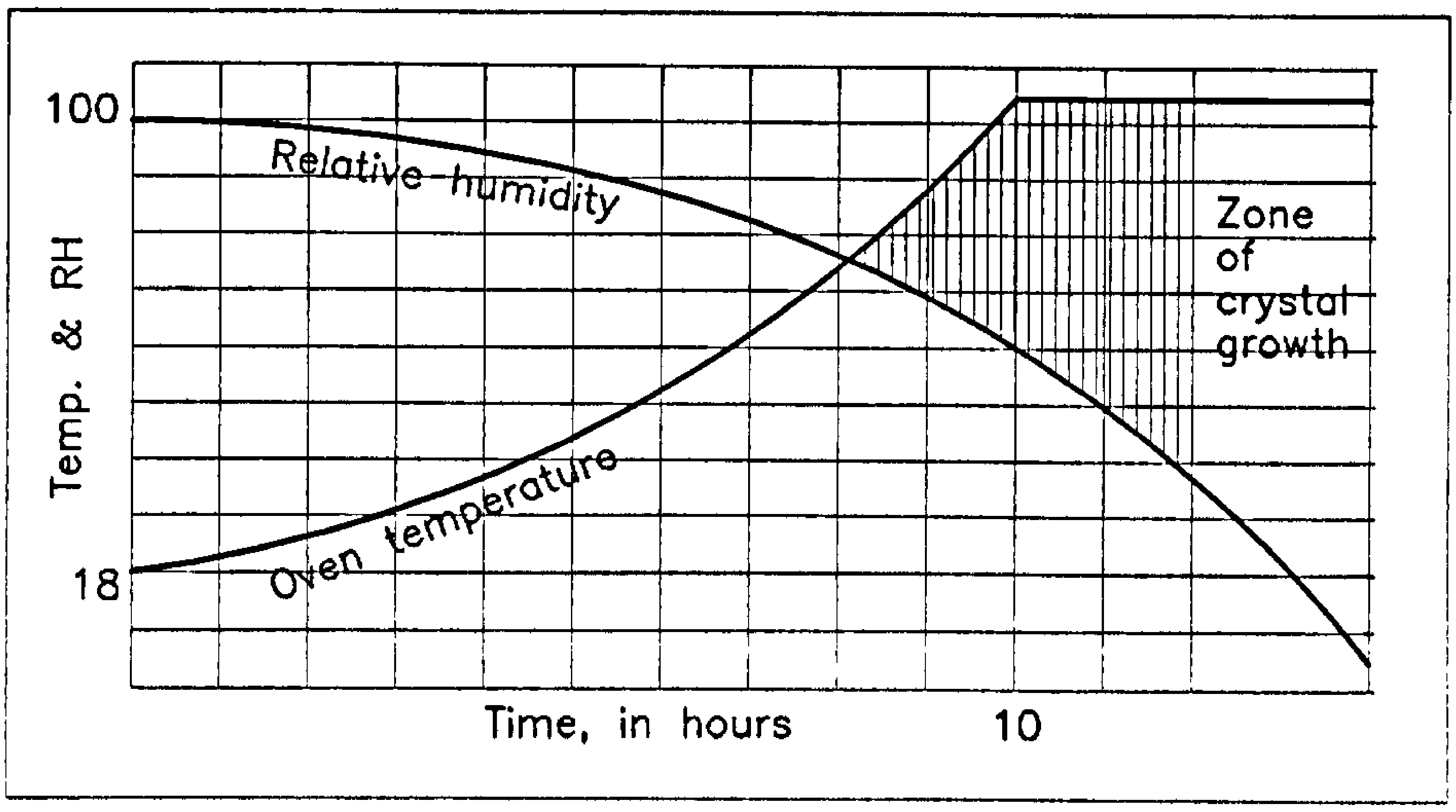


Figure 4.4 *BS EN 12370* salts test: key parameters

This method relies on the forced evaporation of water from the salt solution, until the solution becomes supersaturated and the relative humidity is less than the equilibrium relative humidity of the salt; crystals will then grow. The critical parameters of the test method are indicated in Figure 4.4.

Figure 4.5 shows the theoretical conditions which must be met for salt crystal growth, induced by evaporation of the salt solution. Salt crystal growth in this model is dependent upon the relative humidity of the air and the degree of saturation of the solution at a particular temperature; that is, assuming that the solubility of the salt is temperature-dependent, which many salts are (Goudie and Viles, 1997, p.109). No crystal growth occurs if the relative humidity of the air is

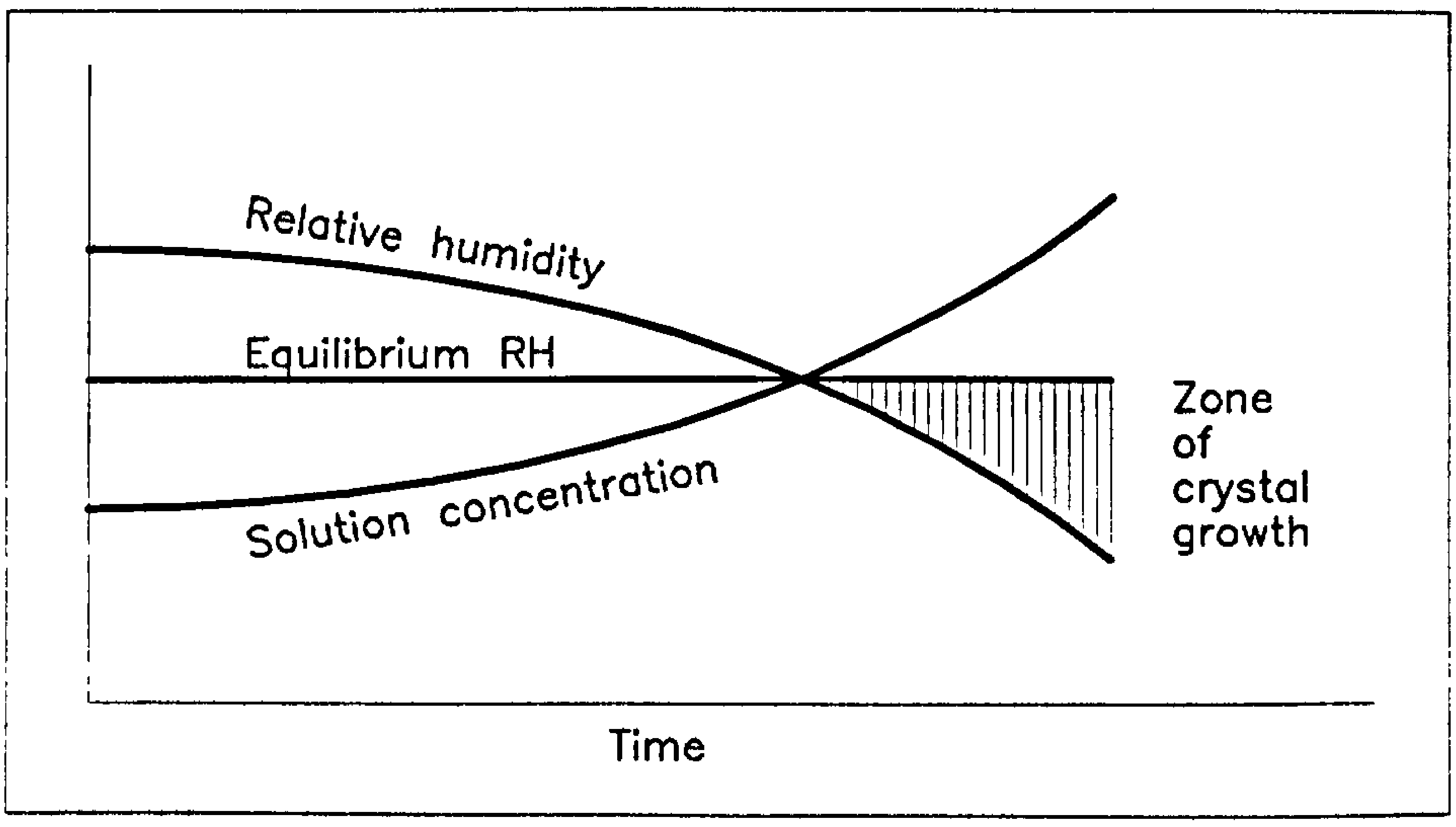


Figure 4.5 Theoretical parameters for salt crystal growth

above the equilibrium relative humidity of the salt solution. The zone on the graph in Figure 4.5, within which crystals will grow, is where the relative humidity has fallen below the equilibrium relative humidity of the salt and the solution has become supersaturated.

Supersaturation is essential for crystal growth, and the following theoretical graph, Figure 4.6 plots the relevant parameters of solution concentration and solution temperature.

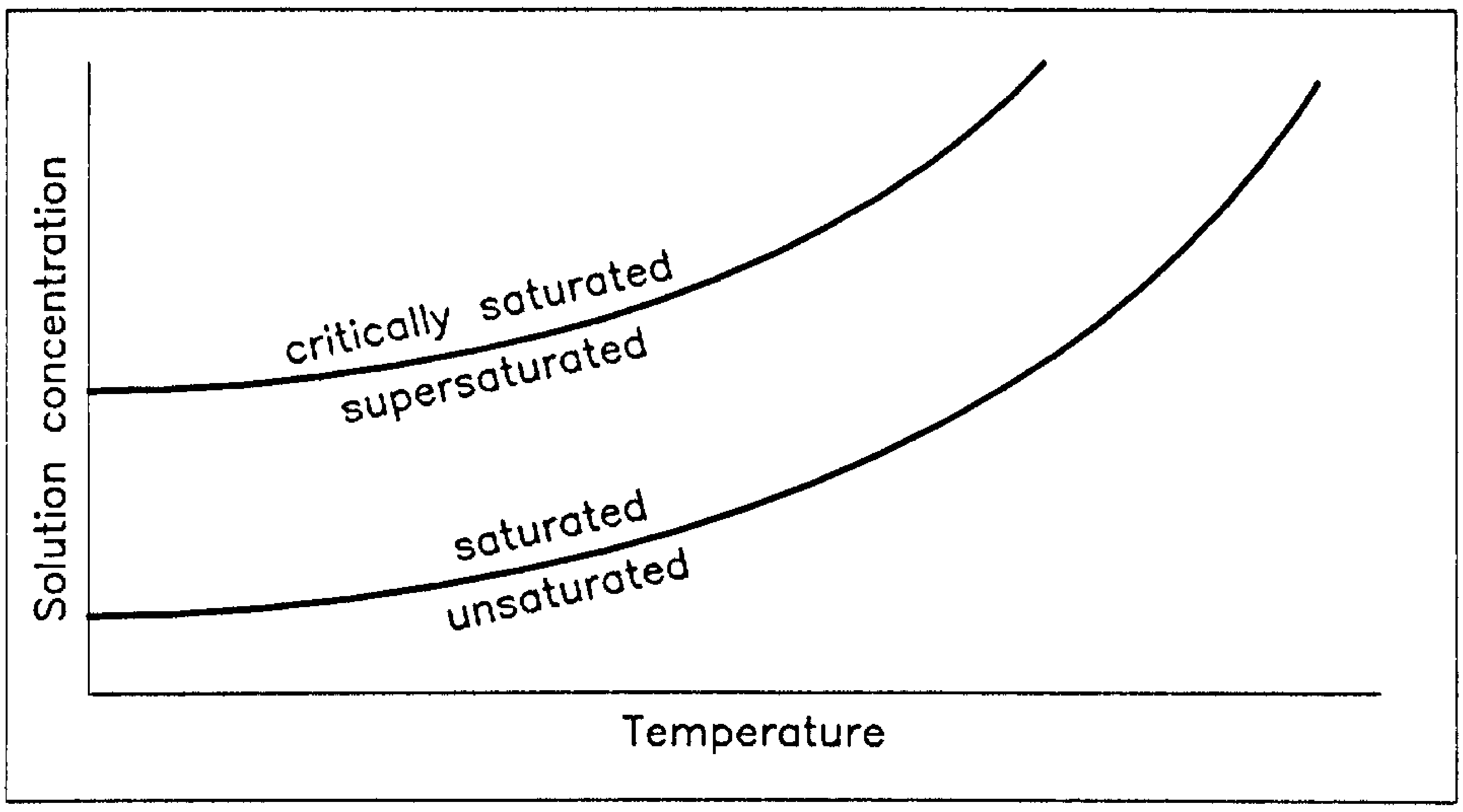


Figure 4.6 Solution concentration and temperature
Redrawn from Winkler (1994, p.164, fig. 2.2)

Some salt crystals have a temperature-dependent solubility, and crystal growth can occur either as a result of a temperature drop at constant concentration, or as a result of increased concentration due to evaporation at constant temperature. It can also occur due to a combination of both (Winkler 1994). This is in comparison to the mode of action of the European Standard test method. It is however, difficult to determine if resultant weathering to stone is caused by pressure exerted due to crystal growth, or by thermal expansion of the crystals (Winkler 1994, p.163). Alternatively, as has been observed during test in this research, damage can occur as a result of hydration pressures exerted as fresh solution is added to a dry sample replete with crystals. Under these conditions fine grains of material can be observed to 'stream' from the faces of the sample, into the solution. The mechanism acting here is due to the volume change as the crystals change from the anhydrous state to the hydrated state discussed in Chapter

Three. Goudie and Viles list hydration pressures for some common salts, all of which exceed the tensile strength of most stone types by at least a factor of ten (Goudie and Viles 1997, p.130-133). An alternative explanation for this observed phenomenon is that as the sample goes through the oven-drying part of the cycle, the growing crystals displace material, but hold it in place in a similar manner to the way a protective salt crust acts on the surface of stone. These dislodged fragments of stone are subsequently released, but only when the crystals are taken back into solution as fresh solution is added.

Alternative method

From the above discussion it can be seen that it is theoretically possible to induce crystal growth by causing the solution temperature to fall. This could form the basis of an alternative test method, but in order to understand how it might work and what the critical parameters are, it is necessary to investigate the properties of sodium sulphate in solution.

The solubility curve of sodium sulphate is at a peak at 32.2°C, as shown in Figure 4.7, below. It changes little above that temperature, but falls almost exponentially as the temperature falls towards 0°C. So long as a solution, saturated at a particular temperature, is kept at that temperature no crystal growth can occur, providing that no evaporation can take place. As the solution temperature falls the solution will become supersaturated and sodium sulphate will come out of solution. The solubility of sodium sulphate solution with respect to temperature is indicated in Figure 4.3, with the solubility of sodium chloride shown for comparison.

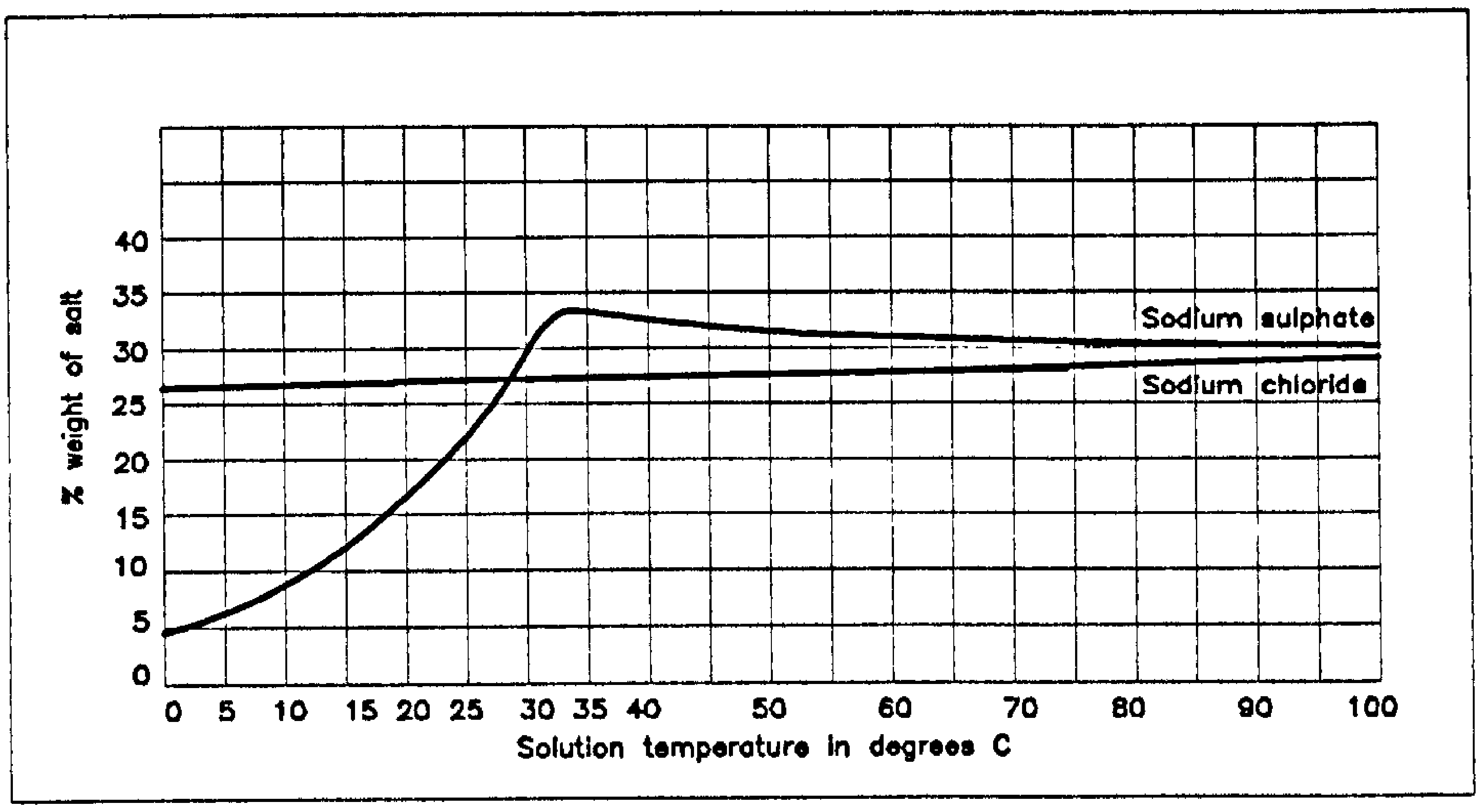


Figure 4.7 Solubility and solution temperature

Based upon Goudie and Viles (1997), p.109., fig. 4.4.

The following theoretical graph, Figure 4.8, shows the relationships between time, temperature and solution concentration which would permit crystal growth induced by reduction of the temperature of a saturated solution of sodium sulphate. If stone samples are soaked in saturated sodium sulphate at 32.2°C, and then left to cool to room temperature, of say 15°C, there will inevitably also be a loss of solution by evaporation. So the process which induces crystal growth will in this case be a combination of both evaporation and of cooling. It is assumed that the ambient relative humidity will always be below the equilibrium relative humidity of sodium sulphate, which is stated by Goudie and Viles, referring to Zehnder's work of 1993, as 97.9% at 20°C (Goudie and Viles 1997, p.154).

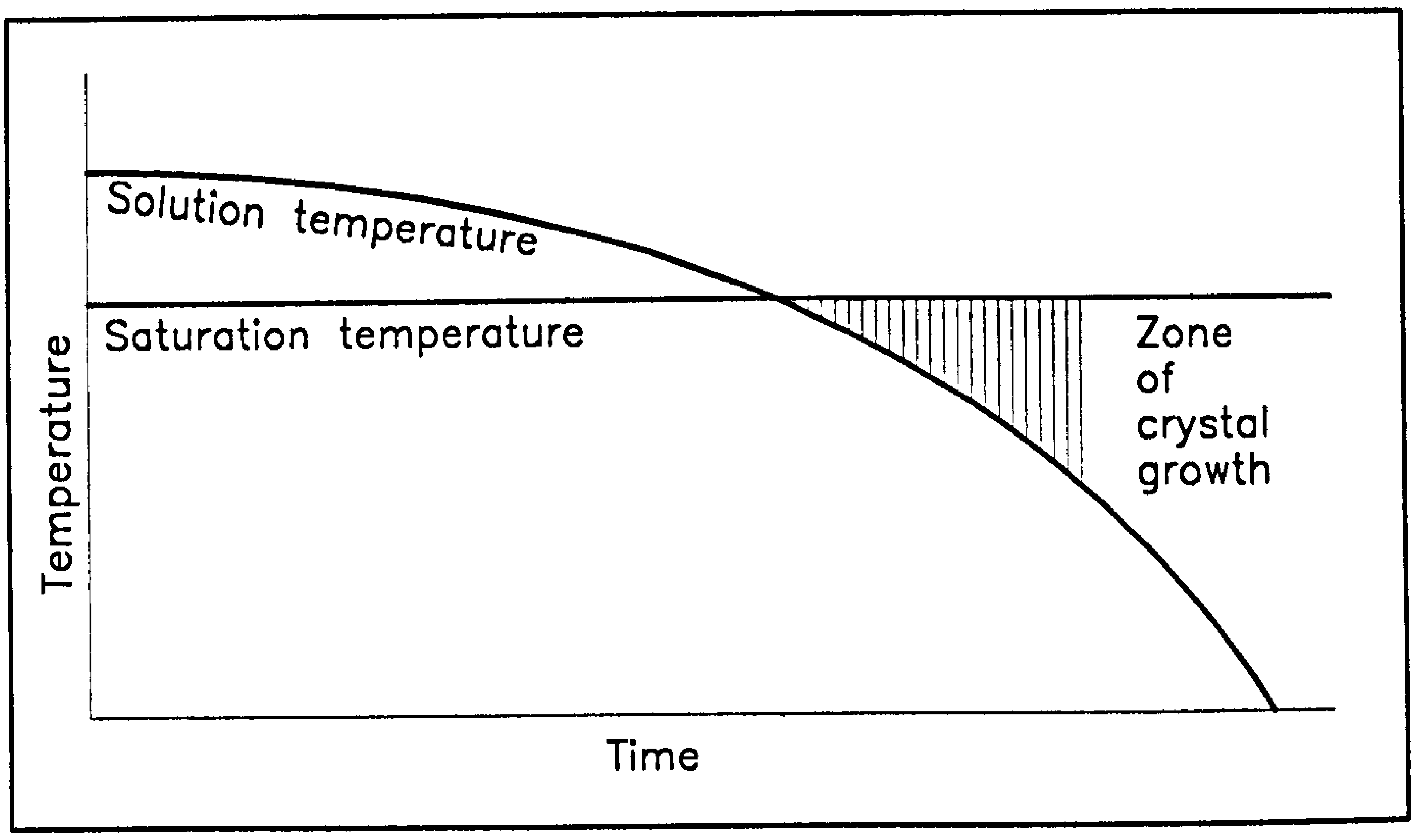


Figure 4.8 Sodium sulphate crystal growth induced by cooling

Cooling-induced salt crystallisation affects a much greater volume of salt per unit time than evaporation-induced crystallisation, which is a much more gradual process (Goudie and Viles 1997, p.107); thus, it might be expected that the former method would simulate weathering of stone in fewer cycles than the European Standard test method. It would be independent of relative humidity and would not subject the sample to the high temperature required in the oven-drying part of the cycle. This last factor would ensure that the plant growth on the samples was preserved – a factor essential in this investigation. But it is also worth bearing in mind that higher solution concentrations have the potential to produce more or larger crystals, but crystal growth induced by a temperature drop can be rapid and therefore produce smaller crystals. Winkler points out that larger crystals are produced by lower concentrations, and slower crystallisation rates (Winkler 1994, p.164) and so it can be concluded that that the rate of cooling of the solution in a temperature-induced crystallisation test is a critical factor in the ability of the test to simulate weathering.

Test procedure

A test procedure had to be devised for the new test, and the variables which were identified and needed consideration were:

- The solution strength to be used;
- the initial solution temperature;
- the soaking time for the samples;
- the temperature drop required to promote crystal growth;
- the cooling time for the samples;
- the number of cycles for which the test should be run.

In the following descriptions *Method A* refers to the test method, based on the European Standard, used in the preliminary salts tests referred to earlier in this chapter under the heading '*Tests to simulate weathering processes*'. The method being developed in this section will be referred to as *Method B*.

Solution strength

The solution strength and the starting temperature, as explained earlier, are interdependent with sodium sulphate because the solution needs to be saturated before it is allowed to cool to ensure crystal growth. An unsaturated solution could be used, but it would be necessary for the solution to become saturated at some temperature during its cooling. The graph in figure 4.3 indicates that a solution strength of about 33% is required to achieve maximum saturation.

Solution temperature

It was considered that the test would achieve maximum effect if the solution was saturated at 32°C. This is the temperature at which sodium sulphate has its maximum solubility and would allow the greatest possible temperature drop of the solution.

Soaking time

In order for the performance of the test to be compared with *Method A*, it was decided that the soaking times should be twenty-four hours, the same as had been used previously.

Temperature drop

If the starting temperature of the solution was 32°C, a temperature drop of approximately sixteen degrees would be achieved if the samples were allowed to cool to the ambient laboratory temperature of 16°C; however, there was no control available for that lower temperature.

Cooling time

In order for the performance of the test to be compared with test *Method A*, it was decided that the cooling time should be twenty-four hours, the same as the drying time used in *Method A*.

Number of cycles

If this test is to be compared directly with *Method A*, then the two tests should be run for the same number of cycles and the final weight losses resulting from each test procedure compared. Previous tests using *Method A* were run for both forty and twenty cycles. The latter gave good results which can be achieved for a trial in less time.

Results and observations

The precise method which was developed from those key variables is included in Appendix 1. Also in Appendix 1 are the results of the first trial of the test, details of how the method was subsequently modified and details of subsequent trials. There are, however several critical factors which emerged from those trials, which affected the reliability of the test method, and are worth repeating here.

Mode of action

In the first trial of the test, sample cubes were allowed to cool to room temperature in free air. So the weathering induced by the test would be due in part to crystal growth induced by cooling and in part to crystal growth due to evaporation. It became apparent that the latter mechanism was the dominant, and the evidence was in the form of efflorescence which formed on the surface of the test cube after each cycle. This surface efflorescence accumulated during the course of the test. Although it was brushed off before the cubes were weighed, it eventually formed a crust over the surfaces of the test cube, inhibiting the mode of action of the test. It was also noted that only minimal weathering had resulted after eleven cycles.

Two courses of action were taken. The first was to ensure that in the second trial no evaporation could take place. This was achieved by keeping the samples in covered beakers during the soaking and the cooling part of the test. The beakers also remained in a water bath, used to control the solution temperature, for the duration of the test. The second course of action was to verify, by experiment, that the solution strength used was a saturated solution at the specified temperature.

Solution strength

The method adopted to verify the solution strength is described in Appendix 1. The strength which had been used in the first trial was 33%, at 32°C, taken from Figure 4.7, but a review of relevant literature revealed disagreements between writers and a new starting point was established as 36.8% at 20°C. This indicates a solubility considerably higher than stated by Goudie and Viles (Goudie and Viles 1997, p.109). After several experiments, the solubility of sodium sulphate decahydrate was established as 59.8% at 20°C which was the strength of solution used in subsequent trials.

Cooling time

Once the solution strength had been verified, the test produced results, but the destructive power of the test was far in excess of that anticipated; test cubes completely disintegrated after only six cycles as a result of the growth of crystals up to 5mm long. It was clear that the cooling time was of critical importance. The time taken for the water bath to cool from the saturation temperature of the solution to room temperature was the critical factor and so the only way to reduce the cooling time was to adopt a lower temperature difference.

Temperature difference

There are two aspects regarding temperature difference which emerged from the trials of the modified test procedure. The first aspect arose from the decision that the beakers containing test cubes immersed in solution should remain in the water bath for the duration of the test. The growth of crystals and their return to solution was achieved by cyclical alterations to the water-bath temperature. In order to ensure that crystals were taken back into solution at the end of each cycle, the solution temperature needed to be raised at least five degrees above the saturation temperature. The result was that the maximum temperature drop which could be achieved during the cooling phase of each cycle was reduced by five degrees. The consequence for the test procedure was that as time passed and the daily air temperature in the laboratory rose, a point was reached where crystal growth could no longer be achieved because the temperature drop was insufficient. The test procedure became more and more unreliable and further development was eventually abandoned.

Summary

The alternative salts test was to have provided a means of investigating by experiment the action of soluble salts on stone test cubes with lichen colonisation.

The development of a test method, which induced crystal growth by allowing the solution containing the sample to cool, proved to be fraught with problems.. The reliability of the test method depended upon the predictability with which crystals of a given size would grow from a solution of given concentration for a given drop in temperature, in a given time. Efforts to establish that reliability proved to be time consuming, and the results often unpredictable. The critical factor was the lack of a effective means of controlling the rate of temperature drop of the solution during the cooling phase of each cycle and the lack of control of that critical phase of the test eventually prompted further development to be abandoned.

In the next chapter, the results of the test which *were* successful will be presented, the results analysed and the results of the analyses discussed.

CHAPTER FIVE

LABORATORY TEST RESULTS AND ANALYSES

INTRODUCTION

The last Chapter described the methods adopted to investigate how plants might influence the weathering of stone. In this chapter, the results are presented and analysed, and the results of the analyses are discussed. This Chapter is organised into three discrete sections. The first section deals with the results and analyses of the tests to determine the physical properties of the stone types from the case-study sites. The second section considers the results of the simulated weathering test and the third considers the results of the saturation and drying tests.

PART 1: TESTS TO DETERMINE STONE PROPERTIES

The two properties under consideration are: open porosity and pore size distribution. Data generated by these two tests are to be found in Appendix 2, along with the graphs which were plotted form those data.

TEST TO DETERMINE OPEN POROSITY

Introduction

This section considers two aspects of open porosity:

- The mean open porosities of the stone types;
- the variability of open porosity of each stone type.

The porosities of the samples were calculated using the data generated by Saturation and Drying Test 4. The calculation of open porosity was carried out using the formula given in Borrelli (Borrelli 1999a, p.11). The steps of the calculation, and the calculated open porosities, are included in Appendix 4 part 1.

Results

Figure 5.1 shows the open porosities of the thirty samples tested. The sample references have the meaning shown Table 5.1, below.

Sample reference	Source	Stone type
DP3L	Duncombe Park	Jurassic Sandstone
DP3U	Duncombe Park	Jurassic Sandstone
HC	Harewood Castle	Carboniferous Gritstone
HW	Rievaulx, Hollins Wood	Jurassic Oolitic Limestone
LQ	Rievaulx, Laskill Quarry	Jurassic Sandstone
PPQ	Rievaulx, Penny Piece Quarry	Jurassic Sandstone
QBW	Rievaulx, Quarry Bank Wood	Jurassic Sandstone
RVX-C	Rievaulx Abbey Church Quarry	Jurassic Sandstone
RVX-Q	Rievaulx Bank Quarry	Jurassic Oolitic Limestone
SL-1	Slingsby Castle	Jurassic Sandstone
SL-2	Slingsby Castle	Jurassic Oolitic Limestone

Table 5.1 Laboratory test samples: references, sources and stone types

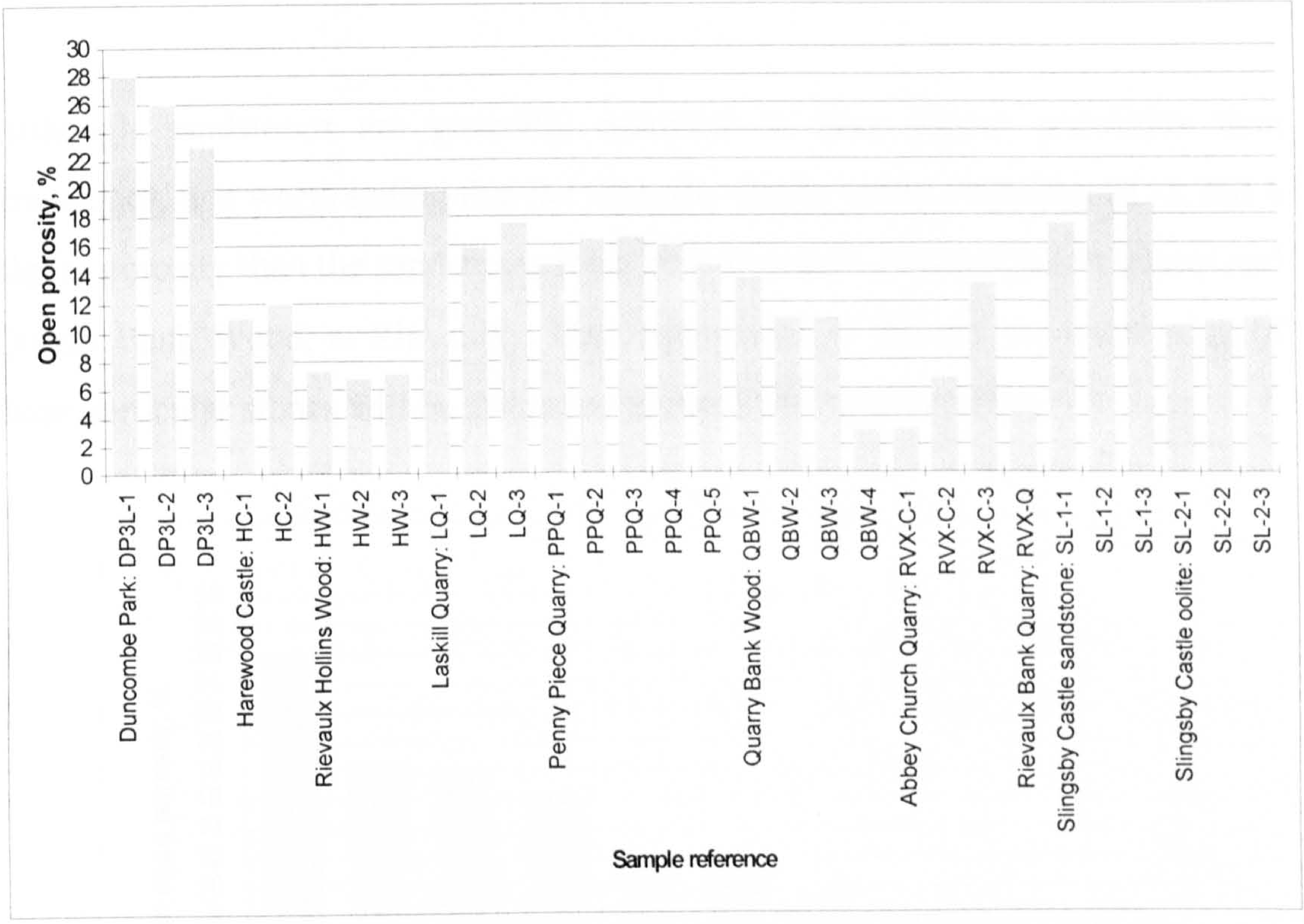


Figure 5.1 Open porosities, %

Discussion

Two important properties can be deduced from the bar chart shown in Figure 5.1. These are the spread of porosities across the range of samples, and the homogeneity within samples of the same stone type.

If the mean values of the open porosities are calculated for each stone type, and the values arranged in numerical order, a clearer indication of the relative porosities can be achieved, and this is shown in Figure 5.2. For example, the Duncombe Park sandstone, reference DP, has the highest porosity, while the oolitic limestone from Rievaulx Bank Quarry, reference RVX-Q, has the lowest.

Although sandstones are generally assumed to have higher porosities than limestones, it is worth noting that the Slingsby Castle oolite, reference SL-2, has a higher porosity than the sandstones from both Rievaulx Abbey Church quarry and Quarry Bank Wood, at Rievaulx. The implications of this for the weathering of these particular stones will be discussed in Part Two of this chapter.

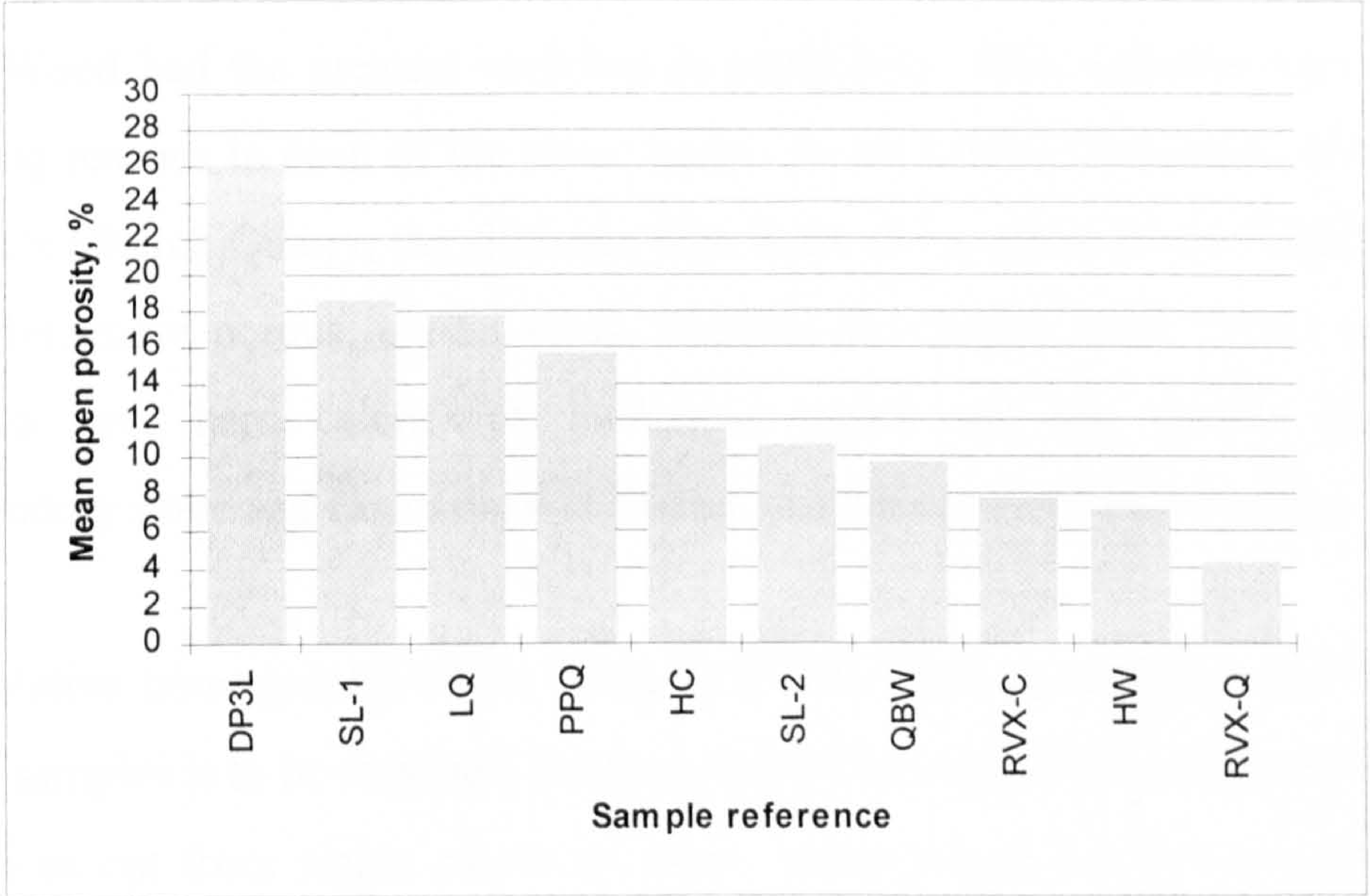


Figure 5.2 Mean open porosities, %

Figure 5.1, whilst plotting the mean values of the porosities of the ten stone types tested, does not reveal the homogeneity between samples of the same stone type. This can be achieved by calculating the percentage difference between the maximum and the minimum values for each. Figure 5.3 shows the results, arranged in increasing order of homogeneity. The *y*-axis values were calculated with reference to the highest porosity recorded for each stone type.

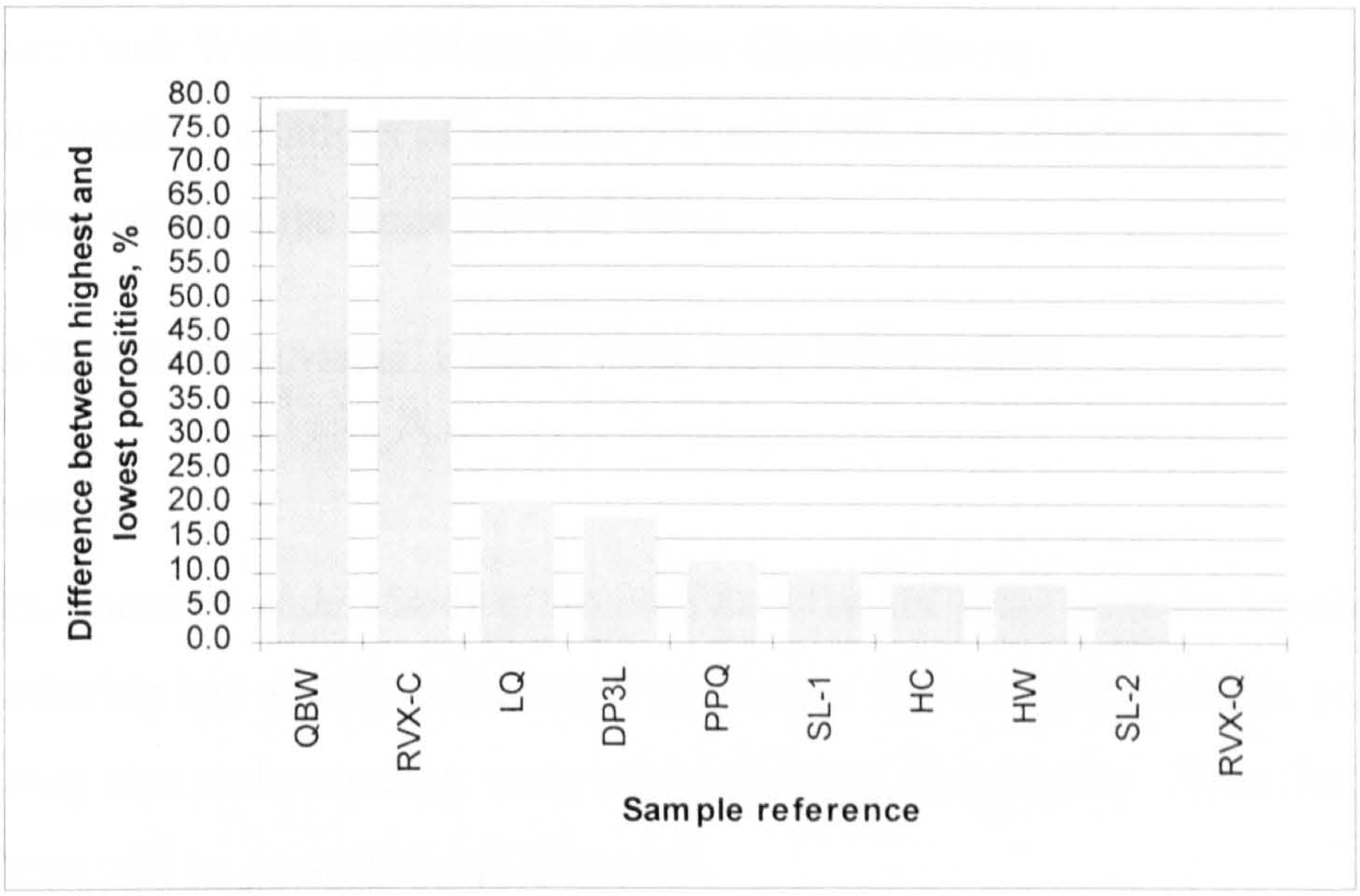


Figure 5.3 Open porosities: range

It is clear that the samples from both Rievaulx Church Quarry and from Quarry Bank Wood had the greatest variation in porosities. This variation was due to differing reasons in each of the stone types. In the Lower Calcareous Grit from Rievaulx Church Quarry, the siliceous blue heart of the stone is often surrounded by softer, more porous, oolitic areas, whereas the Quarry Bank Wood samples tend to have hard calcite-rich inclusions which are less porous than the surrounding stone and can cause differential weathering in both stone types.

The relative homogeneity of the Slingsby Castle, Harewood Castle and Hollins Wood samples is to be expected, because each of the samples for each of the stone types was cut from single pieces of stone; nevertheless, this demonstrates that even with a single stone the porosity can vary by as much as 10%. This too has implications for the weathering of these stones.

Summary

- The mean open porosities of the samples ranged from almost nil for the Rievaulx Bank oolite, to 26%, for the Duncombe Park sandstone;
- the greatest variation in open porosity was found in the samples from Rievaulx Quarry Bank Wood, and Rievaulx Abbey Church Quarry;
- open porosity variations of between 5% and 15% were observed, even between samples cut from the same piece of stone.

TESTS TO DETERMINE PORE SIZE DISTRIBUTION

Introduction

The importance of understanding the pore structure of stone, and the implications for weathering has already been stated in Chapter Three. The methods available for gaining that understanding were explored in the last chapter. Now the results of the tests will be presented and discussed.

Capillary rise test

The mean capillary rise time of each sample tested was calculated from the data generated by that test and which appears in Appendix 2. The graphs which were plotted from the data also appear in Appendix 2. It should be noted that the test was only carried out over a twenty-four hour period. This was because in the denser samples, those with fewer pores, or samples with large pores, where the capillary rise time was longer than twenty-four hours, surface evaporation from the samples made it virtually impossible to determine the precise height of water rise. For these samples the capillary rise-time has been interpolated from the results, with the aid of the graphs. The time taken for water to reach the top of the samples is related to the mean radius of the pores and so a comparison of those times gives an indication of the relative mean pore radii of the samples tested.

Results

The results generated have been split into two groups: samples in which water reached the top of the cube within twenty-four hours and those in which water took longer than twenty-four hours. The results are shown in the two bar charts, Figures 5.4 and 5.5, which follow.

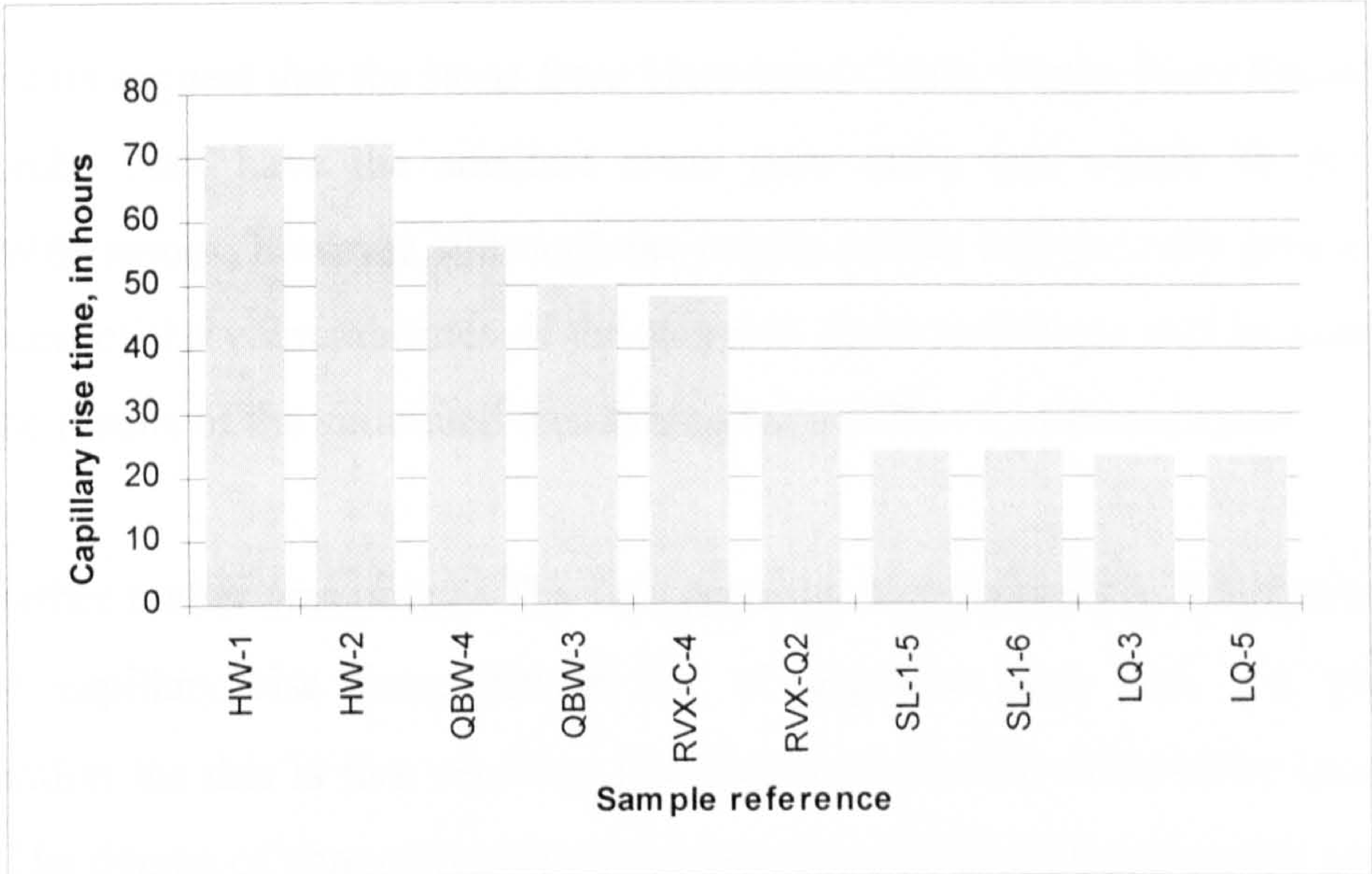


Figure 5.4 Samples with capillary rise time over twenty-four hours

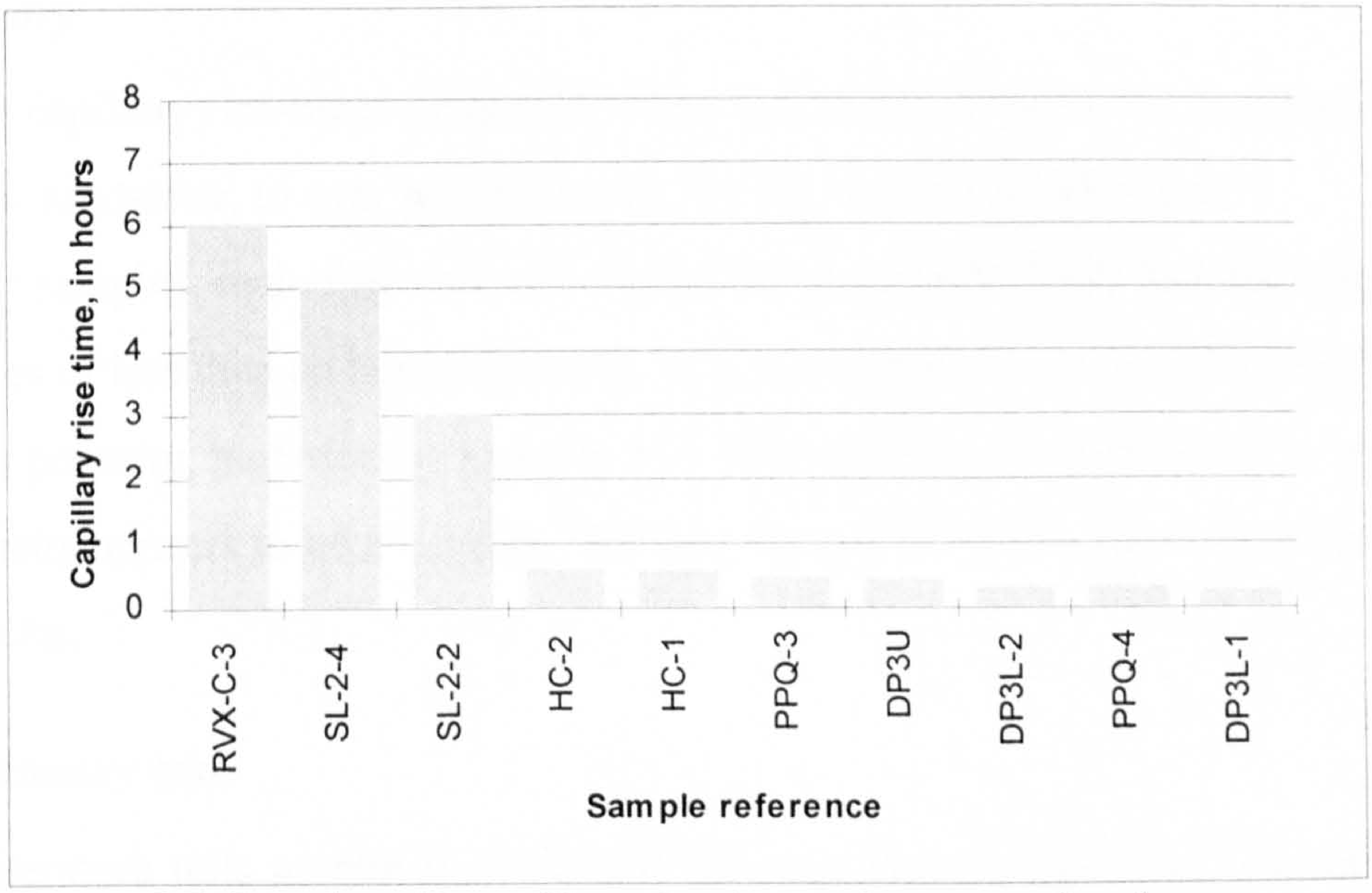


Figure 5.5 Samples with capillary rise time under twenty-four hours.

Discussion

It would be expected that the samples in Figure 5.4 would have the largest mean pore radius and would therefore be less vulnerable to the effects of frost and soluble salts. Similarly, it would be expected that the samples in Figure 5.5 would be more vulnerable to the effects of frost and soluble salts.

The results suggest that the stone from Harewood Castle, Penny Piece Quarry, and Duncombe Park have the smallest mean pore radii, and would be the most vulnerable stones; however, although the results of this test can only give a broad indication of the vulnerabilities of the samples, these indicators will be correlated with the results of the simulated weathering tests in Part 2 of this chapter.

One further matter was noted. The low porosity, highest density samples had the longest capillary rise time, irrespective of apparent pore size. A possible explanation for this is that capillary rise time is not solely dependent upon pore size. The degree of connectivity between pores is clearly a critical factor and so it seems likely that there will be an optimum porosity range within which this test can accurately indicate mean pore size.

Summary

- The capillary rise-times ranged from less than thirty minutes, for the Duncombe Park sandstone, to over seventy hours, for the Hollins Wood oolite;
- four samples, including two stone types for Duncombe Park, had capillary rise times of less than on hour, indicative of a large proportion of small pores;
- low porosity, high density samples had long capillary rise times and so sample density appears to be a limiting factor in the ability of this test to provide valid results.

Porosimetry test

The literature tells us that it is not just the mean pore radius, but the pore size distribution which is important in determining resistance to these weathering agents (Everett 1961; Bell 1992), and so it is the results of the porosimetry test which would be expected to provide the most reliable indicators of the likely weathering performance of the stones.

Five samples from the case study sites were tested. From the data produced, frequency distributions of pore width were generated. From the frequency distributions, four key parameters indicative of vulnerability to weathering by frost and salts were calculated. The data are included in Appendix 2, along with the frequency distribution histograms which were plotted from the data.

Results

The results of the tests are summarised in Table 5.2, below. The sample references have the same meanings as are given in Table 5.0, at the beginning of this chapter.

	Sample references				
Parameter	**DP3L**	**HC**	**PPQ**	**SL-1**	**SL-2**
% of pore volume over 5 microns	68	56	71	19	5
% of pore volume under 5 microns	32	44	29	81	95
Mean pore width, microns	25.5	29.1	38.8	6.6	5.3
Mode pore width, microns	54.5	54.5	54.5	3	0.3

Table 5.2 Summary of porosimetry results

Discussion

The work of Bell (1992), and Everett (1961) was discussed in Chapter Three. From their work, critical parameters for predicting resistance to freeze/thaw cycles and to some extent to the action of soluble salts, can be deduced. They are:

- The proportion of pores greater than 5 microns wide, because stone with a high proportion of pores above this width is considered to have resistance to freeze/thaw cycles;
- the proportion of pores less than 5 microns wide, because stone with a high proportion of pores below this width is considered to be vulnerable to freeze/thaw cycles.

In addition, the proportion of pores above and below 5 microns gives an indication of the space available in which crystals can grow and the reservoir capacity for water to feed the growing crystals, respectively. Also the calculation of the mean pore width allows the results of this test to be compared with the results of the capillary rise test, but the use of the mode value is likely to provide a better correlation because the capillary rise time will depend not so much on the average, but on the pore width with the highest frequency.

There is one further consideration – that is the total porosity of the stone types. A stone with high porosity, and a pore structure less than 5 microns wide, will be more vulnerable than one with the same pore structure but with a lower porosity, because there are proportionately more pores in which crystal growth can take place.

The results for the five porosimetry tests were compared with the capillary rise-time results for the corresponding five samples. The Spearman's rho correlation coefficient was calculated and gave a figure of –0.566 with a significance of 0.322. A significance of less than 0.05 indicates a significant correlation. In this case, the correlation was shown to be non-significant and it can be concluded that the relationships between the two sets of results are chance relationships.

It is not easy to provide an explanation as to why the two sets of results do not agree. One explanation could be due to the limitations of the porosimetry test, since it is known to be unreliable when used on very fragile materials (Borrelli 1999a, p.8). The stone from Duncombe Park, for example, is a particularly fragile stone, and the lack of correlation between the two sets of results could be explained by enlargement of the pore structure of the sample during the course of the porosimeter test, providing spurious results; the maximum pressure applied during these tests was over 200,000kPa (about 300,000psi). This may also be true of other samples which were tested. So it can be concluded that for some of the samples tested porosimetry may not provide valid results. The capillary rise-time test, although much simpler, may have produced more reliable results with the sample set under consideration in this research, although it too has its limitations. In part three of this chapter, the results of these two tests will be compared to the results of the simulated weathering tests and this may indicate which test is the more accurate predictor of weathering performance.

Summary

- Mean pore widths for the samples ranged from 38.8 microns, for the Penny Piece Quarry sample, to 5.3 microns, for the Slingsby Castle sandstone;
- Both of the Slingsby Castle stones might be expected to be vulnerable to weathering by salts and frost, because their mean pore width is in the region of the critical 5 microns;
- The validity of the results produced by this test can be in doubt if samples are fragile.

PART 1 SUMMARY

- The mean open porosities of the samples ranged from almost nil to 26%;
- a variability of over 75% was found between samples of the same stone type, and a variability of 5% to 15% between samples cut from the same piece of stone;
- the capillary rise-times ranged from less than thirty minutes, to over seventy hours;
- four samples had capillary rise times of less than one hour, indicative of a large proportion of small pores;
- mean pore widths for the samples ranged from 38.8 microns to 5.3 microns;
- some of the samples might be expected to be vulnerable to weathering by salts and frost, because their mean pore width is in the region of the critical 5 microns;
- The validity of the capillary rise time results is in doubt for the low porosity, high density samples; similarly, the validity of the porosimetry results is in doubt for the high porosity, fragile samples.

The value of the results discussed above, in predicting the performance of stone under simulated weathering tests, will be assessed in the second part of this chapter.

PART 2: SIMULATED WEATHERING TESTS

INTRODUCTION

The last chapter described the laboratory tests methods used on samples from the case study sites. The data produced by these tests were tabulated, and are included in Appendix 3, along with graphs plotted from the data and details of the statistical analyses. In this section, the results are presented and the results of the analyses discussed. The implications of the results of the analyses will be considered in detail in the next chapter.

Some tests, such as the diagnostic tests, were specific to a particular case study site – the results and their implications will be included in the discussion section of those particular case studies. The three tests which are under consideration here are:

- The resistance to freeze/thaw cycles;
- the resistance to the action of soluble salts;
- the resistance to acid rain.

TEST TO DETERMINE THE RESISTANCE TO FREEZE/THAW CYCLES

Introduction

Two samples of each stone type from the case study sites were tested, but with the following exceptions: one sample from Duncombe Park; one sample from Rievaulx Hollins Wood; one sample from Rievaulx Bank Quarry; and no samples from Harewood Castle because the foot-and-mouth outbreak prohibited access to the site to collect further samples. The test ran for a maximum of 100 cycles.

Results

Figure 5.6 shows the results arranged in ascending order of resistance to the freeze/thaw test; the samples which had the highest weight loss are on the left of the bar chart. The adjusted percentage weight loss takes account of the number of

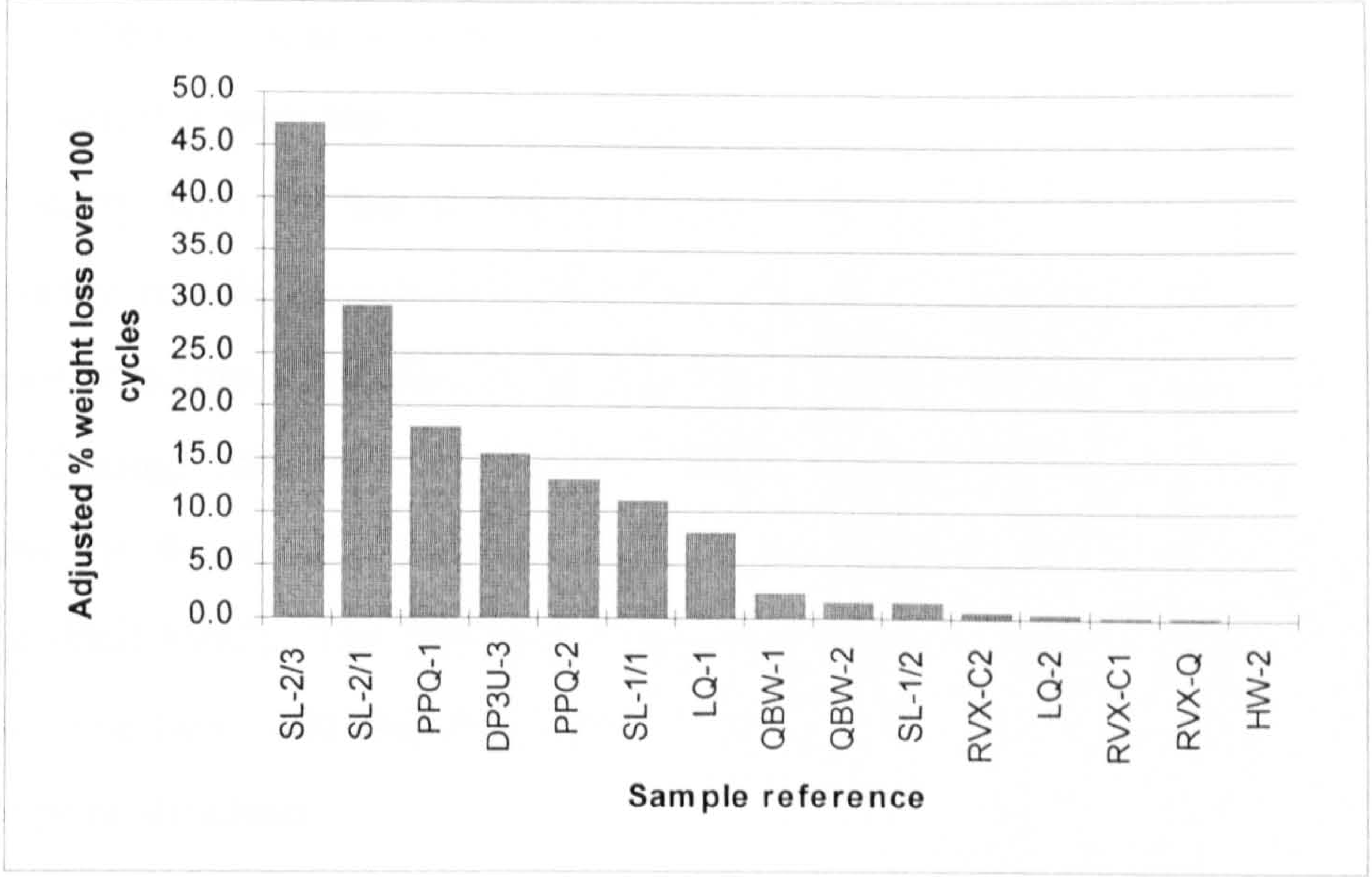


Figure 5.6 Sample performance subjected to the freeze/thaw test

cycles completed by each sample and provides a uniform basis for comparisons between samples. Mention was made in the last chapter of the fact that certain criteria had to be met if a sample was to be withdrawn from the test before the 100 cycles had been completed: either the sample had lost five percent of its original weight, or it had become so friable that it could no longer be handled without disintegrating. The adjusted percentage weight loss does, however, make an assumption about the performance of the samples. It assumes that the rate of material loss up to the time of its withdrawal from the test would continue over subsequent cycles had it not been withdrawn. It is possible that a sample would have completely disintegrated before it had completed 100 cycles and so it must be accepted that this way of considering the data makes certain assumptions.

A final step in the analysis is to relate the results to the physical properties of the stone types and to determine whether the results accord with the literature on stone properties and susceptibility to weathering by frost action.

Analysis

It is clear, but perhaps surprising, that the two samples of oolitic limestone from Slingsby Castle lost most material during this test. If resistance to frost is a function of the pore size distribution, as Everett suggests (Everett 1961), and if capillary rise time is an indication of mean pore radius, then it might be expected that the samples with the shortest capillary rise time, Duncombe Park and Penny Piece Quarry, have the highest susceptibility to material loss during this test. The porosimetry results, however, showed that the Slingsby Castle oolite has a very fine pore structure. Ninety-five percent of the pores are less than five microns wide. Although this stone had a relatively low porosity, only 10.5%, the pore size is below the figure of 5 microns, which Bell claims increases the risk of frost damage (Bell 1992). The Slingsby Castle sandstone, by comparison, had a longer capillary rise time, and showed greater resistance under this test, because it has a coarser pore structure.

Perhaps one of the most surprising outcomes of this test is the performance of the Hollins Wood sample. This is an oolite, very similar to the Slingsby Castle oolite, but it survived the one hundred cycles of this test intact; furthermore, this is a sample of a stone type not known to have been used in the building of Rievaulx Abbey, despite the ease with which it can be cut. But the extent of the beds from which the sample came is largely unknown. It may be that this stone type does not occur as a freestone and, as Salzman describes, forms part of the overburden layer removed by medieval masons, to reach the freestone beds beneath (Salzman 1997, p.124).

The mode of loss of material and the condition of the largest remaining piece of the sample are as important as the amount of material lost. A brief description of the samples at the end of the test is given in Table 5.3 which follows.

Ref.	Mode of weathering	Condition after test
DP3U-3	Fragmentation; granular disintegration; splitting	Sample in two large pieces, and many smaller fragments; fissures along boundaries of harder inclusions;
HW-2	None detected	Intact
LQ-1	Fragmentation; splitting	Sample in one large piece and many smaller fragments; fissures along boundaries of harder material
LQ-2	Fragmentation	Largely intact; one corner lost through fragmentation, and three fissures
PPQ-1	Granular disintegration	Corners and arises well-rounded, but otherwise intact
PPQ-2	Granular disintegration	Corners and arises well-rounded, but otherwise intact
QBW-1	Fragmentation; fissuring	Largely intact; material loss at one corner; three minor fissures
QBW-2	Fragmentation; fissuring	Largely intact; material loss at one corner; three minor fissures
RVX-C1	None detected	One minor fissure, otherwise intact
RVX-C2	Fragmentation	Three corners lost to fragmentation, otherwise intact
RVX-Q	Erosion; fragmentation	Minor fissures, and surface erosion, otherwise intact
SL-1/1	Spalling; granular disintegration	One corner and four edges lost; partially detached surface skin evident on three faces; minor fissure
SL-1/2	Spalling; granular disintegration	One edge lost to spalling; surface skin evident
SL-2/1	Granular disintegration by loss of ooliths	Corners and arises well-rounded, fissures along bedding planes
SL-2/3	Granular disintegration by loss of ooliths	Corners and arises well-rounded, fissures along bedding planes

Table 5.3 Freeze/thaw test: mode of weathering and sample condition at end of test

The descriptions used in the Table 5.3 are based broadly on descriptions of weathering forms developed by Fitzner (Fitzner *et al*, 1992), and have the following meanings:

erosion, where material is only lost from the surface of the stone;

fissuring, where material is lost along lines of weakness such as bedding planes, faults, or boundaries of differing densities of material;

flaking, where material is lost from the surface in small sheets, or flakes;

fragmentation, where the sample breaks into several discrete pieces;

granulation, where grains of material are lost from the sample;

spitting, where the sample breaks along bedding planes, or planes of weakness, into two or more pieces.

Correlation between physical properties and freeze/thaw resistance

The performance of the samples under this test was then related to the relevant physical properties of the stone types. This was done by plotting scattergraphs which showed the relationship between the dependent and independent variables. Correlation coefficients were then calculated for the pairs of results. The significance of the correlation coefficient was then tested by calculating the t value. The coefficient of determination (r^2) which gives an indication of the degree to which the dependent variables influence the independent variables was also calculated. These statistical calculations, along with the scattergraphs, are included in Appendix 3.

A conventional level of significance of 0.05 was assumed, with a degrees of freedom value of 13 (N–2). Table 5.4 illustrates the results and the significant values are indicated in bold type.

Criteria	**Correlation coefficient r**	**calculated t**	**critical t**	**Coefficient of determination r^2**
% weight loss and open porosity	+0.434	0.720	+2.160	0.118
% weight loss and capillary rise time	–0.684	**–3.090**	–2.160	0.468
% weight loss over 100 cycles, and capillary rise time	–0.563	**–2.459**	–2.160	0.317

Table 5. 4 Freeze/thaw test: correlations between variables

For a correlation coefficient to be statistically significant it must be greater than the critical +value, or less than the critical –value. For the correlation between percentage weight loss and percentage open porosity, it can be seen from the table that the calculated value of t is not greater than the critical value of +2.160; therefore, the correlation is not statistically significant and could have occurred by chance.

For the correlations between percentage weight loss and capillary rise time and between adjusted percentage weight loss per 100 cycles and capillary rise time, it can be seen from the table that the calculated *t* values are less than the critical value of –2.160 so the correlations are statistically significant. They could not have occurred by chance; however, we are constantly reminded by statisticians that a significant correlation neither proves nor implies any causal relationship between the two variables (Coolidge 2000; Rowntree 2000; Robson 1994;). In the above example small pores cannot cause frost damage to stone, only water freezing in the pore structure can do that. Note also that these two correlation coefficients are negative. As capillary rise time increases, indicating progressively larger mean pore radii, so the percentage weight loss of the samples induced by this test reduces. It should also be noted that the correlations have been shown to be significant, despite the limitations of the capillary rise test to provide valid results for low porosity samples.

This analysis broadly confirms what the literature concerning frost action suggests: that stone with pores of less than 5 microns wide tend to be vulnerable to cycles of freezing and thawing (Bell, 1992), although Price (1996) maintains that most sandstones are frost-resistant. The outcome of this test means – in the case of this sample set – that the samples with the lowest capillary rise time are the ones with the finest pore structure and therefore the most vulnerable to frost action. It might be expected that the same sort of correlation would be evident from the results of the tests conducted to determine the resistance to the action of soluble salts. This will be investigated in the next section of this chapter – but first the limitations of this test need to be highlighted.

Any test which simulates over a short time-span and under controlled conditions that which happens in reality over a long time-span is to a greater or lesser degree artificial. It should be borne in mind that this test ran for only one hundred cycles and one-third of the samples lost virtually no material. In real-world terms this probably represents exposure to little more than five British winters, but Rievaulx Abbey, for example, has been a ruin since the 1530s. If the results of the test on the stones of Rievaulx Abbey are extrapolated to a time-span of several hundred years, clearly, at the rate of weathering induced by this test, many *real* stones in historic monuments would have disintegrated long ago. But nevertheless, these monuments are still standing, and so this test cannot be used to predict the longevity of stone-types, but only their likely relative resistance to frost action, assuming of course that there are no other weathering agents acting concurrently. The beauty of simulated weathering tests is that the action of one agent can be isolated and studied, but they cannot pretend to replicate what happens in the real world, and that is a point to consider in the interpretation of all the results presented in this and subsequent sections of this chapter.

Summary:

- A significant correlation was found between the samples which performed badly in this test and those with the shortest capillary rise time – those with a high percentage of pores less than 5 microns wide;
- the samples which lost more than five percent of their original weight, adjusted over 100 cycles were: Slingsby Castle sandstone and limestone; Duncombe Park sandstone; Rievaulx Penny Piece and Laskill Quarry samples;
- the porosimetry results did not predict the relatively poor performance of the high porosity samples, particularly the Duncombe Park sandstone.

TEST TO DETERMINE THE RESISTANCE TO THE ACTION OF SOLUBLE SALTS

Introduction

One sample of each of the case study stone types was tested, with the exception of Duncombe Park and the Slingsby Castle sandstone, of which two samples were tested. The test was run for a maximum of twenty cycles.

Mention was made in the previous chapter of the fact that a salts test had been used in the past as a predictor of the resistance of stone samples to the action of frost, and so it might be expected that the results of this test will be similar to the results of the freeze/thaw test. It is the time available for crystal growth and the size of the resultant crystals which differ between tests and which might influence the degree of weathering induced in the samples.

Results

The following bar chart, Figure 5.7, shows the weight losses of all the samples tested and the number of cycles completed by each sample.

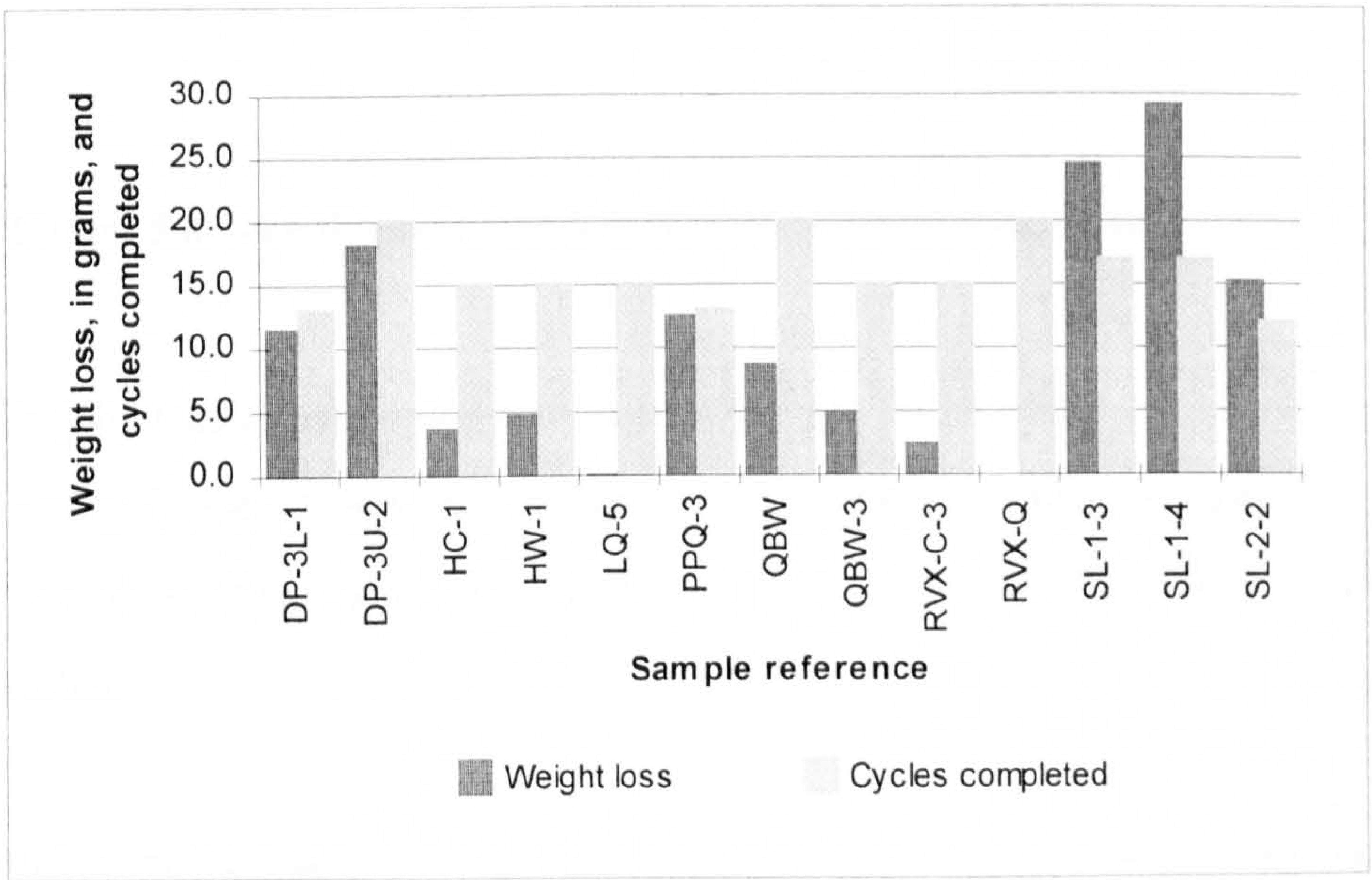


Figure 5.7 Salts test: weight losses and cycles completed

Analysis

The data was analysed by plotting bar charts of relative weight losses adjusted to a common fifteen cycles followed by a correlation analysis between dependent and independent variables and significance test on the correlation coefficient. In addition, the correlation between the results of this test and of the freeze/thaw test were calculated.

Figure 5.8 shows the relative performance of the samples, arranged in increasing order of resistance to the action of the test.

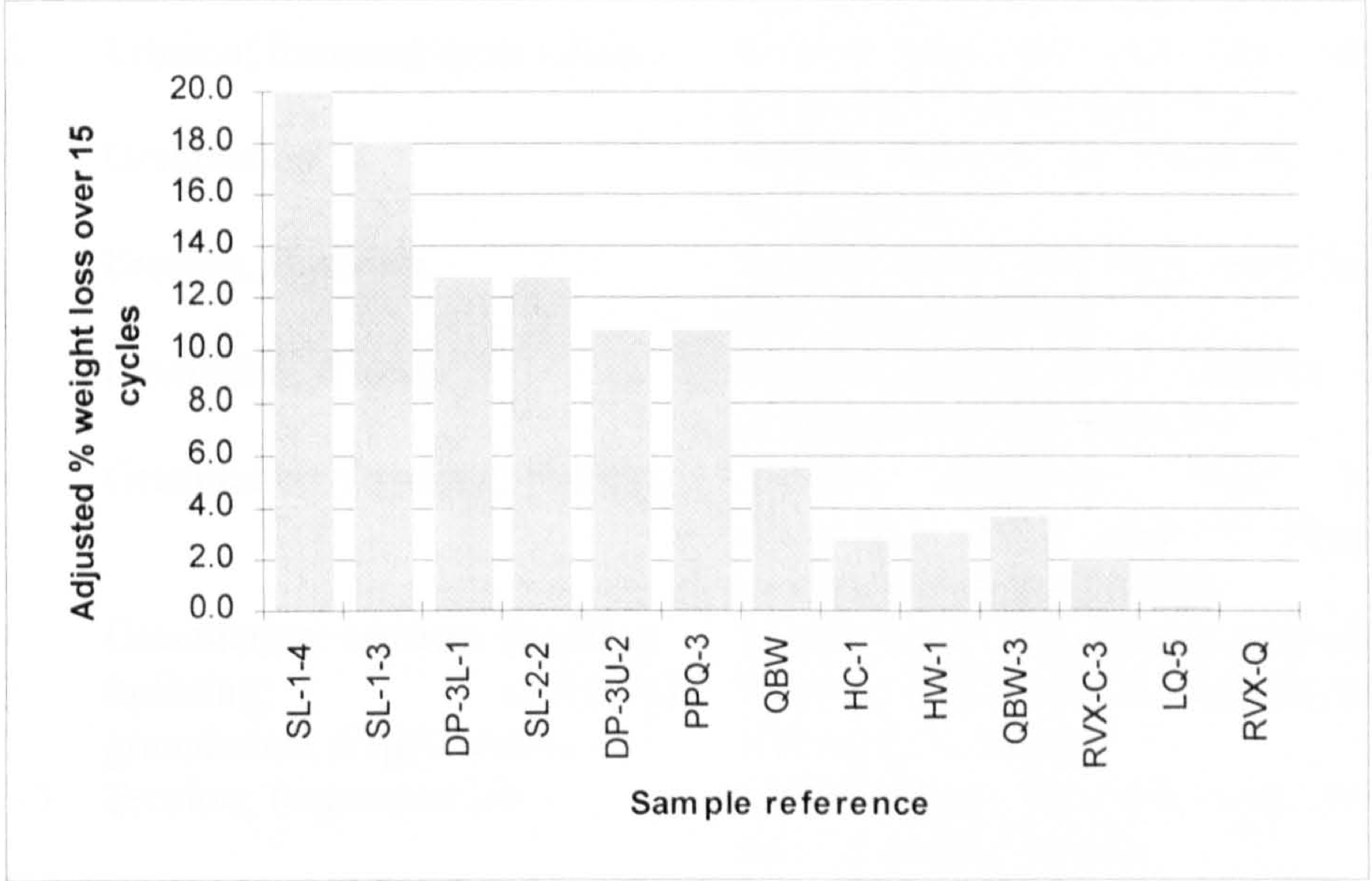


Figure 5.8 Sample performance subjected to salts crystallisation test

The Slingsby Castle sandstone samples performed worst of all, but the Duncombe Park, Penny Piece Quarry and Slingsby oolith samples also performed poorly. These are all samples with short capillary rise times and therefore the smallest pore widths.

It is worth mentioning that in this test, the percentage weight losses were adjusted to fifteen cycles, compared to the 100 cycles of the freeze/thaw test. This demonstrates the relative power of this test to simulate weathering.

As with the freeze/thaw test, the mode of loss of material and the condition of the largest remaining pieces of the samples at the end of the test, are as important as the amount of material lost. Included in Appendices 1 and 2 are detailed descriptions of the mode of failure of the samples, noted after periods of significant material loss. Those descriptions have been consolidated and along with a brief description of the conditions of the samples at the end of the test, are set out in Table 5.5, below.

Ref.	Mode of weathering	Condition after test
DP3L-1	Erosion; granulation; flaking; fragmentation;	Sample intact, but, edges and corners rounded; surface fissured; harder inclusions standing proud of surrounding surfaces by 1 to 2 mm
DP3U-2	Erosion; fissuring; granulation;	Sample intact, but with large areas of granulation losses; deep fissures
HC-1	Granulation	sample intact; slight rounding of edges and corners
HW-1	Erosion; fissuring	Sample intact, but with deep fissures, and eroded surfaces
LQ-5	Cavitation; erosion	Sample intact; some cavities where softer material has been lost
PPQ-3	Granulation; fissuring; flaking;	Sample comprises three loosely connected, deeply fissured fragments; corners and edges rounded
QBW	Granulation; erosion; fissuring	Sample intact, but surfaces eroded
QBW-3	Splitting; cavitation; granulation; fragmentation	Sample in two pieces; surfaces eroded, with some cavities
RVX-C-3	Erosion; fragmentation	Sample intact, but with one detached corner; surface erosion
RVX-Q	Granulation – loss of surface ooliths	Sample intact; loss of ooliths on edges and surfaces
SL-1-3	Granulation; flaking; fissuring	Sample intact but deeply fissured along bedding planes
SL-1-4	Granulation; flaking; fissuring	Sample intact but deeply fissured along bedding planes
SL-2-2	Granulation– loss of surface ooliths; flaking	Sample intact, but with well-rounded corners and edges; one fissure

Table 5.5 Salts test: mode of weathering and condition of samples at end of test

The descriptions used in the above table are the same as those listed beneath Table 5.3 in the previous section, but with the addition of one further term:

cavitation, where material is lost, to a depth of several millimetres from the surface, but with no apparent weathering to adjacent areas.

The performance of the samples under this test was then related to the relevant physical properties of the stone types. This was done by plotting scattergraphs, which showed the relationship between the dependent and independent variables. Correlation coefficients were then calculated for the pairs of results. The significance of the correlation coefficient was then tested by calculating the *t* value. The coefficient of determination (r^2) which gives an indication of the degree to which the dependent variables influence the independent variables was also calculated. These statistical calculations, along with the scattergraphs, are included in Appendix 3.

A conventional level of significance of 0.05 was assumed, with a degrees of freedom value of 11 (*N*–2). Table 5.6 illustrates the results.

Criteria	**Correlation coefficient *r***	**calculated *t***	**critical *t***	**Coefficient of determination r^2**
% weight loss and open porosity	+0.128	0.456	+2.201	0.016
% weight loss and capillary rise time	–0.208	–0.773	–2.201	0.219
% weight loss over 15 cycles, and capillary rise time	–0.300	–1.042	–2.201	0.090

Table 5.6 Salts test: correlations between dependent and independent variables

Table 5.5 indicates that significance could be obtained for none of the criteria selected and even the highest correlation coefficient of –0.300 could only account for 9% of the relationship between capillary rise time and percentage weight loss over 15 cycles. The remaining 91% is unexplained. It is not surprising that the correlation coefficient of 0.400 between the results of this test and the results of the freeze/thaw test also proved to be non-significant. Table 5.7, below, illustrates the results:

Criteria	**Correlation coefficient *r***	**calculated *t***	**critical *t***	**Coefficient of determination r^2**
Freeze/thaw test and salts test, % weight losses per cycle	+0.400	+1.307	+2.262	0.160

Table 5.7 Correlation between freeze/thaw test and salts test results

It is difficult to understand why a significant correlation does not exist between the results of the two tests. It would be expected that the samples which were vulnerable to weathering by frost would also be vulnerable to weathering by the action of soluble salts, since the severity of action is largely a function of the pore size distribution of the samples; however, the tests were not conducted on the same number of samples, nor the same numbers of each stone type, but this was taken into account in the analysis. The calculation of r was made by using the mean percentage weight losses per cycle only for the eleven stone types which were common to each test. There is a reluctance therefore to admit that a lack of significance is as a result of any flaw in the experimental design and the explanation may lie in the limitations of the analysis method.

Limitations of the analysis method

There is an acknowledged problem associated with small sample sizes and obtaining significance for a correlation coefficient (Coolidge 2000, p.126). The problem is that significance tests are artificially dependent upon samples size. This test was carried out on only thirteen samples, two less than the freeze/thaw test, and so the chance of obtaining significance is less with these results. It can be seen from the above Table 5.6, that the highest correlation coefficient obtained with the salts test was only –0.300, with a calculated t of –1.042, which proved to be non-significant. If we examine the results of the correlation between the results of the salts test and the results of the freeze/thaw test, for which there were only eleven pairs of samples, Table 5.7 shows that the correlation coefficient was 0.400. It can be calculated from the formula for t, given in Appendix 3, that r would need to be at least 0.603 to produce a significant t value. Conversely, the calculated r of 0.400 would produce a significant t value, only if $N - 2$ was greater than 27. In other words, if there had been 29 pairs of samples, instead of just eleven, $r = 0.400$ would be significant. This demonstrates the disproportionate influence which the sample size can have on the production of a significant t value; the smaller the sample size the larger the correlation coefficient needs to be to be statistically significant.

Summary:

- No significant correlation was found between the samples which performed badly in this test and any of the physical properties of the samples;
- the samples which lost more than five percent of their original weight adjusted over fifteen cycles were: the Slingsby Castle sandstones and limestone; the Duncombe park sandstones; the Rievaulx Penny Piece and Quarry Bank Wood samples;
- the correlation between the results of this test and the results of the freeze/thaw test proved to be non-significant, but this may be a function of the sample size.

TEST TO DETERMINE THE RESISTANCE TO ACID RAIN

ACID IMMERSION TESTS 2 AND 3

Introduction

This test, as well as being a simulation of weathering by acid rain, also served as an indicator of the calcium carbonate content of the samples. The test was conducted in three parts:

- Test 1, the trials of the test, comprised nine samples, five of which were from the case study sites. The results appear in Appendix 1 and the way in which the method was modified for Tests 2 and 3 was described in the last chapter;
- Tests 2 comprised fourteen samples from the case study sites;
- Test 3 comprised fourteen samples from the case study sites, but with lichens on one face of each sample.

ACID IMMERSION TEST 2

Results

The following bar chart, Figure 5.9, shows the percentage weight losses of the samples tested. The numbers, '5' and '10' after the sample reference indicate the percentage concentration of acid solutions used to test those samples. It should be noted that although the sample references have the same meaning as indicated in Table 5.1, at the beginning of this chapter, one additional sample has been used in this test. The sample reference CRF is from Chesters Roman Fort in Northumberland and has been substituted for a sample from Harewood Castle, as further samples for this test were unavailable because of restrictions of access due to the foot-and-mouth outbreak in 2001. It is a Carboniferous Gritstone with the same mineralogy as the Harewood Castle stone and for the purpose of this test serves as a good substitute.

While Figure 5.9 gives an indication of the relative performance of the samples, it gives no indication of the condition of the samples at the end of the test. Table

5.8, which follows, describes the condition of each sample at the end of the test, and also indicates a score, which is related to that condition.

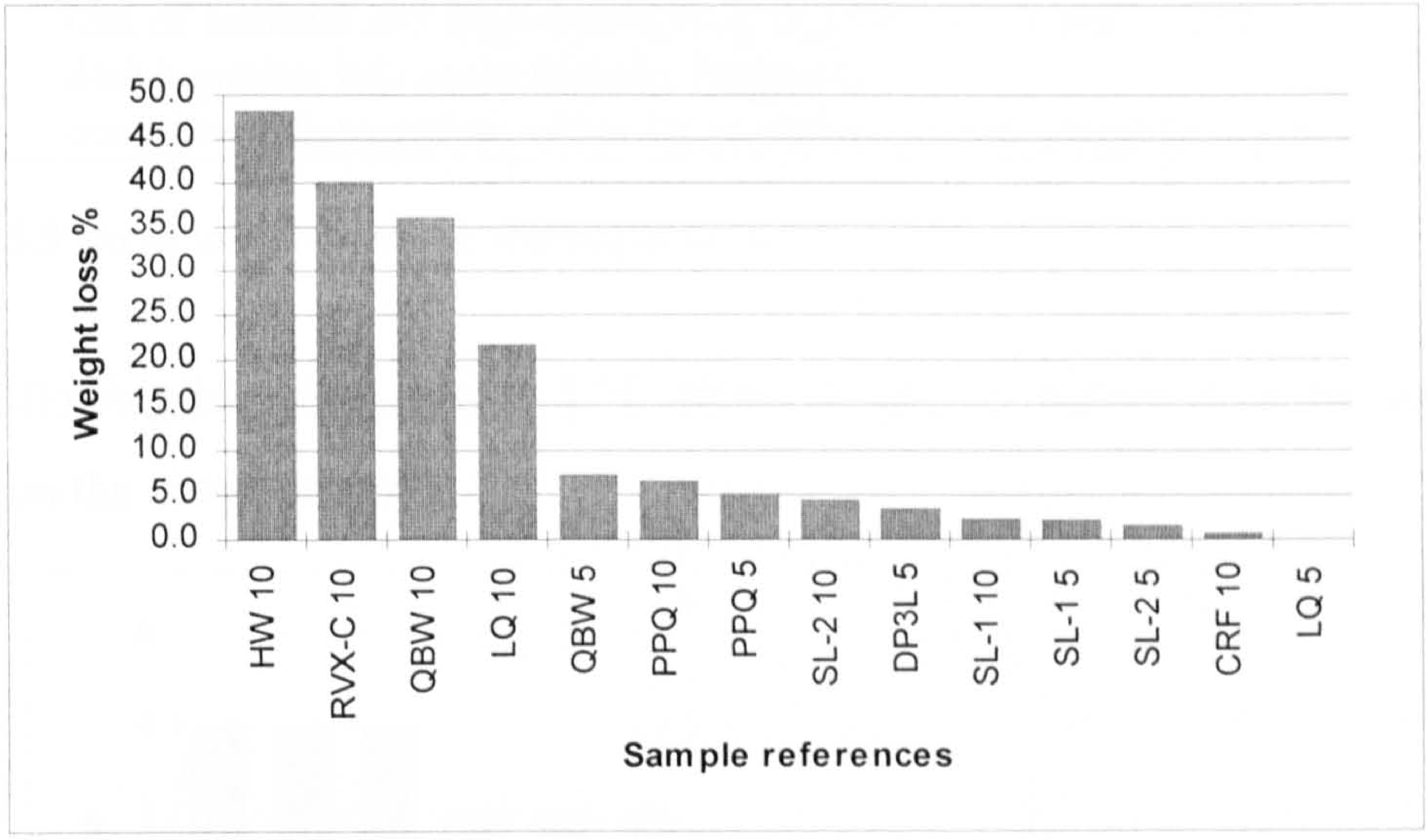


Figure 5.9 Acid immersion test 2: % weight losses

Sample ref.	Condition	Score
HW 10	Reduced in volume by 50%, remainder as gypsum and ooliths	4
QBW 10	Harder portion in one piece; disintegration of remainder	4
RVX-C 10	Two main fragments; many smaller, or disintegrated	4
DP3L 5	One large piece, and several small fragments; bleached	3
LQ 10	One fragment with several splits; many smaller fragments	3
QBW 5	One fragment with several splits; many smaller fragments	3
SL-2 5	Intact, but surface pitted, and covered by gypsum crust	2
SL-2 10	Intact, but surface pitted, and covered by gypsum crust	2
PPQ 10	Intact; bleaching; slight surface erosion	1
CRF 10	Intact; slight bleaching	0
LQ 5	Intact; slight bleaching	0
PPQ 5	Intact; slight bleaching	0
SL-1 5	Intact; slight bleaching	0
SL-1 10	Intact; slight bleaching	0

Table 5.8 Acid immersion test 2: sample conditions at end of test, and scores

Table 5.9 shows the criteria adopted for scoring the performance of the samples, irrespective of percentage weight losses.

Score	Condition of sample
0	no change in mass, nor volume
1	evidence of surface erosion, chemical conversion, or pitting
2	obvious loss of material due to dissolution, but no fragmentation
3	loss of material and fragmentation; sample in two or more pieces
4	disintegration into many discrete fragments
5	complete disintegration, either into solution, or into constituent grains

Table 5.9 Acid immersion test: scoring criteria

The following bar chart, Figure 5.10 shows the scores allocated to the samples, based on the above criteria.

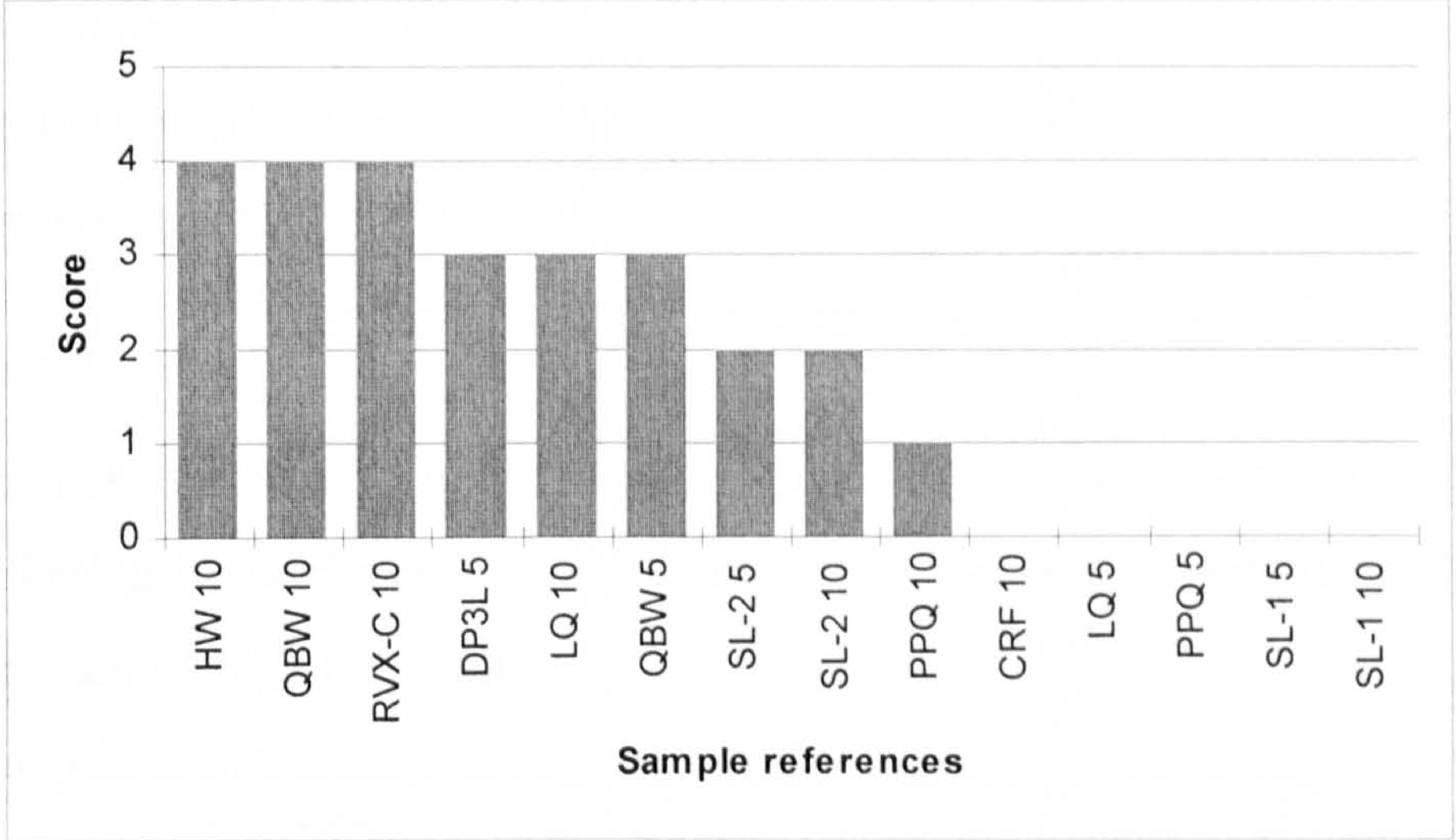


Figure 5.10 Acid immersion test 2: samples scores

Discussion

As a demonstration of the effect which mineralogy can have on stone durability, the Hollins Wood sample is worth mentioning. This is the stone type which survived 100 cycles of the freeze/thaw test with no evidence of weathering and which, under the action of the salts test, lost less than three percent of its original dry weight. Under the action of *this* test the sample lost over 45% of its original dry weight, mainly by dissolution of the softer carbonate matrix which cements the harder ooliths and shell fragments together. This sample also demonstrates that it is not always high porosity stones which are vulnerable to weathering by acid rain. The porosity of this stone type was calculated to be 10.5%, compared to the mean value of all the samples tested, of 14.5% and a highest and lowest of

44.8% and 3.0%, respectively. The Penny Piece quarry samples and the Slingsby Castle sandstones which lost nearly 20% and 10% respectively of their original dry weights, lost less than 5% of their original weight during this test, indicating a small proportion of carbonate. The Chesters Roman Fort sample was unaffected by this test, and would therefore have a high resistance to weathering in polluted atmospheres.

Although Price maintains that salts pose the greatest weathering hazard to our built heritage (Price 1996), for stone types with carbonates performing a critical structural function in the stone, atmospheric pollution and the resultant acid rain, pose, in the writer's view, an even greater potential threat and this is an argument which will be pursued in Chapter Six.

Summary:

- It is not necessarily high porosity stone types which are vulnerable to weathering by acid rain – stone types with a mineralogy soluble in low pH waters are highly vulnerable;
- higher concentrations of acid caused greater degrees of weathering.

ACID IMMERSION TEST 3

Results

It is not the intention that the samples from this group be compared directly with the samples which were subjected to Test 2. This is because the two tests were not designed in the same way as, for example, the saturation and drying tests, described in Part 3 of this chapter. This is because it proved virtually impossible to locate samples comparable to the test 2 samples, but with lichens on one face, so *that* level of control between samples in Test 2 and 3 has not been achievable. By a quirk of the sampling procedure, however, all the samples in this test are from two sources, with the exception of the Slingsby Castle sample. It was a combination of the mineralogy of the stone – which provided a suitable substratum for lichen colonisation – and the aspect of the sites, which provided optimum illumination levels for lichen growth, which resulted in the Laskill and the Rievaulx Abbey Church quarry sites yielding sufficient suitable samples for this test.

All the samples in this test were subjected to 5% sulphuric acid solution, as described in the last chapter.

The following bar chart, Figure 5.11, shows the percentage weigh losses of each of the samples at the end of the test.

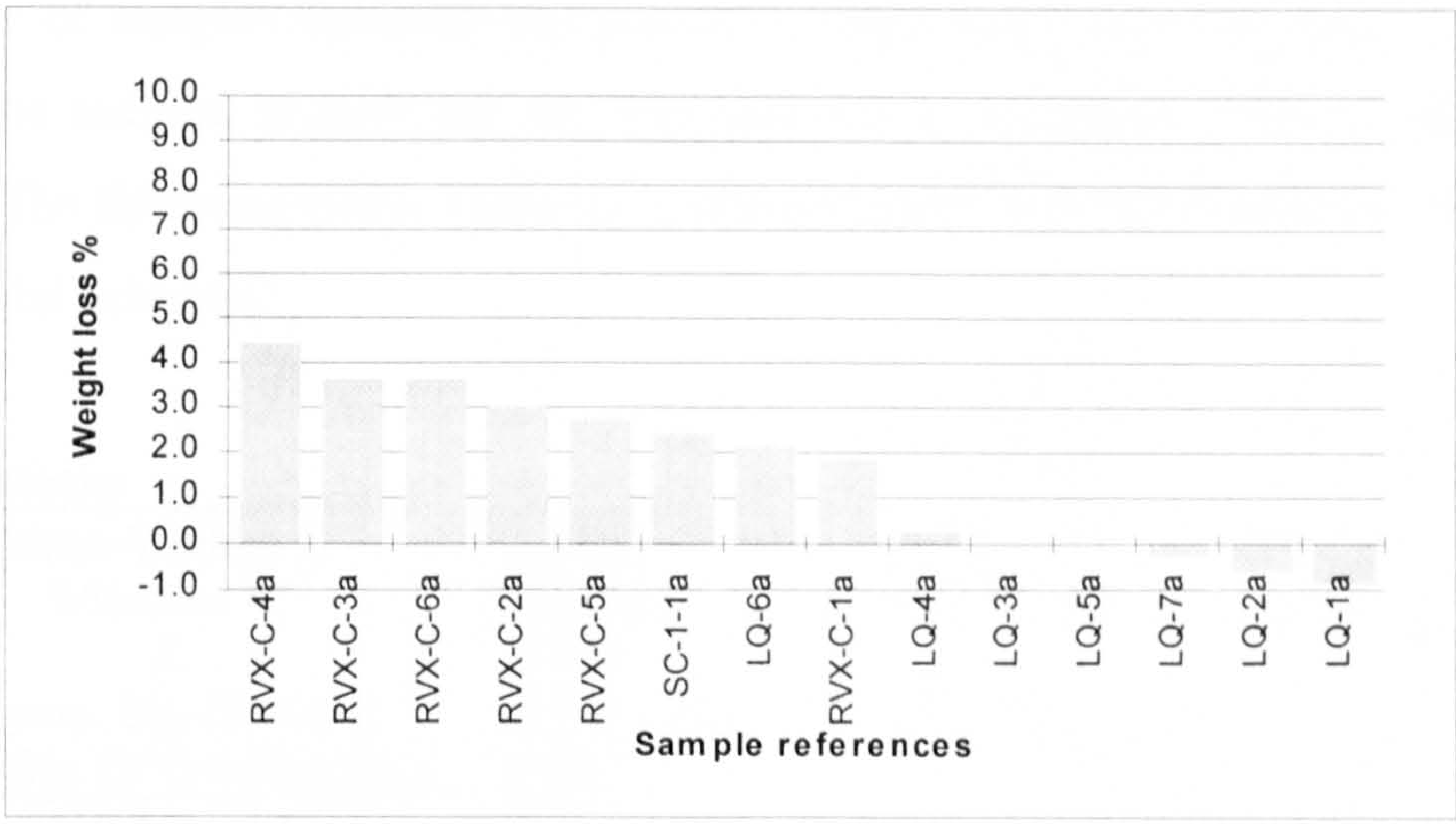


Figure 5.11 Acid immersion test 3: % weigh losses

Discussion

It should be noted that although all the Rievaulx Abbey Church samples lost weight during the test, three of the Laskill Quarry samples gained weight. The reason for this is unclear, but it might be due to incomplete drying of the samples after washing at the end of the test.

Since five percent acid was used on all the samples in this test, there were none of the large percentage weight loses recorded which were associated with the ten percent solution used in Test 2; however, if the mean weight losses of the Test 2 samples subjected to five percent acid is compared with the mean weight losses recorded in this test, a degree of comparison can be obtained. Table 5.10 indicates those mean values.

Acid immersion test	Mean weight loss from samples, %
Test 2 samples subjected to 5% solution	3.2
Test 3 samples	1.6

Table 5.10 Acid immersion tests: comparison between Test 2 and Test 3 results

These means can be subjected to significance testing, but because of the small number of samples involved non-parametric techniques must be used. In this case, the samples in each test are unrelated and so the Mann-Whitney test was used. The following table, Table 5.11, was generated by *SPSS* (Statistics Package for Social Sciences).

Test Statistics	
Mann-Whitney U	28.000
Wilcoxon W	133.000
Z	-1.157
Asymp. Sig. (2-tailed)	0.247
Exact Sig. [2*(1-tailed Sig.)]	0.274[1]

[1] Not corrected for ties.

Table 5.11 Acid immersion Tests 2 and 3: results of statistical analysis

It can be seen that the calculated *Z* is not less that the critical value of –1.96 and so is non-significant at the 0.05 level for a two-tail test: the null hypothesis, that the lichen cover on the Test 3 samples provided no protection against the effects of the acid solution must, therefore, be retained.

If this aspect of the test has failed to provide significance, then a further aspect, not so far discussed, must be considered to be highly significant. In four of the Laskill Quarry samples, the lichens survived the test intact. This may have been a chance occurrence, but nevertheless it occurred and demonstrates that those species may have the ability to survive levels of atmospheric pollution far in excess of anything likely to be experienced in the natural environment.

Summary:

- This test gave an indication of the carbonate content of the samples; high carbonate samples were generally more vulnerable;
- The samples which had the greatest structural disruption at the end of the test were Rievaulx Hollins Wood, Rievaulx Quarry bank Wood, Rievaulx Abbey Church Quarry, and Duncombe Park;
- The percentage weight loss was largely independent of sample porosity;
- The degree to which lichens influenced the outcome of the test was inconclusive, partly because of differences in stone types between Tests 2 and 3, and partly due to the small sample size;
- four of the lichen species survived the test intact.

PART 2 SUMMARY

The four most vulnerable stone types, and the three most resistant to the three simulated weathering tests are identified in Table 5.12, below.

Sample reference	**Freeze/thaw test**	**Salts test**	**Acid immersion test**
CRF			Good
DP3L		**Poor**	
DP3U	**Poor**	**Poor**	**Poor**
HC			(good)
HW	Good		**Poor**
LQ		Good	
PPQ	**Poor**		Good
QBW			**Poor**
RVX-C	Good	Good	
RVX-Q	Good	Good	**Poor**
SL-1	**Poor**	**Poor**	Good
SL-2	**Poor**	**Poor**	

Table 5.12 Resistance of samples to the three simulated weathering tests

In addition, the following factors have also emerged:

- The samples which lost more than five percent of their original weight, adjusted over 100 cycles in the freeze/thaw test were those with a high percentage of pores less than 5 microns wide, but the porosimetry results did not predict the relatively poor performance of the high porosity samples, particularly the Duncombe Park sandstone.

- the correlation between the results of the freeze/thaw test and the salts test proved to be non-significant, probably as a result of the small sample size;
- The samples which had the greatest structural disruption at the end of the acid immersion test were those with a carbonate matrix, but the percentage weight loss was largely independent of sample porosity;
- The degree to which lichens influenced the outcome of the acid immersion test was inconclusive, partly because of differences in stone types between Tests 2 and 3 and partly due to the small sample size;
- four of the lichen species survived the acid immersion test intact.

The implications of the presence of plants on the outcome of the test results described in this part of this chapter will be investigated in Part 3.

PART 3 TESTS TO DETERMINE SATURATION AND DRYING TIMES

INTRODUCTION

The test method used to determine saturation and drying times of sample cubes was described in Chapter Four. This section describes the ways in which the data produced were analysed and is divided into three parts:

- Analysis of the saturation and drying time data;
- analysis of the uncontrolled variables during the tests;
- identification of the causes of the significant results.

The data obtained from the saturation and drying test are included in Appendix 4 part 1. The results of all the statistical tests and the reasons for their selection, can be found in Appendix 4 part 3.

ANALYSIS OF SATURATION AND DRYING TIMES

The results from the four stages of the test sequence were divided into two pairs of groups, as described in Chapter Four. The resultant paired-groups were: Group 4 without plants and Group 6 with plants; Group 5 without plants, but with five sealed faces and Group 7 with plants and five sealed faces. The aim of the analysis was to determine if there was a statistically significant difference between the saturation times of the pairs of groups and between the drying times of the pairs of groups.

The initial analysis of the data was conducted in three steps:

- Time series graphs were plotted for each sample tested;
- the frequency distributions of the saturation and drying times of each group were analysed to determine if they were normally distributed;
- significance testing was carried out on the frequency distributions of the two pairs of groups to determine if plants had a significant effect on saturation or drying times.

The saturation and drying time-series graphs enabled the 'shape' of the data to be determined and gave a preliminary visual overview of the results. These time-series saturation and drying graphs can be found in Appendix 4 part 2.

The analysis of the frequency distributions for normality gave an indication as to the appropriate statistical test to be employed. The details of the frequency distribution analyses are included in Appendix 4 part 3, along with the justifications for the choice of the test methods.

The significance testing revealed whether the differences in the results between pairs of groups was statistically significant, or whether they were likely to have occurred by chance. Details of the significance tests are included in Appendix 4 part 3.

Analysis of frequency distributions of saturation and drying times

The frequency distributions of the four groups were analysed using a combination of manual calculation, *Microsoft Excel* analysis tools, and *Statistical Package for Social Sciences*, version 10.0 (*SPSS*). Table 5.13, below, summarises the results of this stage of the analysis. Normally distributed refers to the normal, or bell-shaped distribution curve.

Sample group	Saturation distribution	Drying distribution
Group 4	not normally distributed	not normally distributed
Group 6	not normally distributed	not normally distributed
Group 5	normally distributed	normally distributed
Group 7	not normally distributed	normally distributed

Table 5.13 Analysis of saturation and drying time frequency distributions

It can be seen that only the drying distribution for Groups 5 and 7 were normally distributed. These pairs, as explained in Appendix 4 part 3, can be analysed using parametric test methods. The remainder must be analysed using non-parametric techniques.

Analysis of saturation and drying times

The null hypothesis used in the significance testing of the saturation and drying times was that was that there was no difference between those times, between pairs of groups. The alternative hypothesis was that there was a difference. The tests were, therefore, two-tail tests, and the standard significance level of 0.05 was used. The results are shown in Table 5.14, below.

Sample groups	Analysis method	Result
Groups 4 and 6: saturation times	Mann-Whitney	non-significant
Groups 4 and 6: drying times	Mann-Whitney	significant
Groups 5 and 7:saturation times	Wilcoxon	non-significant
Groups 5 and 7:drying times	Wilcoxon	significant

Table 5.14 Results of saturation and drying time significance tests

In addition, the data for the drying times of the Group 5 and Group 7 samples were analysed using the *t* test, because their frequencies were normally distributed. The coefficient of effect size, which reveals the degree to which plants affected the drying time, was also calculated. Details can be found in Appendix 4 part 3, and the results are summarised in Table 5.15, below.

Sample groups	*t* test	Result	Effect size
Groups 5 and 7:drying times	dependent	significant	large

Table 5.15 Groups 5 and 7 drying time *t*-test results

It can be seen from Tables 5.14 and 5.15, that the use of these three analysis methods has revealed that the data from the saturation and drying test show that the presence of plants had no significant effect on the saturation times of the samples, other than that which could be expected by chance; the null hypothesis has been retained. The implication is that the plants on the samples of Groups 6 and 7 appear to be 'transparent' to water uptake. This analysis has also shown that the presence of plants in both pairs of groups has a significant effect on the drying times of the samples, an effect which could not have occurred by chance. In both of these significant results, the null hypothesis has been rejected and the alternative hypothesis proved. The direction of the significance can be determined by referring to values of the means for each group, as shown in Table 5.16.

Sample groups	Mean drying time	Direction of the significant difference
Group 4	7.0 days	
Group 6	5.5days	group with plants dried more quickly
Group 5	14.4 days	
Group 7	17.1 days	group with plants dried more slowly

Table 5.16 Saturation and drying time test analysis: direction of significance

Summary

- The difference in saturation times for both pairs of groups was shown to be non-significant – plants had no effect on saturation times; plants are, in effect, transparent to the passage of water into stone;
- The difference in drying times for both pairs of groups was shown to be significant – the Group 6 samples with plants dried faster than the Group 4 samples without plants, but the Group 7 samples with plants dried more slowly than the Group 5 samples without plants.

It is surprising that the Group 6 samples dried more quickly than the Group 4 samples and it is not easily explained. The direction of any significant difference might be expected to be the same for both groups of samples. An examination of the uncontrolled variables in the test may reveal the reasons for the directions of both significant results.

ANALYSIS OF UNCONTROLLED VARIABLES IN THE SATURATION AND DRYING TESTS

There were three uncontrolled variables in these tests which may have affected the outcome:

- The relative volumes of the samples – not all samples were perfect cubes, particularly samples with plant cover on one face;
- the relative surface area available for water absorption and evaporation varied – some cubes, especially the cubes with plant cover, had an irregular face which could have an increased surface area compared to standard cubes;
- the relative humidity in the laboratory during the drying phases of the tests varied – it influences rates of water evaporation and hence the drying times of the samples.

Analysis of sample volumes

Larger, heavier, samples have more pores than smaller, lighter, samples of the same stone type. The pore volume is, therefore, directly proportional to samples weights, for any given stone type. The sample weights used in this analysis were those recorded at the end of the drying phase of tests, when they had reached an equilibrium weight at room temperature. There were two steps to this analysis: analysis of frequency distribution for normality and significance testing.

The frequency distribution of the sample weights was analysed using *SPSS*, and the output generated can be found in Appendix 5. Table 5.17 summarises that analysis.

Sample group	Sample weight frequency distribution
Group 4	normally distributed
Group 6	normally distributed
Group 5	normally distributed
Group 7	normally distributed

Table 5.17 Results of analysis of sample weight frequency distributions

All of the analyses of frequency distributions were shown to be normally distributed, and so the data was analysed using a parametric method. These tests were carried out using *Microsoft Excel*, and the output generated appears in Appendix 5. Table 5.18 summarises the results.

Sample groups	***t* test**	**Critical *t***	**Calculated *t***	**Result**
Groups 4 and 6:	independent	2.006	–0.193	non-significant
Groups 5 and 7:	dependent	2.145	–2.901	significant

Table 5.18 Results of significance test on sample weights between groups

The results show that the calculated value of *t* indicated that the difference in mean weights of the samples in Groups 4 and 6 was non significant in a two-tail test at the 0.05 level of significance. The difference could have occurred by chance and the null hypothesis was retained. It can be concluded that the differences in weights would have had no effect on either saturation, or drying times.

For Groups 5 and 7 the calculated value of *t* was greater than the critical value and so the difference was significant. The direction of the significance can be determined by reference to the mean value of the weights of those two groups, which were 132.3grams and 135.3grams, for Groups 5 and 7 respectively. It can be deduced that the Group 7 samples were significantly heavier than the Group 5 samples and this difference could not have occurred by chance. The effect of this would be to artificially increase both the saturation and the drying time of the Group 7 samples and could explain why the Group 7 samples dried more slowly than the Group 5 samples; however, it has already been demonstrated that the difference in the saturation times between Groups 5 and 7 was non-significant. If the differences in sample weights did not affect saturation time, it seems unlikely that those differences would affect drying time. So the difference must be a function of the independent variable – the plants.

Summary

- The difference in mean sample weights between Groups 4 and 6 was non-significant;
- the difference between mean sample weights between Groups 5 and 7 *was* significant – the Group 7 samples were heavier than the Group 5 samples, but it is unlikely that this would be a factor in the prolonged drying times of the Group 7 samples.

Analysis of relative surface area

It takes a large difference in surface area to have a measurable effect on saturation and drying time, for samples with equal volumes. This is evident by comparing the saturation and drying times across Groups 4 and 5; the Group 4 samples have six times the free surface area of the Group 5 samples and a comparison of the mean saturation and drying times for these two groups is shown in Table 5.19.

	Group 4	Group 5
Mean saturation time	13.5 days	25.3days
Mean drying time	7.0days	14.4days

Table 5.19 Across groups comparison of saturation and drying time

No statistical analysis is required to be able to see that large differences in surface area *do* have large effects on the relative times to saturate and to dry, even in samples of this size, but in a comparison of samples between groups, these differences are small, of the order of a few square millimetres, amounting to differences in the order of less than 0.5%.

Two further aspects need to be considered. The first concerns the saturation times of the samples in Groups 4 and 6. Slight differences in surface area between these two groups might have resulted in a reduced saturation time of the Group 6 samples because they had slightly larger surface areas, but there was no significant difference detected. The second aspect concerns the samples in Groups 5 and 7. These were the same samples, with plants, and then with the plant removed. Great care was taken during the removal of the plants to preserve the surface contours of the colonised surface, and it is not feasible that there was any appreciable difference in surface areas between this pair of groups.

The relationship between evaporation losses and surface area, assuming uniform pore distribution, is complex, however. Salisbury and Ross point out that a greater number of pores available for evaporation does not result in greater evaporation rates (Salisbury and Ross 1992, pp.70-71). They highlight this in their discussion of the boundary layer between a free surface of water and the atmosphere. Diffusion rates from water into the atmosphere depend on the distance water molecules have to travel before their concentration reaches that of the atmosphere. The boundary layer is the layer where this occurs. Water evaporates faster from a surface with sparsely distributed pores than from a free surface of water because the boundary layer is nearer the surface and hence the moisture gradient is steeper. Salisbury and Ross further point out that nature has used this principle to good effect. The stomata of leaves through which transpiration takes place have been found to be almost optimally spaced to ensure maximum gas or vapour diffusion (Salisbury and Ross 1992, p.71). The consequences for the evaporation of water from stone, assuming that the foregoing equally applies, is that small changes in surface area, and therefore the number of pores available from which evaporation can take place, is unlikely to be a critical factor in determining drying times of test cubes.

Summary

- It is unlikely, although it was not proved conclusively, that differences in surface area available for water uptake and evaporation between pairs of groups had any significant effect on either the saturation times, or the drying times of the sample groups.

Analysis of relative humidities

Three steps were used in the analyses of the relationship between relative humidity and drying times:

- The data were analysed to confirm that relative humidity was the critical environmental variable in evaporation losses compared to other measured laboratory environmental variables;
- the frequency distributions of the relative humidities recorded during the drying phases of the tests were analysed for normality;
- the frequency distributions were analysed for significance differences between pairs of groups.

The need to derive correction factors for the daily losses from samples during drying was dependent upon the outcome of this stage of the analysis.

The daily relative humidities were related to water losses recorded from an open petri dish of water placed in a shaded part of the laboratory. The daily weights of petri dish and water can be found in Appendix 5.

The relationship between the measured values of laboratory environmental variables and water losses was analysed first by plotting scattergraphs of the pairs of variables, and then by calculating the Pearson Product Moment correlation coefficient. These coefficients were then subjected to significance testing by calculating the *t* value. The calculations were carried out using the analysis tools provided by *Microsoft Excel*, and the *t* value was calculated by using the formula given in Coolidge (2000, p118). The scattergraphs and the calculations of the *t* values can be found in Appendix 5. Table 5.20 summarises the results.

Pairs of variables	**correlation**	***t* value**	**critical *t***
Atmospheric pressure and daily water losses	0.059	0.399	> 1.990
Wet bulb temperature and daily water losses	–0.11	–1.057	< –1.990
Air temperature and daily water losses	0.163	1.583	> 1.990
Relative humidity and daily weight losses	–0.623	**–7.728**	< –1.990
Mean daily RH and daily weight losses	–0.656	**–8.317**	< –1.990
Mean daily RH and mean water losses	–0.844	**–11.887**	< –2.010

Table 5.20 Correlation coefficients and significance tests on laboratory environmental variables

The mean relative humidities were the averages of each pair of consecutive relative humidities, whilst the mean water losses were the averages of all the water losses recorded for each recorded value of relative humidity.

It can be seen from Table 5.20 that only the correlations between relative humidity and water losses proved to be significant. These are indicated in bold type. The correlation between them is negative; as humidity rises, water evaporation reduces, and that is what was expected (Nelkon and Parker 1974). It should be noted however, that a perfect correlation of '1' is unlikely to be achieved, because real-world data gathering rarely provides perfect data, even when scientific theory tells us that perfect correlations should exist.

The next stage in the analysis was to test the relative humidity frequency distributions for normality. This was carried out using *SPSS* and the output generated appears in Appendix 5. Table 5.21 summarises the results.

Sample group	**Relative humidity frequency distribution**	**Number of values**
Group 4	not normally distributed	166
Group 6	not normally distributed	216
Group 5	not normally distributed	145
Group 7	not normally distributed	361

Table 5.21 Results of relative humidity frequency distribution analysis.

It can be seen that none of data are normally distributed and so the analysis must be by non-parametric methods. Since the number of values in each pair of groups is unequal, the Mann-Whitney test was used and because of the large number of values in each pair of groups the analysis was carried out using *SPSS*. The full output appears in Appendix 5 and Table 5.22 summarises the results:

	Groups 4 and 6	**Groups 5 and 7**
Mann-Whitney U	11109.000	16519.000
Z score	-1.181	-11.606
Asymp. Sig. (2-tailed)	0.238	0.000

Table 5.22 Between-groups relative humidity significance test results.

The *z* score for groups 4 and 6 is greater than the critical value of −1.96, and so is non-significant at the 0.05 level for a two-tail test. It can be concluded, therefore, that there is no significant difference between the relative humidities recorded during the drying phases of the tests on the samples in Groups 4 and 6. Fluctuating relative humidities will have had no effect on the drying times of the samples in those groups and so no correction factors need be calculated.

The *z* score for Groups 5 and 7 is below the critical value of −1.96, and so there *is* a significant difference between the relative humidities prevalent during the drying phases of the samples in Groups 5 and 7. This suggests that correction factors may need to be calculated, but first the direction of the difference needs to be determined by reference to the means of the frequency distributions. Table 5.23 shown the relationship between these means and the direction of the significant difference.

Sample groups	Mean R.H.	Direction of the significant difference
Group 5 drying	67%	greater than Group 7
Group 7 drying	57%	less than Group 5

Table 5.23 Relative humidity frequency distributions: direction of significance

It can be seen by comparing the results shown in Table 5.23 and 5.16, that the Group 7 samples dried more slowly than the Group 5 samples, but the Group 7 samples dried at lower relative humidities. If the Group 7 relative humidities had been the same as those of Group 5, the samples would have dried even more slowly; the already significant difference between the drying times would become even greater. Under these circumstances no correction factors are required.

Summary

- The difference in mean daily relative humidities under which the Group 4 and Group 6 samples dried was non-significant – the difference would have had no effect on the drying times of the two groups;
- the Group 7 samples dried at significantly lower mean daily relative humidities than the Group 5 samples and so their recorded drying time was artificially low.

The analysis of the uncontrolled variables has shown that none is likely to have had a significant effect on saturation and drying times, except for relative humidity. The effect of relative humidities on the drying times of the Group 7 samples was to provide artificially low drying times relative to the Group 5 samples and so the significant results remain valid. The next part of the analysis was to determine why those significant differences in drying have occurred.

IDENTIFICATION OF THE CAUSES OF SIGNIFICANT DIFFERENCES IN DRYING TIMES

Four reasons have been identified which may explain why the significant differences in drying times occurred:

- The mean water gains may not have been equal to the mean water losses, due to incomplete drying of samples at the start, or end of the test;
- large weights of water may have been held by plants by capillary attraction, resulting in longer drying times for those samples;
- plants may have inhibited drying, by slowing evaporation;
- test design may be invalid.

There were four stages in the analysis of these possible reasons:

- Analysis of the mean water gains and losses within groups and between groups, in order to establish homogeneity of water gains and losses;
- analysis of the differences in water gains and losses between pairs of samples within groups and between groups, to establish whether the plants had any significant influence on the amount of water uptake and subsequent losses;
- analysis of water uptake and losses from specimens of plant material, in order to establish whether these accounted for the differences in saturated weight between pairs of samples with and without plants;
- re-evaluation of test design, in order to confirm homogeneity of stone types between pairs of groups.

Analysis of mean water gains and losses between pairs of groups

First, the frequency distributions of the water gains and losses for each sample group were analysed for normality. This would determine the analysis techniques to be used. Details of the analyses are included in Appendix 6, and the results are summarised in table 5.24.

Sample group	Water gains	Water losses
Group 4	data normally distributed	data normally distributed
Group 6	data not normally distributed	data normally distributed
Group 5	data normally distributed	data normally distributed
Group 7	data normally distributed	data normally distributed

Table 5.24 Water gains and losses: analysis of frequency distributions

It can be seen from table 5.24 that only the data for Group 6 gains were not normally distributed and therefore the gains and losses of Group 6 required analysis by non-parametric methods. The remainder were analysed using parametric methods.

The tests were carried out on the assumption that the null hypothesis was true; plants had no effect on the water gains and losses between pairs of samples. The alternative hypothesis was that they had an effect; therefore, two-tail tests were carried out. The results of these tests can be found in Appendix 6, but Table 5.25 summarises the results as being significant, or non-significant at the 0.05 level for a two-tail test.

Sample group	Within groups analysis Water gains and losses	
Group 4	non-significant	
Group 5	non-significant	
Group 6	significant	
Group 7	non-significant	
Sample groups	**Between groups analysis Water gains**	**Water losses**
Group 4 and 6	non-significant	non-significant
Group 5 and 7	non-significant	non-significant

Table 5.25 Water gains and losses: results of significance tests

There was only one significant difference detected, and that was between the mean weight of water gained and lost by the Group 6 samples. The mean gains and losses were 11.6g and 12.2g respectively. If the samples contained residual moisture at the start of the test, they would require proportionately less water to saturate, but on drying to constant weight all the absorbed water would be lost. The difference in water gains and water losses is a consequence of the Group 6 samples not having achieved an equilibrium weight at the start of the test; nevertheless, the difference between gains and losses between Groups 4 and 6 proved to be non-significant and this may have been influenced by the Group 6 samples.

None of the other gains and losses were significant – they could have been chance occurrences. The consequence of this is that the significant difference in drying times between the Group 4 and 6 samples and the Group 5 and 7 samples was not a function of any differences in weights of water absorbed or lost. The differences is likely to have been due to the plants.

Summary

- There was a significant difference between water gains and losses within the Group 6 samples, probably due to incomplete drying at the start of the test.
- There was no significant difference in the weights of water gained between the Group 4 samples without plants, and the Group 6 samples with plants;
- there was no significant difference in the weights of water gained between the Group 5 samples without plants, and the Group 7 samples with plants.

Analysis of differences in water gains and losses between pairs of samples

The differences in water gains and losses between pairs of samples were analysed by plotting graphs of the daily differences in weight, calculated from the saturation and drying test data. These graphs revealed the precise effect the plants had on the rate of saturation and the rate of drying and were plotted for all the sample-pairs tested.

All these saturation and drying time 'difference' graphs are included in Appendix 6, but three examples are discussed below. Samples without plants are referred to as the 'reference' samples, and the samples with mosses or lichens are referred to as the 'test' samples.

Although it is generally accepted that graphs should be self-explanatory, in the case of these difference graphs, a commentary aids their understanding.

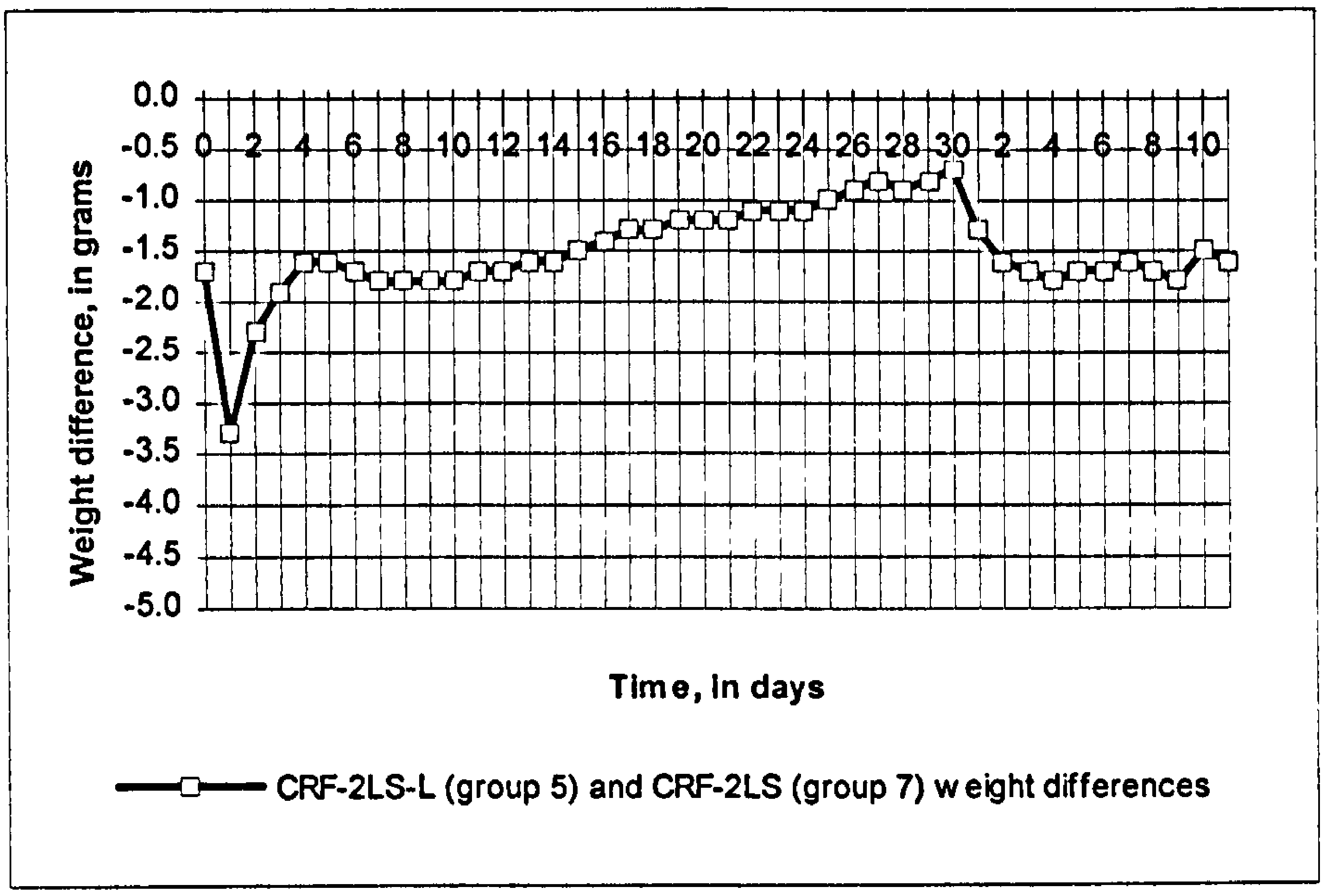


Figure 5.12 Chesters Roman fort samples: weight differences during saturation and drying

The graph in Figure 5.12 above shows the weight differences between a sample from Group 7, and a sample from Group 5. These are samples from Chesters Roman Fort, with and without lichen cover. At the start of the respective tests the weight difference between the samples was 1.7grams, accounted for by the weight of the lichen cover, and the small amount of material loss as a result of the subsequent removal of the lichen. During the saturation part of the cycle the lichen sample initially absorbed more water then the sample without lichen cover, leading to the large difference in weight after the first day. This initial difference can probably be attributed to the re-hydration of the lichen, but whether that is likely or not will be confirmed by the outcome of the penultimate step of this analysis. The weight difference gradually reduced over the following four days. By the eighth day the sample with lichens was saturated, but the sample without lichen continued to absorb water for a further twenty-two days. By the eleventh day the weight difference had returned to the same value as at the start of the test, but the sample without lichens continued to absorb water and so the weight difference continued to reduce. It is significant that at the end of thirty days, when the sample without lichens had also become saturated, the weight difference was less than at the start of the test. This is because although the reference sample was lighter at the start of saturation, it absorbed more water and so was heavier at the end of the saturation cycle. The reference sample had absorbed 8.9 grams, but the lichen sample had gained only 7.9 grams, which included the weight of water required to re-hydrate the lichen.

Over the first four days of the drying phase, drying of the sample with lichens is inhibited by the lichens. The difference in weights rose, until both samples were losing weight at roughly the same rate and the weight difference became, more or less, constant. When both samples had returned to their original weights, the weight difference had returned to the same value as at the start of the test.

The following difference graph is for samples from Laskill Quarry, with and without lichens.

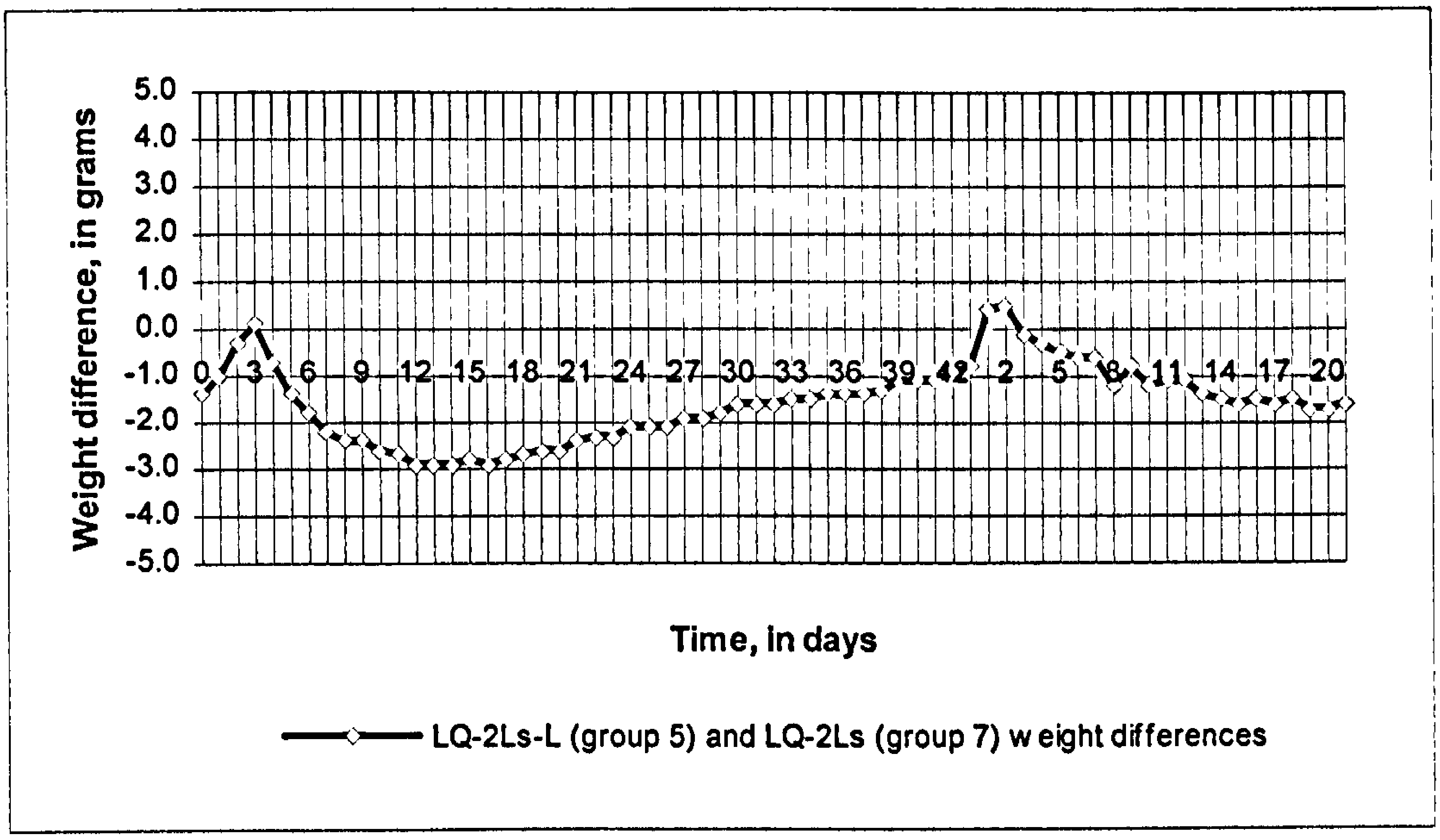


Figure 5.13 Laskill quarry, sample 2: weight differences during saturation and drying

This difference graph, Figure 5.13, shows a trend contrary to that of the Chesters Roman Fort sample. Here the initial weight difference was 1.4 grams. The fall in the weight difference over the first three days of the saturation part of the cycle was attributable to the greater daily up-take of water by the reference sample. Thereafter the sample with lichens consistently absorbed more water per day than the reference sample, until day sixteen, by which time the sample with lichens absorbed no further water. The reference sample continued to absorb water until day forty-three, during which time the difference in weight between the two samples gradually reduced. With these two samples, also, the difference in weights at saturation is less than the initial difference.

In the first day of the drying phase the sample with lichens lost more water than the sample without and hence the weight difference reduced. Thereafter, the sample without lichens lost more water per day than the lichen sample and so the difference in weight rose until both samples were dry. The difference in weights returned to within 0.1gram of the starting difference.

The weight difference between samples with moss cover and with the moss removed show a further trend.

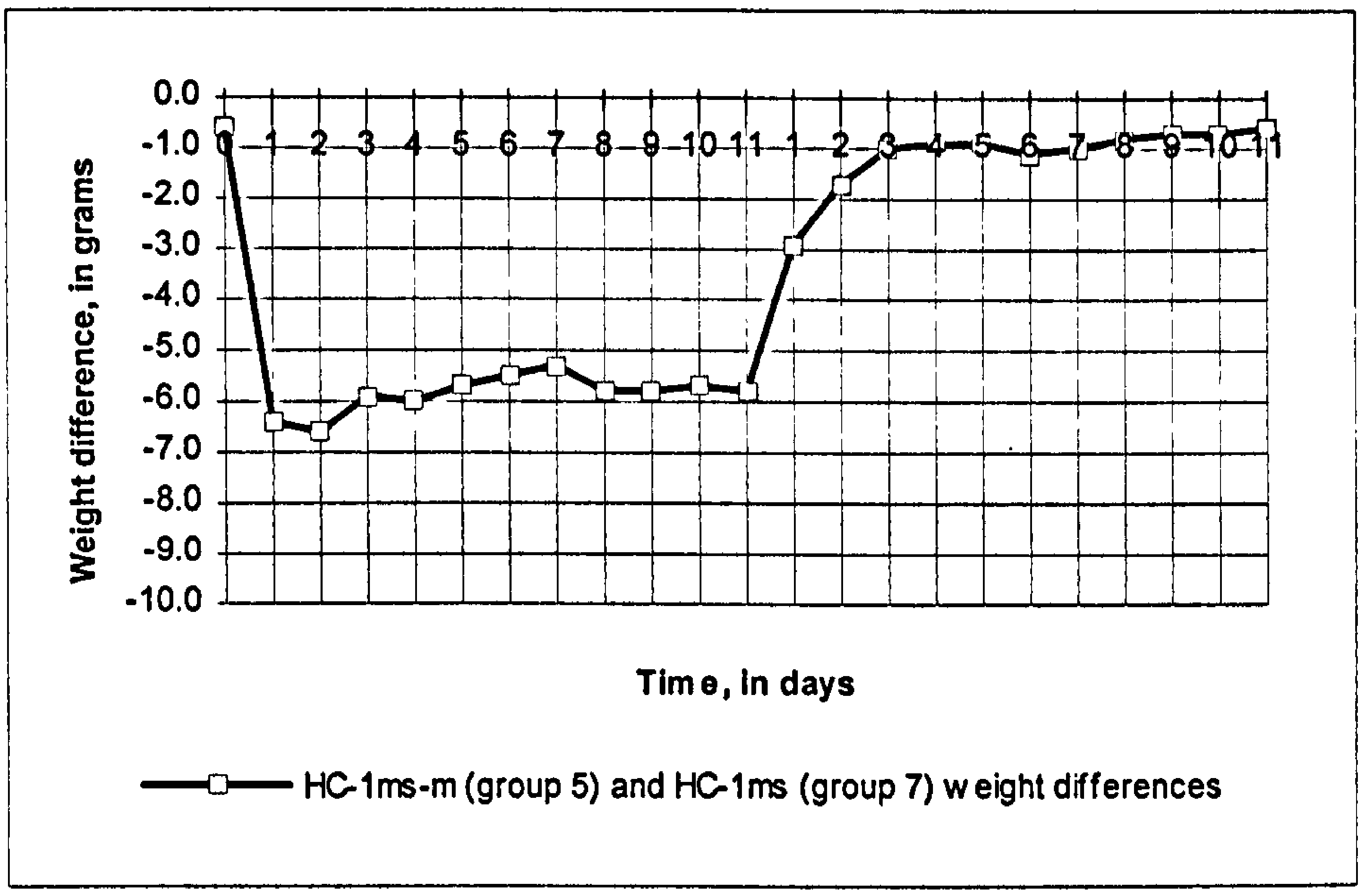


Figure 5.14 Harewood Castle, samples 1: weight differences during saturation and drying

Figure 5.14, shows the weight-difference graph for a sample of Carboniferous sandstone from Harewood Castle, with and without moss. The initial difference in weight of 0.6 grams can be attributed to the weight of the moss cover.

The increase in weight difference of almost 6 grams over the first twenty-four hours, was due to the uptake of water by the moss, on the sample with moss cover. Thereafter, the sample without moss absorbed water at a slightly faster rate than the sample with moss and so the weight difference gradually reduced. Both samples were saturated by the eleventh days.

During the drying phase of the cycle, the daily weight losses from the sample with moss cover were greater than from the sample without and hence the weight difference reduced over the first three days. For the remainder of the drying cycle the two samples lost water at almost the same rate, until both samples had returned to their original weights. Then, the weight difference was the same as at the start of the test.

The pattern of saturation and drying weight differences shown in Figure 5.14 was repeated for all the moss-covered samples tested. Only the abundance of the growths and the porosity of the stone influenced the magnitude of the differences. With the lichen samples more than one pattern of weight difference was encountered. This suggests that a combination of species-form and the pore structure of the stone influence the pattern of water absorption and subsequent evaporation.

It is clear from these results that there is more to the influence of plants on water movement in and out of stone than just the effects on saturation and drying times. It is also important to understand how the two plant groups under consideration affect the rate of water uptake and subsequent evaporation, since the quantities of water involved and their movement over time are critical to the weathering influence of those plant groups.

Analysis of differences in water gains and losses between groups

The next step in the analysis was therefore to analyse the trends which underlie the 'difference' graphs and particularly the mode of water loss. The factors which have been identified correspond to the four phases of the saturation and drying cycle described in Chapter Four. These are:

- The initial rate of water uptake;
- the subsequent rate of water absorption;
- the initial rate of water loss;
- the subsequent rate of water loss

There are three possible outcomes for each of these four phases: plants may increase, decrease, or have no effect on these phases. This is also true of the total saturation and drying times. In addition, the proportion of the effects attributable to the two plant groups, lichens and mosses, was also investigated.

Although the aim was to investigate how the two plant groups influenced water losses, all four stages of saturation and drying were investigated. The results of the analyses of the drying phases are discussed below and the results of the analyses of the saturation phases can be found in Appendix 6. The frequency distributions of the two effects were calculated from the difference graph data and plotted on the two bar charts, which appear below.

In the following narrative, and in the statistical analyses in Appendix 6, the term 'initial water uptake' is used in preference to 'initial water absorption', to signify that it is not necessarily the stone which is gaining weight in the first phase of the saturation and drying cycle – it may be due, either in part, or wholly, to water held by capillary attraction by the plant material.

Groups 4 and 6

Figure 5.15, below, shows the effects of the two plant groups on the two phases of drying and the difference in drying times between the Group 6 and Group 4 samples.

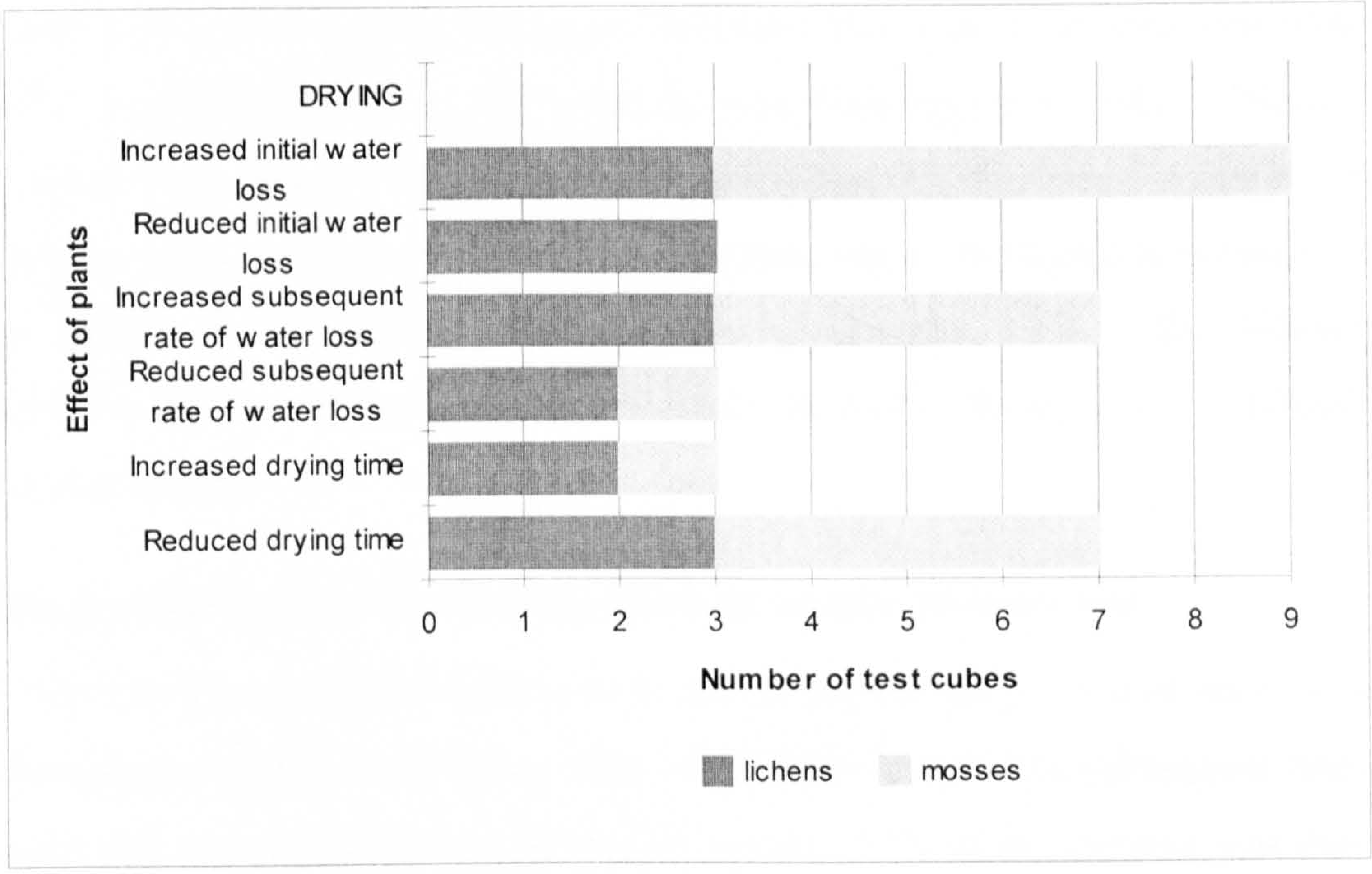


Figure 5.15 Difference between Group 6 and Group 4 samples during drying

Table 5.26 summarises the results of the significance tests on twelve sample-pairs from Group 4 and 6.

Phase of the Saturation and Drying cycle	z score	sig. z
Difference in the rate of initial water loss	−1.790	≤−1.96
Difference in the mean subsequent rate of water loss	−1.129	≤−1.96

Table 5.26 Differences in water losses: analysis summary for Groups 4 and 6

From Figure 5.15 above it is possible to determine why the non-significant differences, shown in Table 5.26, have occurred and what portion of those difference are attributable to each of the two plant groups. While statistical analyses will identify significant difference, there still are clear trends observable within the non-significant differences. Something has to happen to create non-significant differences. That ‘something’ may be significant in itself.

Group 4 and 6 difference in initial water losses

Table 5.26 shows that the difference in water losses over the first twenty-four hours was non-significant. Yet it can be seen from Figure 5.15 that 75% of the samples with plants showed an increased initial rate of water loss compared to the samples without plants. 66% of this difference can be attributed to mosses – all the samples with mosses – and only 33% to lichens. 33% of the difference between the two groups was due to reduced initial drying rates, attributable entirely to lichens.

Group 4 and 6 differences in subsequent mean rates of water loss

Table 5.26 shows that the difference in the subsequent mean rates of water losses was non-significant, although in 58% of the sample pairs the subsequent rate of water loss was increased, largely due to mosses. 57% of the increase was due to mosses and the remainder to lichens. In 25% of the sample pairs, the rate of subsequent water loss was reduced. In 17% of the sample pairs there was no difference in the subsequent rates of water loss.

Group 4 and 6 drying times

The difference in drying times has previously been shown to be significant: the samples with plants took less time to dry than the samples without plants. With this small number of matched pairs of samples from these two groups it can be seen that in 58% of the sample-pairs, the total drying time was reduced. Of this reduced drying time, 57% can be attributed to mosses, and the remainder to lichens. In only 25% of the sample pairs was the difference in drying time increased: 66% due to lichens, 33% due to mosses. In two of the sample-pairs, there was no difference in drying time.

Summary

- There was no significant difference in either the initial rates, or the subsequent rates of water losses between the Group 4 and Group 6 samples; but taken together there was a significant difference in the overall drying time between the two groups, but the reason is still not clear.

Groups 5 and 7

Figure 5.16 shows the differences in the two phases of drying, and the difference in drying times between the Group 7 and the Group 5 samples.

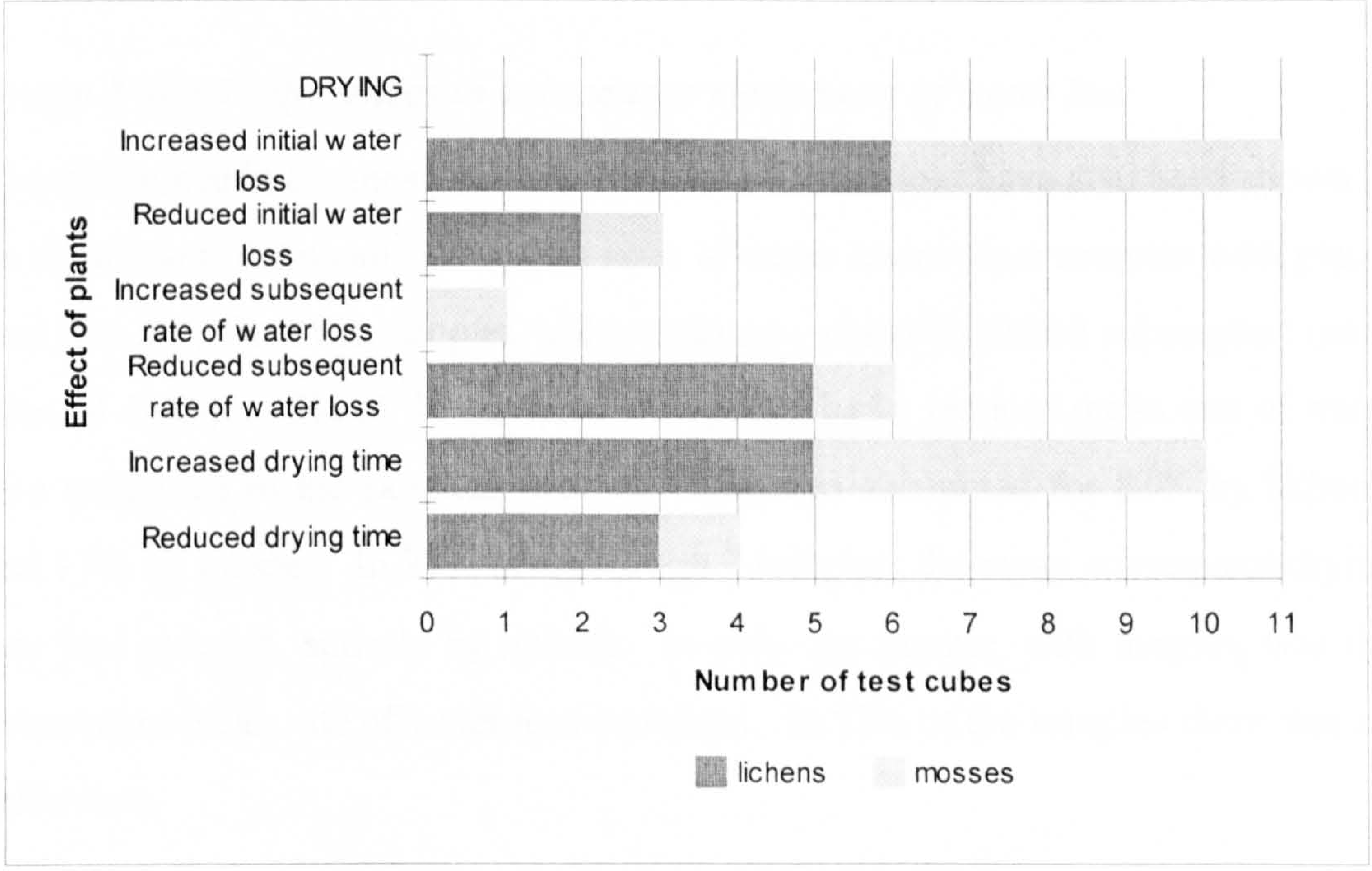


Figure 5.16 Differences between Group 7 and 5 samples during drying

Table 5.27 below summarises the results of the significance test on the Group 5 and 7 samples. Significant results are shown in bold type. Full details of the analyses can be found in Appendix 6.

Phase of the Saturation and Drying cycle	***z* score**	**sig. *z***	***t* value**	**sig. *t***
Difference in the rate of initial water loss	**–2.387**	≥ –1.96		
Difference in the mean subsequent rate of water loss			**2.2**	≥ 2.1

Table 5.27 Differences in water losses: analysis summary for Groups 5 and 7

From Figure 5.16 above it is possible to determine why the significant differences shown in Table 5.27 have occurred. It is also possible to determine what portion of those differences are attributable to each of the two plant groups under consideration.

Group 5 and 7 difference in initial water losses

The difference in initial water losses between these two groups has been shown to be significant. The bar chart reveals why this is so. 73% of the Group 7 samples had a greater initial water loss compared to the Group 5 samples. 54% of that difference was attributable to lichens, 46% to mosses. In only 20% of the samples was there a reduced initial water loss, attributable to lichens and mosses in the ratio 2:1 and in only one pair of samples was there no difference.

Group 5 and 7 differences in subsequent mean rates of water loss

The difference in the mean subsequent rates of water loss have also been shown to be significant; the mean subsequent rates of water losses from samples with plants was less than from the samples without plants – plants inhibited subsequent mean rates of drying. 40% of the samples with plants had a reduced mean rate of water loss compared to the samples without. This was accounted for 83% by lichens, and 17% by mosses. In 27% of the Group 7 samples, the mean subsequent drying rate was reduced, entirely by lichens. In only one sample, with mosses, was the subsequent mean rate of water loss increased. In 53% of the samples there was no difference.

Group 5 and 7 drying times

The overall drying time of the Group 7 samples, compared to the Group 5 samples has already been shown to be significant. Figure 7 indicates that in 67% of the samples the drying time was increased by plants, and in only 27% of the samples was it reduced. The significant increase in drying time can be attributed 50-50 to mosses and to lichens, but the reduced drying time can be attributed only 25-75. In only one sample-pair was there no difference in overall drying time.

Summary

- The differences between the initial, and subsequent rates of water losses between the Group 5 and the Group 7 samples were both significant;
- the Group 7 samples initially lost water faster than the Group 5 samples, due to water losses from the plants, but the subsequent rates of drying were inhibited to a greater degree by the lichens than by the mosses. This resulted in the significantly increased drying times of the Group 7 samples – this is an important finding, and will be discussed further in the next step on the analysis.

Analysis of water uptake and evaporation from lichens and mosses

The water uptake and subsequent evaporation from lichen and mosses was tested by subjecting specimens of these two plant groups to a saturation and drying test. The results would reveal whether the weight differences observed in the previous subsection could be accounted for by the corresponding increases and decreases in the weights of the plant material alone.

Four species of lichens and three species of mosses were tested. The lichen species, *Phaeophyscia orbicularis*, *Xanthora parietina*, *Parmelia caperata* and *Parmelia saxatalis* are all broadly classed as foliose species, but the majority of the species on the stone samples tested in this research were crustose species. The terms crustose and foliose are broad classifications which describe the habit of the species and a fuller description can be found in the Glossary. The consequence is that the test specimens may absorb more water than the species on the test cubes.

Included with each time-series graph for the tests on lichens is a table which shows the measured surface area of the specimen, the total weight of water absorbed and the cube-equivalent absorption, which is the weight of water that a specimen could be expected to absorb if it covered one face of a test cube. This enabled a direct comparison to be made between the weight differences of pairs of test cubes during saturation and drying. It also enabled comparisons to be made between specimens.

Two of the moss species tested, *Brachythesium rutabulum*, and *Hypnum* spp., comprised the moss mats removed intact from the Duncombe Park and Harewood Castle samples, respectively. Due to difficulties encountered in handling these specimens when wet, they were saturated, and then tested for drying time only. A further species, *Bryum capillare*, was also tested, and because of its larger size and compact habit, was tested for saturation *and* drying time.

The data generated by these tests is included in Appendix 6 along with the time-series graphs which were plotted from the data.

Results 1: lichens

Of the four species tested, *Phaeophyscia orbicularis* was the one which can most closely be likened to the crustose species on the test cubes of Groups 6 and 7. This is because it has a thin thallus and a prostrate habit, being more closely adpressed to the substratum than most foliose species. The result of this is that there is a minimum amount of air space between the underside of the thallus and the substratum and a minimum amount of airspace between the 'branches' of the thallus, both of which could be available for water uptake by capillarity. Crustose species, by comparison, tend to have very thin thalli, with the medulla enmeshed within the superficial pore structure of the stone. Foliose species tend to trap organic debris under the thallus, which may affect both the apparent total weight of water absorbed by the lichen, and the drying time.

It is evident from the time-series graphs for *Phaeophyscia orbicularis* that the thallus became saturated after the first day of immersion in water and subsequently lost all the absorbed water within the first day of drying. The average cube-equivalent weight of water absorbed by the two specimens of this species was 1.35 grams. If this figure is compared to the mean difference, of −1.3 grams between the Group 5 samples, and Group 7 samples with lichens after the first day of saturating, it can be seen that the lichens inhibited water uptake. If the converse had been true, a mean gain in excess of +1.35 grams might have been expected. It is worth noting, however, that the more foliose species tested took a greater time to saturate, but it cannot be predicted, from the small samples of *Phaeophyscia orbicularis*, that if they were of the same surface area as one face of a test cube, that they would still saturate within twenty-four hours; nevertheless, the disparity between recorded mean initial differences in weights of the two groups of samples pairs and absorption of the lichen specimens themselves, suggests a significant difference, despite the statistical analysis of the groups' differences indicating a non-significant difference.

The statistical analysis of the initial rate of drying, however, indicated a significant difference; the samples with plants lost more water in the first twenty-four hours than those without. The test on *Phaeophyscia orbicularis* showed that all the absorbed water was lost within the first day. Only the larger samples of the more foliose species tested took more than one day to return to their original weight. The mean weight losses from *Phaeophyscia orbicularis* was 1.35 grams. But the mean initial weight differences between lichen samples in Groups 7, and corresponding samples in Group 5, was only 0.4 grams. There could be more than one reason for this result. It could be that the lichen species on the test cubes absorbed less water than the lichen specimens now under consideration. It could be that the lichen species on the test cubes inhibited water loss to a far greater extent than the statistical analysis would suggest. The first of these propositions can easily be tested by examining the mean difference in total water gains between Group 7 samples with lichens, and the corresponding Group 5 samples. This mean difference was calculated to be 0.1 grams. This suggests that in fact both propositions are true, since the mean excess weight of absorbed water is virtually nil and so the samples with lichens have virtually no excess water to lose during drying. This suggests a greater significance for both the increased subsequent rate of drying and for the increased overall drying time of the Group 7 samples; however, it does not explain the increased initial rate of water losses of the Group 7 samples. This may be due to the moss samples in the groups, and might be revealed by examining the pattern of water gains and rates of water loss from the moss specimens themselves.

Summary

- It is likely that the lichens on the test cubes inhibited initial rates of water absorption;
- it is likely that the lichens of the test cubes lost all their absorbed water in the first twenty-four hours of drying;
- water uptake by lichens was negligible compared to the total water absorption of the test cubes;
- lichens probably inhibited drying of the test cubes to a greater extent than the statistical analysis would suggest.

Results 2: mosses

The time-series drying graphs of the moss specimens can be found in Appendix 6. The differences in the water losses between reference and test samples and the corresponding losses from their respective moss-mats is shown in Table 5.28 below.

Sample	**Difference in losses between test, and reference cubes**	**water lost from moss specimen alone**
DP3L-1ms	8.9 grams	9.4 grams
DP3L-2ms	7.6 grams	10.3 grams
HC-1ms	5.1 grams	7.4 grams
HC-2ms	5.8 grams	7.8 grams
Mean	6.9 grams	8.7 grams

Table 5.28 Losses from test cubes compared to water losses from moss specimens

It can be seen from Table 5.28, by comparison of the mean values, that there is a discrepancy between the differences in losses from the test cubes, and the losses from the moss specimens. This can be accounted for by the manner in which the test cubes were treated to remove excess water from the moss mat at the end of the saturation phase, described in Chapter Four. The consequence is that the weight of water held within the moss-mat on the test cubes was artificially low, compared to that of the moss specimens alone. If this is the case, then the difference in the losses, and the gains, between test and reference cubes is entirely due to the weight of water absorbed into the moss-mat – that is entirely to be expected.

The question remaining is to what extent mosses inhibited drying of the test samples. The statistical analysis has shown that the Group 7 samples took a significantly longer period to dry from saturated than the Group 5 samples, and within Group 7 were five test cubes with mosses. Table 5.29 shows the comparative mean drying times of the moss specimens, sample cubes with mosses, and the corresponding reference cubes.

Samples	Mean drying time
Moss specimens	7.5 days
Test cubes with mosses	15 days
Reference cubes	12 days

Table 5.29 Losses from moss specimens, test cubes with mosses, and reference cubes.

From the figures in Table 5.29, it can be concluded that mosses had only a marginal effect of the drying of the test samples, because their mean drying time was less than the combined time of the moss specimens and the reference samples and because Figure 5.16 showed that most of the water gained by the moss was lost in the initial stage of drying.

Samples with mosses and lichens, as a group, have been shown to have a statistically significant effect on the drying time of stone sample cubes. But there are important distinctions to be made regarding the contribution of the two groups of plants. The samples with lichen had very little excess water to lose compared to the reference samples, but had a longer mean drying period. The samples with mosses had a large amount of excess water to lose, but had a similar mean drying period to the lichen samples. This suggests that mosses are less effective at inhibiting water evaporation from stone than lichens and that is an unexpected outcome. If mosses had no excess water to lose they would have little effect on drying times, and so in situations where the principle moisture supply to stone is other than through the plant layer, from groundwater for example, mosses would have no effect on drying times, but lichens would.

Summary

- The difference in weight between test cubes with mosses and the corresponding reference cubes can be accounted for by the weight of water taken up by the moss;
- the sum of the mean drying time of the moss specimens and the mean drying time of the reference cubes was greater than the mean drying time of the test cubes with mosses. This indicates that excess water within the moss mat is evaporating concurrently with water within the stone.

Re-evaluation of the test design

The foregoing results have shown why the significant difference in drying times between Groups 5 and 7 occurred. It has not been possible to explain why the Group 6 samples dried faster than the Group 4 samples – an analysis of the influence of the two plant groups has not provided the answer. It may be possible to provide an answer by examining why the Group 4 samples, without plants, dried more slowly. This involves 'unpicking' the test design and analysing the sample composition of Group 4.

The samples in Groups 5 and 7 were always considered as matched pairs, with and without plants in the test design and in the subsequent analyses of the results. The samples in Groups 4 and 6 were never considered as matched pairs, but have been dealt with as unrelated groups of random samples. As such, the analyses of the data and the results are still valid and the significant difference in drying times between them can only be seen as valid within those parameters.

The sample composition of Group 4 can be analysed to determine why that significant difference occurred. This can be achieved in two steps:

- Remove the samples from Group 4 whose stone type was not represented in Group 6 and re-test the drying time frequency distributions for significance;
- remove from both groups samples which were not matched by stone type and re-testing the drying time frequency distributions for significance.

In the first step, seven samples were removed from Group 4, leaving twenty-four in each group. The result of the significance test, using the Mann-Whitney test, gave a *z* score of –1.570. This is greater than the critical *z* value –1.960 for a two-tail test at the 0.05 level of significance and so the difference in drying times was then non-significant. The reason why this has happened can be seen by examining the drying times of the seven samples and comparing the mean with the mean drying time of the new Group 4 samples. The mean drying time of the seven samples was higher than that of those remaining in Group 4 and so it can be concluded that they artificially raised the mean drying time of the original group.
In the second step, twelve further samples were removed from Group 4 and twelve from Group 6, leaving twelve matched pairs, with and without plants. The results of the significance test using the Wilcoxon test gave a *z* value of –0.261. This is greater than the critical value of –1.960, for a two-tail test at the 0.05 level of significance and therefore the difference in drying times is non-significant.

Samples removed from Group 4 had a mean the same as those remaining in the group, but the samples removed from Group 6 had a mean less than those remaining in that group. The effect would be for the mean drying time of Group 6 to be lower than Group 4 had the samples not been removed.

There is one further consideration. If a straight line graph is plotted, of percentage plant cover of the samples tested, against percentage increase in drying time of samples with plants, the first point on the graph would be 0,0, because no cover means no difference in drying time for a particular stone type. The other point on the graph would be 100,16.1, because 100% plant cover resulted in a 18.75% difference in drying time between Groups 5 and 7. This assumes that the relationship is linear and, if it is, a prediction can be made about the difference in drying times to be expected between the Group 4 and Group 6 samples, which have only 16.7% plant cover. The result is illustrated in Figure 5.17, below.

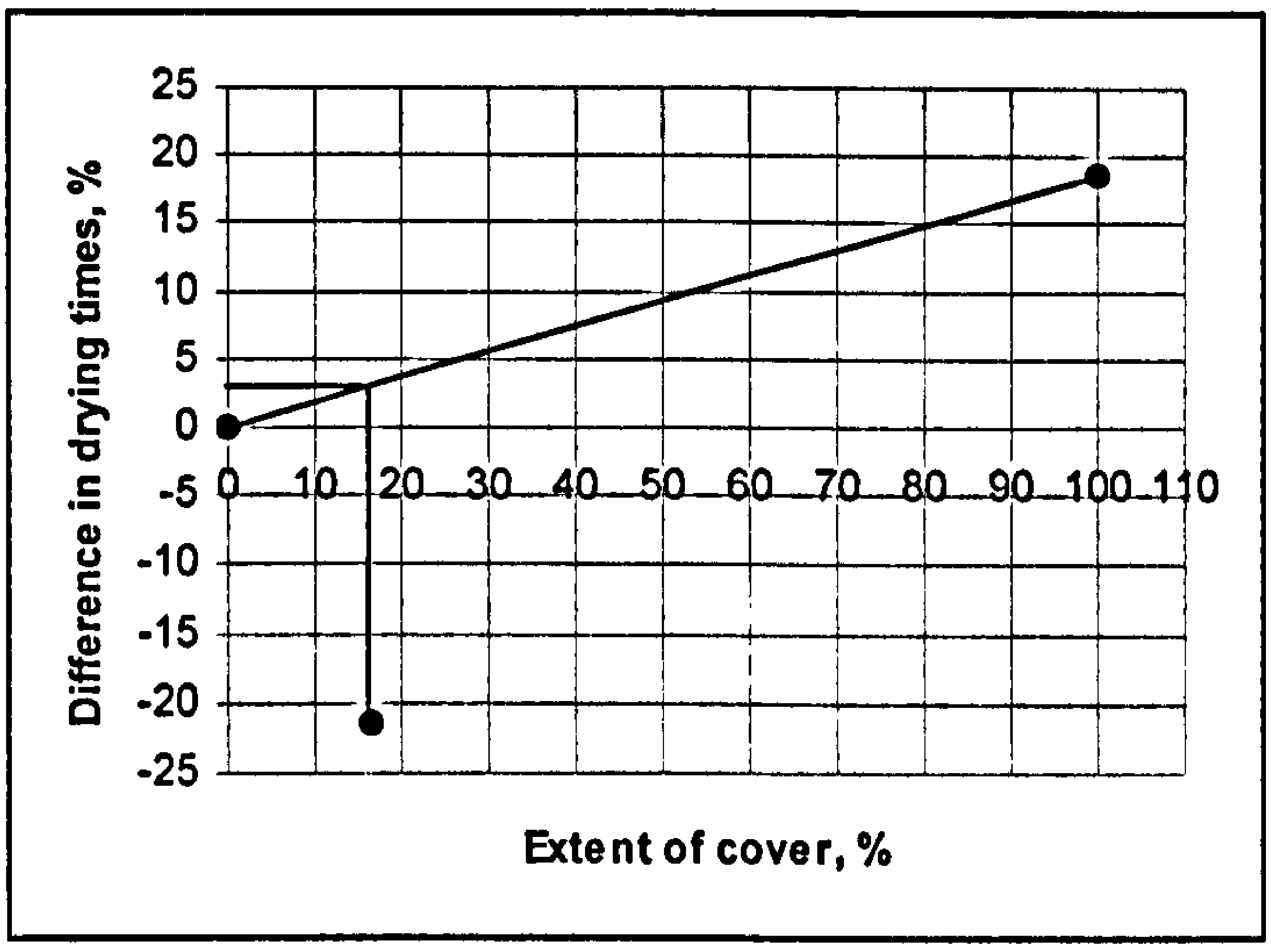


Figure 5.17 Sample Groups 4 and 6: drying time difference prediction

The predicted value can be seen to be about 3.0%. This can be compared to the percentage difference calculated for the original Groups 4 and 6, of –22%, the modified Group 4, of 14.3%, and Group 4 and 6 comprising twelve matched pairs, which had a difference of 5.4%, neither of which proved to be significant – they could have occurred by chance. Whether the 5.4% difference or even the 18.75% difference is within the limits of experimental error can only be determined by further test on matched pairs of samples. This will also reveal whether the relationship is linear or curvilinear. All that can be said for now, is that the original analysis of the drying times of the Group 4 and 6 samples failed to provide the predicted result because of lack of homogeneity between the stone types within the two sample groups.

PART 3 SUMMARY

- Plants had no effect on saturation times; they were found to be virtually transparent to the passage of water into stone;
- Plants had a significant effect on drying times, although the two sets of results were contradictory; it was subsequently established that the results were not directly comparable. The outcome was that plants increase drying times

significantly, irrespective of the weights of water which they take up during saturation;

- the uncontrolled variables in the tests have not invalidated the results;
- Lichens were found to be far more effective at prolonging drying times than mosses and that is an important finding.

CONCLUSIONS

The results of the tests discussed in this chapter have shown that the critical issue is not whether lichens, or mosses for that matter, provide a protective covering to stone surfaces – that theory is now largely disproved by the results of the four saturation and drying tests. The critical issue is that lichens have the capacity to inhibit water losses from stone and some species are unaffected by low pH water. The implication of this is that vulnerable stone types, such as those with high porosity and mineralogies soluble in acid rain, particularly carbonate-cemented sandstones, become doubly vulnerable in the presence of lichen colonisation, where acidic waters may be inhibited from drying. The extent of colonisation is a critical factor, because the greater the extent of cover, the greater will be the drying time, and the greater will be the potential for dissolution of carbonates in the stone.

This chapter has investigated the results of tests at individual sample level, in order to investigate the physical properties and weathering characteristics of the stone types under consideration. Only an examination of the case study sites will reveal the implications of those results and this will be achieved by focusing on three key aspects:

- The extent of visible decay of the masonry;
- the extent of plant colonisation of the masonry;
- the potential for acid rain to be a major component of weathering.

CHAPTER SIX

CASE STUDIES

INTRODUCTION

Those three key aspects of the case studies, highlighted at the end of the last chapter will be investigated in relation to four sites, which constitute the three case studies considered in this chapter. These sites are:

- The two temples at Duncombe Park near Helmsley, North Yorkshire;
- Rievaulx Abbey, also near Helmsley, North Yorkshire;
- Slingsby Castle, to the west of Malton, North Yorkshire;
- Harewood Castle, to the north of Leeds, in the West Riding of Yorkshire, which together with Slingsby Castle comprised a single case study.

The general criteria for the selection of the case study sites was set out in Chapter One and the detailed aims and objectives are described with each case study. The particular characteristics of these sites and their potential for investigation is described below.

The temples at Duncombe Park are in private ownership and there is extensive weathering to their masonry with associated lichen flora. The cause of this weathering is unknown and there was scope within this case study to investigate whether there is a causal relationship between the masonry decay and the lichen colonisation.

Rievaulx Abbey is a property in Guardianship, built of several different stone types, and has in the past undergone extensive consolidation and repair; consequently, there is now little evidence of active weathering, but there is an extensive lichen flora. The investigation in this case study focused on the relationship between the different stone types and their degree of lichen colonisation. This enabled a risk assessment method to be developed which related the weathering characteristics of the stone types to the degree of lichen colonisation and hence the risk of lichen colonisation increasing the potency of other weathering mechanisms.

Slingsby Castle and Harewood Castle are both in private ownership and have been neglected for much of the twentieth century. They have contrasting degrees of weathering and lichen colonisation and are built of different stone types. This case study provided the opportunity to compare the regional significance of the lichen flora and the relative risk which it posed to the respective stone types.

An investigation of the levels of atmospheric sulphur dioxide pollution at the case study sites was a continuing theme throughout all three case studies. It was carried out to determine whether atmospheric sulphur dioxide is a significant cause of weathering at these sites. A method was developed whereby the lichen flora of the four sites could be analysed to provide an indication of the direction of change in atmospheric pollution levels, because that is important in considering the level of weathering risk to the masonry at these sites, particularly when lichens are present.

PART 1 – THE TEMPLES AT DUNCOMBE PARK

INTRODUCTION

Geographical location

Duncombe Park lies one kilometre to the south-west of the North Yorkshire market town of Helmsley, which is situated on the north-western edge of the Vale of Pickering. Duncombe Park, its house and its designed landscape is located on high ground above meanders in the river Rye, as shown in Figure ap9.3 in Appendix 9.

Background

The two temples at Duncombe Park are not ruins in the same sense as are neighbouring Helmsley Castle, or the nearby Rievaulx Abbey; nevertheless, they were considered important enough to include as a case study, because they exhibit severe stone decay, particularly to their columns, with associated extensive lichen and algal growths. The cause of this decay has exercised several eminent minds in the past, and a verifiable diagnosis has yet to be proposed. The search for that diagnosis has guided the direction of much of this research.

Initial observations, photographic and measured recording on the Tuscan Temple, included in Appendix 9, were made over several visits early in 1998. This was followed by many further visits to both temples over the course of the two years following, as the research method was developed. Unrestricted access to the temples was provided for this research by kind permission of Lord and Lady Feversham, the present owners of the Estate, to whom the writer is greatly indebted.

Aims and objectives

The aims

- To establish a theoretical framework for the investigation of the cause of the decay of the columns on the temples;
- to record the areas of botanical colonisation on the columns;
- to identify the species present;
- to locate the source of any previous lichen surveys of the area;
- to record the areas of stone decay of the columns;
- to record the surface moisture contents of the columns;
- to record the surface temperatures of the columns;
- to locate the source of the stone used in the construction of the temples.

Objectives

- To determine the physical properties and weathering characteristics of the stone – described in Chapter Five;
- to determine the extent to which the botanical growths might be implicated in the weathering processes;
- to provide a diagnosis for the decay, and to relate that diagnosis to the findings from the results of the laboratory analyses.

HISTORICAL OVERVIEW

The house at Duncombe Park is one of the most important English Baroque houses in Northern England. It is ascribed to William Wakefield, whose work was influenced by Sir John Vanbrugh and was built for Sir Thomas Duncombe in about 1710.

It is clear that the site was chosen for its landscape potential. A curved, turfed, terrace was formed on elevated ground, with contrived views down the steep valley sides to the river Rye below and to the surrounding countryside, including Helmsley Castle. The terrace is backed by woodland, so as to isolate it from the house, except for a broad opening on the axis of the house; this gives access to the terrace by way of a garden. The layout of the terrace, and the design of the views, is in the tradition of the Picturesque, and at each end of the terrace, stands a temple on a promontory, from which there are also contrived views into the surrounding countryside. At the north end stands the Ionic Temple and at the south, the Tuscan Temple.

The woodland, much of which was planted at the time the grounds of the house were laid out, is now considered to be of exceptional ecological significance, due to its age and the diversity of wildlife for which it provides habitat. The Rye valley and associated steep, wooded banks, now constitute a Site of Special Scientific Interest, notified in 1985 under section 28 of the *Wildlife and Countryside Act 1981*, (HMSO 1981). It covers an area of 117.8 hectares and is noted for certain species of beetles associated with the broad-leaved woodland, and species of mayflies and stoneflies. The site is also a National Nature Reserve, designated under section 35 of the *Wildlife and Countryside Act 1981*. The Estate is still in the ownership of a descendant of Thomas Duncombe.

THE TEMPLES

Built Forms

The Tuscan Temple

The Tuscan Temple is located at Ordnance Survey grid reference SE 607826, is circular, with sixteen peripteral, un-fluted stone columns with Tuscan capitals supporting a frieze and cornice. It has an inner stone drum which has a lead-clad domed roof, enclosing one room containing three windows and one door opening. The temple dates from 1730s, is listed Grade I, and is attributed to Sir Thomas Robinson. Figure ap9.4 in Appendix 9 illustrates this temple, viewed from the Terrace.

The Ionic Temple

The Ionic Temple is located at Ordnance Survey grid reference SE 606831, is an open rotunda, without a solid core, comprising ten un-fluted Ionic columns supporting a frieze and cornice, surmounted by a lead-clad domed roof. It also dates from 1730s, listed Grade I, and is attributed to Sir John Vanbrugh. The Ionic Temple is illustrated in Figure ap9.5 in Appendix 9.

Condition of the stone

Visible decay

The visible decay of the columns is in the form of extensive surface spalling, and of surface blister formation. The surface decay on each column is spread over roughly half the column perimeter. The surface blisters appear in association with botanical growths. At the times of inspection, there has been no visible evidence of either efflorescence or subflorescence and only one isolated instance of what analysis may prove to be a reaction product of acid rain. Similar patterns of decay can be seen on the Ionic Temple. These decay patterns are illustrated in Figures ap9.6 and ap9.7 in Appendix 9.

Botanical Growths

Visible botanical growths are evident on the outer surfaces of the columns, illustrated in Figure ap9.8. With the help of Don Smith, a member of the British Lichen Society, over a dozen conspicuous species of lichen were identified, along with a widespread covering of an alga of the genus *Trentepohlia.* A typical area of lichen colonisation is illustrated in Figure ap9.8 in Appendix 9. Details of the lichen survey can be found in Appendix 8 and the implications of the species present will be discussed later in this case study. Similar distributions of botanical growths were evident on the Ionic Temple and appeared to be of the same species composition as the Tuscan temple.

The extent of botanical growths and areas of stone decay on the columns of the two temples are indicated on the plans, shown in Figures ap9.9 and ap9.10 in Appendix 9, based on survey information gathered by the writer during site visits in 1998 and are consistent throughout the height of the columns.

Repair history

There is evidence of past stone repairs on the temples, most notably on the columns and the inner drum of the Tuscan Temple. Here, a skim coat has been applied to the decayed surfaces. The material, probably neat Portland cement, is hard, dense, brittle, fine-grained and charcoal-grey in colour but with no obvious evidence of an aggregate. There is also evidence of an applied surface coat of colour which roughly matches the stonework. The samples taken from the drum of the temple were two millimetres thick, but repairs to the columns can be seen to be as much as 25mm thick.

These repairs were probably carried out during the 1920s, although there is no documentary record to support that view. The repairs have, regrettably, accelerated the decay of adjacent areas, probably because of their impermeability. It is possible that water has entered through the porous stone and become trapped behind the impermeable repair, where damage by frost, salts or acid rain, or a combination of the three, has probably resulted in a rapid loss of original material. The consequences of this kind of inappropriate repair are highlighted in many major texts on stone repair, for example: Ashurst and Dimes (1990); Feilden (1996); Price (1996).

In 1996, there were proposals by Martin Stanclifffe Architect of York to dismantle and reconstruct the Ionic Temple, but the level of intervention was considered unacceptable and it was decided that repair was a more realistic option. In 1998, the Ionic Temple appeared on the English Heritage Buildings at Risk register and was noted as 'Slowly decaying; no solution agreed.' (English Heritage 1998, p.VII and 114). But in 2000, trial repairs were started on one of the columns by Carthay Conservation of London. The repair method involved the application of a lime mortar render, using aggregates to match the colour of the stone, applied to a series of stainless steel armatures resined into holes drilled in the stone. This enabled the original surface profile of the columns to be restored. After only a short while on site, the repair was abandoned, because the stone was considered too soft to support adequately the armatures. The present situation is that the stonework will receive a lime-based shelter coat to bind the friable surfaces. The condition of the columns, and the structural stability of the temple, will be monitored on a regular basis. The temple remains on the Buildings at Risk register (English Heritage 2001).

Previous investigation

There is no previous report relating to the cause of the stone decay of the Tuscan Temple; however, there is a geological report relating to the almost identical pattern of stone decay of the Ionic Temple (Senior 1996) and from which the following account is drawn and which makes a useful starting point for *this* investigation of the causes of the decay.

Petrology

The stone is Upper Jurassic, from the Corallian series of fine-grained Middle Calcareous gritstones, with up to 15% bioclastic inclusions (Senior 1996) – sand produced by the weathering of older rocks, with fossil shells, loosely bound with more recently precipitated calcium carbonate. The result is a relatively weak, porous rock.

Findings

The report concludes that the cause of the decay is chemical weathering, due to sulphur dioxide fall-out from power stations to the south. This dissolves any calcium carbonate in the stone, and forms calcium sulphate, which either crystallises below the stone surface causing surface disintegration, or forms characteristic crusts on the stone surface. A contributory cause of the stone decay is the incorrect bedding of the stone; the stones are set with the bed face vertical and not horizontal (Senior 1996).

There is evidence, in the form of visible fossil shells, to support a supposition that the stone from which the columns of the Tuscan Temple are built is similar to that of the columns of the Ionic Temple; consequently, the comments on petrology can be considered applicable to both temples.

LOCAL GEOLOGY

Senior, in his geological report, identified the stone type from which the Ionic Temple was built as Middle Calcareous Grit from the Corallian Series of the Upper Jurassic (Senior 1996). But a knowledge of the local stratigraphy is essential to the identification of the source of that stone.

The geological survey shows that the Rye valley broadly comprises sandstone capped by limestone (British Geological Survey 1909). So the stone used in the construction of the temples had been quarried from the lower beds and the location of places where those beds are exposed was a necessary in order to obtain samples for laboratory testing.

On-site investigation at possible quarry sites, located with the aid of the Ordnance Survey 1:10,000 map of the area (Ordnance Survey 1981a), confirmed that the highest beds, just below the surface of the plateaux upon which the temples and the house is built are composed of a dense, hard, limestone with fossil remains. The lower levels of this limestone capping appear to become increasingly fossiliferous until the rock lower down the sequence becomes oolitic. Lower still, the first sandstone bed has the bioclastic inclusions which Senior describes. It is this bed which forms the second lowest accessible stage of the sequence, from which some of the stone for the temples may have come. The lowest accessible bed, only a few metres above the river flood-plain is similar to the bed above, except that no evidence of bioclastic debris was found, but instead the rock has hard, nodular, inclusions which, after laboratory tests, proved to be of calcium carbonate. There is evidence in the weathering forms of some of the columns of the Ionic Temple that stone from this level was also used.

Quarry sites

The locations of the sites which were investigated are indicated in Figure ap9.11, in Appendix 9. Each site was given a reference number and in Table 6.1 which follows, the descriptions of the stone are based upon examination of test cubes prepared from samples from each site.

Ref.	Grid reference	Stone description
1	SE 6050 8207	Dense limestone, fossil-free
2, upper	SE 6055 8345	Dense limestone with fossils filled with crystalline calcite
2, lower	SE 6055 8345	As above but greater abundance of fossils
3, upper	SE 6095 8325	Calcite-cemented sandstone with clastic debris
3, lower	SE 6095 8325	Calcite-cemented sandstone with calcitic, nodules
4	SE 6055 8285	Dense, shelly oolite
5	SE 6145 8330	Dense limestone with thick crystalline calcite veins

Table 6.1 Duncombe Park quarry sites

There seems little doubt that the stone from which the temples were built came from quarry site 3, or a similar, no longer evident, site further along the banks of the Rye. A track from a meadow on the river flood-plain still exists, which leads to the upper level of the park. This track passes directly below quarry site 3, and stone could easily have been hauled up this track to the level of the terrace above.

Sampling methods

Once the source of the stone had been identified with reasonable certainty, the sampling procedure was relatively simple. Three principal criteria were used in the selection of samples: they should be easily transportable; they should match the stone types for that quarry; they should be randomly selected.

Generally, pieces of stone which are of a size and weight which can be carried by one person are found on the quarry floor. But their origin within the geological sequence has to be established. This was achieved by breaking these pieces with a small hammer and comparing the fresh fracture with fragments of stone which had earlier been found on the plinths of the two temples. Some of these fragments comprised part of the group of samples subjected to the trials of the laboratory tests, described in Appendix 1. Small samples had also been taken from higher up the sequence and so it was relatively simple to establish the provenance of any particular piece under consideration.

The area between the edge of the flood-plain of the river and the quarry face is one of dense tree cover, and so light levels are relatively low, despite the southerly aspect. As a consequence, lichens do not thrive and no suitably-sized samples with lichen cover were found, even after several visits; however, the conditions favoured mosses and so several moss-covered samples were taken for laboratory analysis.

Stone characteristics

The results of the laboratory test on this stone type were set out and discussed in the last chapter, but it is worth repeating the key aspects in the context of this case study.

Characteristics	Quarry 3, upper	Quarry 3, lower
Mean density	2.0g/cc	1.7g/cc
Mean open porosity	18.0%	25%
Mean capillary rise time	0.45 hours	0.29 hours
Pore volume <5µ	not tested	32%
Freeze/thaw resistance	Poor	Poor
Soluble salts resistance	Poor	Poor
Acid rain resistance	Poor	Poor

Table 6.2 Duncombe Park, quarry 3: stone properties and weathering characteristics

Test cubes from this quarry had the second-fastest capillary-rise time of all the samples tested and the porosimetry results confirmed that there was a high proportion of pores less than 5 microns wide. Test cubes from this quarry performed third worst in the freeze/thaw test, based on percentage weight loss per 100 cycles, of the ten case-study stone types tested and second worst in the salts test, based on percentage weight loss per fifteen cycles. Test cubes from this quarry also scored second worst, when immersed in 5% sulphuric acid for fourteen days. These results indicate that the stone from this quarry is of low durability and it is quite possible that weathering could be caused by the most benign effects, such as moisture gradients within the stone (Snethlage and Wendler 1997) which were discussed in Chapter Three. These gradients could be induced by the lichen flora, but chemical weathering effects produced by acid rain could also be implicated, as suggested by Senior.

THEORETICAL BASIS FOR SITE INVESTIGATION

It is a well known phenomenon in human physiology that the evaporation of perspiration from the skin causes cooling and helps maintain normal body temperature, especially in hot weather. It may be supposed that the same cooling effect must be present as water evaporates from stone. If this effect can be detected, and measured in the field, it may give an indication of areas where water is evaporating from the surfaces of the columns of the temples. The aim was, then, to establish the correlations between areas of low surface temperature, moisture content, decay and areas of botanical growths. The objective was to investigate whether the capacity of lichens to inhibit water evaporation from stone, which was established by laboratory tests and discussed in Chapter Five, could be detected in the field and be implicated in the decay of the columns of the temples.

Before measurements on site were attempted, the theoretical basis for the fieldwork was investigated to determine if the cooling effect of water evaporation from stone was of a magnitude which could be measured.

Support by calculation

Evaporation is defined as the change of state from liquid to a gas. Latent heat is required to change a liquid to a vapour at the same temperature. The latent heat is absorbed from the surface from which the liquid evaporates (Nelkon 1974). There should, therefore, be a basis in physics upon which the effects of evaporation of a liquid from a surface can be determined; the change of temperature should be quantifiable.

The theoretical basis of a predictive calculation would be that the heat required to evaporate unit mass of water at a given temperature is equal to the heat lost by the surface from which the water is evaporating. The following information is required to perform this calculation.

- The air temperature;
- the specific latent heat of water at the prevailing air temperature, because the rate of evaporation is dependent on the saturated vapour pressure of the air,

therefore more latent heat is required at lower air temperatures, or higher relative humidities;

- the specific heat capacity of the stone.

The unknown in an equation based on the above variables is the final temperature of the stone surface from which water is evaporating, assuming steady state conditions exist.

It is, therefore, possible to calculate the temperature drop of the stone surface under any given set of conditions, with a stone type of known specific latent heat.

Support by laboratory experiment

The purpose of the following experiment was to determine the extent to which the surface temperature of a sample of stone fell below air temperature as water evaporated from its surface.

Method

Two samples, in the form of 40mm cubes, were immersed in water for twenty-four hours, then removed from the water and placed in a petri dish. The cubes were arranged side-by-side and an electronic temperature sensor was sandwiched between two adjacent vertical faces of the cubes. This enabled the surface temperature of the cube faces to be measured. The air temperature and relative humidity were also measured. The surface moisture content of one of the cubes was also measured using a digital Protimeter.

The sample was allowed to dry at room temperature and the surface temperature, air temperature, relative humidity and moisture content were recorded at thirty-minute intervals over an eight hour period.

Results

Figure 6.1 shows the results.

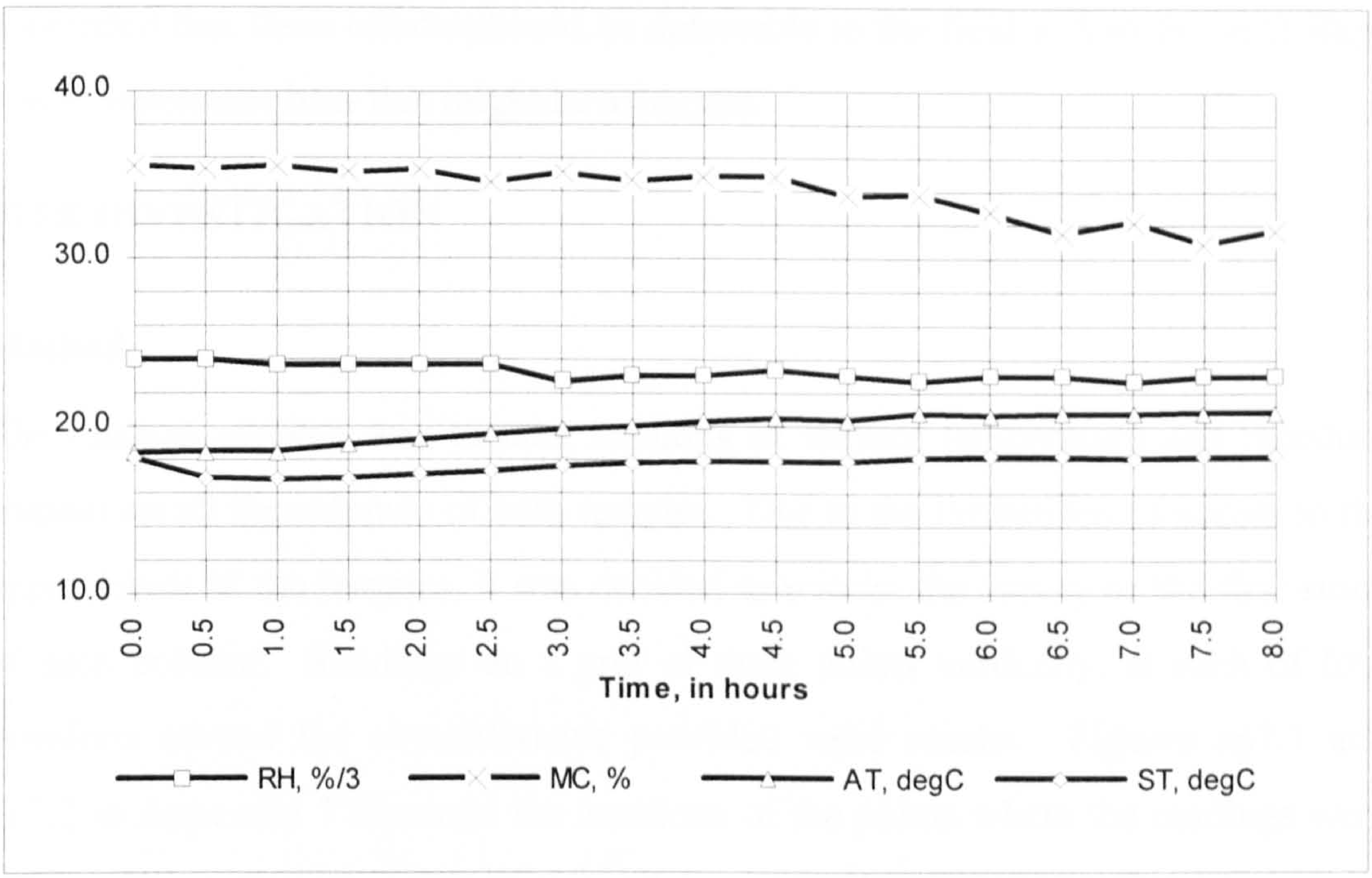


Figure 6.1 Middle Calcareous Grit: drying at room temperature

In Figure 6.1, the following abbreviations have been used: RH = relative humidity; the values were divided by three so that the scale was compatible with the other results. MC = moisture content; AT = air temperature; ST = surface temperature of the stone.

Discussion

It can be seen from the graph that the surface temperature, once moisture had begun to evaporate, was consistently between two and three degrees lower than the surrounding air temperature, and remained so as the moisture content of the stone fell. As the air temperature gradually rose, so the relative humidity gradually fell, but the surface temperature of the sample remained constant. The result of this was that the rate of water evaporation and the difference between surface temperature and air temperature both increased.

This simple test demonstrated that the cooling effect of water evaporating from the surface of a stone sample is of a measurable magnitude, in still air and it is anticipated that in moving air the effect would be more pronounced. It can be concluded that these effects should be detectable in the field and so the next stage was to determine how this might be achieved.

SITE INVESTIGATION

Method

The method adopted was to take readings of surface temperature and moisture content on all the columns of both temples. Due to the limitations of access to the upper levels of the temples, it was decided to restrict the survey to the first stone of each column. Readings on a grid of three points vertically, at each of four positions around the circumference provided valid results. Figures ap7.1 and ap7.2 in Appendix 7 illustrate the locations of the points where the readings were taken. Three sets of readings were taken on the Ionic Temple, and two sets of readings were taken on the Tuscan Temple. In order to verify that no evaporation would take place when the air temperature was below zero, an additional set of temperature readings was taken on the Tuscan Temple under conditions of sub-zero air temperature.

In addition to the recording of surface temperature and moisture content, the areas and severity of decay of the columns were recorded, along with the areas of botanical colonisation of the stone. The key environmental parameters of air temperature, relative humidity, wind speed and direction and extent of cloud cover were also recorded because these uncontrolled variable influence rates of water evaporation. The orientation of the stone surfaces is also an important consideration, and, taken collectively, the columns of each temple have multiple orientations and exposures to micro-climatic influences. The results of the site investigations will reveal therefore whether these factors have an influence on the observed phenomena, or not.

To enable a detailed distribution of the variables to be obtained for comparison, column 6 of the Tuscan Temple, was selected at random and the first stone was marked with a 100mm grid, comprising eleven points around the circumference and nineteen points vertically. Readings of moisture content, surface temperature and the presence of botanical growths were measured as before. The presence of stone decay was measured by taking offsets from a plumb-line to the stone surface, thus enabling the extent of the decay to be quantified.

At Rievaulx Terrace, some 3.5 kilometres north-west of the Tuscan Temple there is also a peripteral Tuscan Temple, with a peristyle of twelve columns, standing on a raised plinth, on an elevated plateaux overlooking the River Rye and Rievaulx Abbey. This temple is illustrated in Figure ap9.12 in Appendix 9. The critical difference between this temple and the Duncombe Park temples is that the columns, and some of the stonework of the inner drum, were replaced with new stone about fourteen years ago; consequently, the columns of this temple have neither surface decay, nor botanical colonisation. It was decided that surface temperature and moisture content would be recorded on the columns in an identical manner to the recordings on the two Duncombe Park temples. In the absence of decay and botanical colonisation, the recorded surface temperatures and moisture contents could be compared with the those of the Duncombe Park temples. Two sets of readings were made on the Rievaulx Terrace temple.

It is generally recognised that surface temperatures and moisture contents of stone are not easy to measure. One problem is that it is often difficult to know whether a thermometer probe is measuring the surface temperature, or if it is measuring air temperature, because only the probe-tip is in contact with the stone. A further problem is that a Protimeter measures moisture content by measuring the electrical resistance between the two probes. The instrument is calibrated for wood and will not give a meaningful reading if used on any other material. That is why the results which follow are given as 'wood moisture equivalent' figures; they are not actual moisture contents, but are still valid on a relative scale. A problem occurs if the water within the stone is contaminated by salts, since under these circumstances the meter gives a high reading because the salt contamination results in a more conductive liquid. Despite these difficulties, there are no alternative non-invasive methods currently available for measuring surface temperature and moisture content of stone (Price, pers com. 1999) and so certain precautions need to be taken.

The following precautions were taken to circumvent the potential problems outlined above:

- To ensure that the thermometer was reading the temperature of the stone and not the air temperature, the thermometer probe was enclosed in 25mm of insulating foam, which was then wrapped in aluminium foil;
- small samples were taken from areas where moisture measurements, taken on 24 May 2000 exceeded 50% and were subsequently analysed for soluble sulphates. Details of the analysis method and the tabulated results can be found at in Appendix 7;
- all measurements were repeated on each temple on different occasions so that the effect of uncontrolled environmental variables could be assessed.

Results

The tables of all the data collected during the site investigations are to be found in Appendix 7. Notes on the data, a discussion of the statistical analysis options, the statistical calculations and the scattergraphs plotted from the results, form the remainder of Appendix 7.

1 Tuscan Temple

Table 6.3, which follows, summarises the results of the correlation coefficient calculations for the four pairs of variables.

Variables	Correlation	Significance and level	Null hypothesis
Surface decay and botanical growths	phi = 0.17; chi-squared = 5.35	significant at 0.05	rejected
Surface decay and temperature 1	Spearman's rho = 0.109	non-significant	retained
Surface decay and temperature 2	Spearman's rho = 0.001	non-significant	retained
Surface decay and temperature 3	Spearman's rho = –0.011	non-significant	retained
Surface decay and moisture content 1	Spearman's rho = 0.001	non-significant	retained
Surface decay and moisture content 2	Spearman's rho = 0.616	significant at 0.01	rejected
Moisture content 1 and surface temperature 1	Pearson's r = 0.076; t = 1.055	non-significant	retained
Moisture content 2 and surface temperature 2	Pearson's r = –0.311; t = 4.868	significant at 0.05	rejected

Table 6.3 Tuscan Temple Duncombe Park: correlations and significance test results

Table 6.4 shows the results of the correlation coeffiecients calculated from the data for column 6.

Measurements on column 6

Variables	Correlation	Significance and level	Null hypothesis
Surface recession and botanical growths	phi = 0.44; chi-square = 40.46	Significant at 0.05	rejected
Surface recession and temperature	Pearson's r = –0.121; t = 1.745	Non-significant	retained
Surface recession and moisture content	Pearson's r = 0.478; t = 7.836	Significant at 0.001	rejected
Surface temperature and moisture content	Pearson's r = –0.138; t = 2.000	Significant at 0.05	rejected

Table 6.4 Tuscan Temple Duncombe Park: correlations and significance test results on column 6

2 Ionic Temple

Table 6.5 summarises the results of the correlation coefficient calculations for the three pairs of variables, and the correlation between surface temperature and moisture content.

Variables	Correlation	Significance and level	Null hypothesis
Surface decay and botanical growths	phi = 0.23; chi-square = 6.35	significant at 0.05	rejected
Surface decay and temperature 1	Spearman's rho = –0.178	non-significant	retained
Surface decay and temperature 2	Spearman's rho = –0.364	significant at 0.01	rejected
Surface decay and temperature 3	Spearman's rho = –0.312	significant at 0.01	rejected
Surface decay and moisture content 1	Spearman's rho = 0.737	significant at 0.01	rejected
Surface decay and moisture content 2	Spearman's rho = 0.712	significant at 0.01	rejected
Surface decay and moisture content 3	Spearman's rho = 0.740	significant at 0.01	rejected
Moisture content 1 and surface temperature 1	Pearson's $r = -0.460$; t = 5.622	significant at 0.001	rejected
Moisture content 2 and surface temperature 2	Pearson's $r = -0.467$; t = 5.765	significant at 0.001	rejected
Moisture content 3 and surface temperature 3	Pearson's $r = -0.529$; t = 6.782	significant at 0.001	rejected

Table 6.5 Ionic Temple Duncombe Park: correlations and significance test results

Soluble sulphate test results

All the tests for soluble sulphates proved negative; however, that does not mean that there were no soluble sulphates in the samples. If calcium sulphate was the sulphate present, and that was the expectation, then the test may not have been sensitive enough to detect that salt because of its very low solubility. Analysis by chromatography and mass spectrometry might have identified any salts present, no matter how minute in quantity.

3 Tuscan Temple at Rievaulx Terrace

Table 6.6 summarises the results of the correlation coefficient calculations for the correlation between surface temperature and moisture content.

Variables	Correlation	Significance and level	Null hypothesis
Moisture content 1 and surface temperature 1	Pearson's r = –0.328; t = 4.152	significant at 0.001	rejected
Moisture content 2 and surface temperature 2	Pearson's r = –0.670; t = 10.807	significant at 0.001	rejected

Table 6.6 Tuscan Temple Rievaulx Terrace: correlations and significance test results

The results for the Duncombe Park temples are summarised in the following bar chart, Figure 6.2.

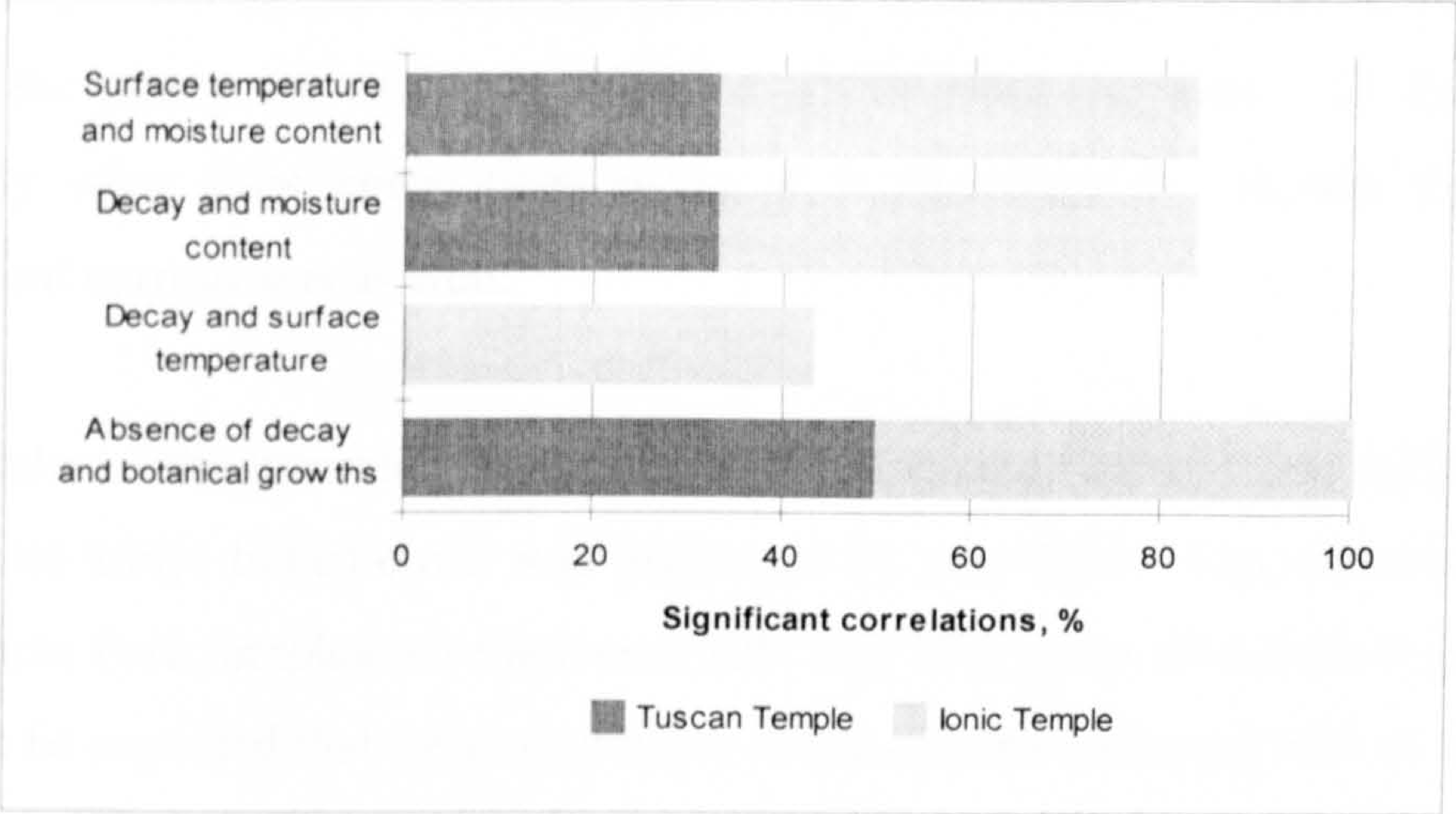


Figure 6.2 Duncombe Park temples: significant correlations

Discussion

If the non-significant and inconclusive correlations, are removed from the results, the significant correlations for each temple can be summarised as follows:

Tuscan Temple:

- the areas of stone decay were where botanical growths are absent;

Ionic Temple:

- the areas of stone decay were where botanical growths are absent;

- the areas of stone decay were the areas of lowest surface temperature;
- the areas of stone decay were the areas of highest moisture content;
- the areas of highest moisture content were the areas of lowest surface temperature.

Tuscan Temple Rievaulx Terrace:

- the areas of highest moisture content were the areas of lowest surface temperature.

Significant correlations between two variables do not mean that there is a causal relationship between them (Coolidge 2000, p.112-113). The significant correlation between the absence of surface decay in the area of botanical colonisation – on the columns of the two Duncombe Park temples, for example – does not necessarily mean that the plants are protecting the stone. Neither does it necessarily mean that the plants are implicated in the decay. What *is* more likely is that the plants are unable to colonise friable stone surfaces. To determine precisely what these correlations mean, it is necessary to consider the other significant correlations as well.

The results of the laboratory saturation and drying tests showed that drying from stone with 100% lichen cover was prolonged by over 16%. The columns of the Duncombe Park temples have between 50% and 75% cover of botanical growths. It might be expected that the drying times of the columns, after periods of wetting, might be prolonged by between 8.5% and 12.5%, assuming a linear relationship between percentage cover and drying time. A prolongation of drying time of these magnitudes, whilst insignificant for the sample cubes which were tested, will amount to a considerable length of time for the stones of the columns, because they have over 7,000 times the volume of the test cubes, but only 250 times the surface area. The ratio of surface area to volume and the shortest distance water has to travel within the pore structure of stone before it can evaporate are clearly critical factors in determining the time required for absorbed water to be lost.

The botanical growths are on the outward facing surfaces of the columns, where illumination levels are greatest and so absorbed water is forced to evaporate in the opposite direction, towards the inner surfaces, but the geographical orientation of the stone surfaces and their exposure to local micro-climatic influences appear to be non-critical factors in determining the areas of colonisation and decay. The result is that the inner surfaces of the columns are coldest and have the highest moisture content, because that is where evaporation, and consequently weathering, is taking place.

But there are two problems with this explanation:

- The pattern of significant correlations observed on the Ionic Temple at Duncombe Park was not consistently repeated on the Tuscan Temple;
- the correlations between surface temperature and moisture content of the Tuscan Temple at Rievaulx Terrace were also significant, despite an absence of botanical growths.

There are three possible reasons why the two temples at Duncombe Park appear to behaving differently. There may have been no evaporation taking place on the days recordings took place on the Tuscan Temple, or if there was, the effects may have been too small to result in significant correlations. It is impossible to say whether relative humidities of 71% and 51% were high enough and the moisture content of the stone low enough to prevent moisture from evaporating on those two occasions when the correlations proved non-significant. It may also be the greater exposure of the Tuscan Temple, and the presence of the inner drum, which are causing it to behave in a different manner because many of the columns are in permanent shade. It may also be that the early repairs to the columns of the Tuscan Temple influence the direction of water evaporation from those columns.

The significant correlations between surface temperature and moisture content in the absence of botanical growths in the columns of the Tuscan Temple at Rievaulx Terrace is somewhat puzzling. A possible explanation is that colonisation of the outer surface of the columns is already taking place, unseen by the naked eye and therefore the same pattern of moisture movement within the stone is already under way. If this is not the case, then there must be another explanation for the significant correlations.

It might be supposed that the inner surface of the columns, protected from the weather, will always be drier than the outer surfaces, and that is the direction in which absorbed water will migrate. But it is the outer surfaces which receive insolation in varying degrees and are likely to stay drier than the inner, more shaded surfaces, and that is the direction in which water migration might be expected. The evidence, assuming an absence of botanical growths, supports neither explanation. Perhaps the outer surfaces of the columns are always drier than the inner surface, because they dry more quickly, but, in the presence of botanical growths, that would contradict the findings of the laboratory saturation and drying tests. This, however, cannot be true of the Ionic Temple, because it is an open rotunda, and at the level on the columns at which readings were taken, all the surfaces receive insolation during some part of the day.

There are two further considerations. In the trials of the laboratory tests it was shown that the decayed stone of the Ionic Temple was more porous than the sound stone. This means that the decayed areas can hold more water, which might result in a higher moisture content reading. Also, the presence of soluble salts, although sulphates were not detected by the laboratory tests, could give artificially high moisture readings.

It seems likely, although the evidence is not conclusive, that the botanical growths on the two temples *are* inhibiting evaporation, and the areas of decay are the result of moisture gradients within the stone, as suggested by Snethlage and Wendler (1997). What is still unclear, though, is whether other mechanisms are also acting to cause the visible decay. The results of the laboratory tests to detect soluble sulphates proved to be negative, but the porosity of decayed stone was higher than samples taken from the quarry face. This indicates a degree of enlargement of the pore structure due to dissolution of the carbonate matrix and so the question which remains to be answered is whether acid rain is implicated. This is the matter which will be addressed in the next section, but first the main findings so far can to be summarised as follows:

Summary

- the areas of stone decay were the areas where botanical growths are absent;
- the areas of stone decay were the areas of lowest surface temperature;
- the areas of stone decay were the areas of highest moisture content;
- the areas of highest moisture content were the areas of lowest surface temperature;
- the data suggests that the botanical growths are inhibiting evaporation from the columns, and the areas of decay are associated with moisture gradients within and evaporation from the stone;
- There is no evidence, so far, to suggest that other weathering mechanisms are involved.
- There may be further factors, such as the built form, exposure and the presence of past repairs on the columns of the Tuscan Temple, which have contributed to the pattern of decay on the columns of this temple.

ANALYSIS OF LICHEN FLORA

Introduction

It will be recalled that Senior's report (Senior 1996), suggested that atmospheric sulphur dioxide in the form of acid rain was implicated in the decay of the columns. No evidence of a protective effect of lichens against acid rain was found in the laboratory tests, but some species survived the test intact. The resistance of lichens to atmospheric sulphur dioxide, in gaseous form, or in solution in water, had been recognised for a considerable time and so the concept of using lichens as indicators of levels of atmospheric pollution is not new.

The antecedents to more recent studies into the use of lichens as indicators of atmospheric pollution are outlined in Gilbert (2000), who reminds us that the first scientific paper on the subject was written by Nylander in 1866. Such studies in Britain originated with the work of Gilbert (1970), Hawksworth and Rose (1970; 1976), Ferry *et al.* 1973 and Richardson (1992). Researchers have written on many different aspects of the subject, including numbers of 'indicator' species at particular sites, changes in substratum preference, physiological influences on individual species (Fields, 1988), mapping air quality (Hawksworth and Rose, 1976; Seaward 1977), and most significantly, the influence which pollution studies on lichens have on legislation aimed at protecting the environment (Sigal, 1988).

The species of lichen which thrive in any particular location are influenced by many factors, but the most important ones are: sufficiently high levels of light to support photosynthesis; a substratum pH at the level which a particular species prefers; and an air quality which the species can tolerate. The last two requirements are to some extent linked, and this will become apparent during the course of this Chapter.

The atmospheric pollutants to which lichens are sensitive include aromatic hydrocarbons, fluorides, ozone and nitrogen compounds, particulates and sulphur dioxide (Richardson 1992). Gilbert (2000) has pointed out that lichens only need brief exposure to levels of sulphur dioxide beyond their tolerance level for physiological stress to be induced, but prolonged exposure can, in sensitive species, inhibit growth, cause the species to become infertile, or to die.

In the past, investigations into the pollution tolerance have been approached by recording species on a 'standard' substratum, for example ash trees or sandstone walls and recording the species along a transect from a known pollution source. The results enable the decline in particular species to be plotted as the pollution source is approached (Gilbert 2000). By relating the results to known levels of air pollution the tolerance level of particular species can be obtained. The result of the work of Hawksworth and Rose (1976) was the production of a map of Britain, indicating the levels of atmospheric sulphur dioxide based on pollution zones and the levels of pollution to which many species are tolerant. The calibration of their scale of pollution levels was only possible because of the relatively stable atmospheres of the 1970s (Gilbert 2000). These tolerance levels are now widely known to lichenologists, and have been conveniently collated by Dobson (Dobson 2000), although the data also appears in the earlier editions of his book. A table giving these pollution zones is included in Appendix 8, and the pollution tolerances of all the species considered in this chapter are included with the consolidated species lists, also in Appendix 8.

The analysis of lichen species at historic sites, and particularly the lichen species on historic buildings has never before been analysed with a view to diagnosing the cause of stone weathering.

Survey method

The lichen flora of the Tuscan Temple at Duncombe Park was recorded and details of the survey method, the species lists and the pollution tolerance of the species can be found in Appendix 8. Also included in the consolidated species list are details of species distribution and more importantly, the substratum on which the species are normally found. This is important to this investigation because a shift of substratum preference from low pH to more basic, or high pH, is also an important indicator of changing levels of atmospheric sulphur dioxide.

Analysis method

The traditional transect method of analysing lichen species assumes that there is an identified source of pollution. The hypothesis here was that there was no source of pollution, and pollution was not implicated in the decay of the columns of the temples and so the transect method was inappropriate. Instead, the analysis was carried out using the frequency distributions of the pollution tolerance of the species which were recorded on the Tuscan Temple in 1998 as part of this research. This frequency distribution was compared to the frequency distribution of the pollution tolerance of species on trees in adjacent woodland, recorded in 1989 (Smith 1989).

The following bar chart, Figure 6.3, shows the frequency distribution of the species recorded on the Tuscan Temple in 1998.

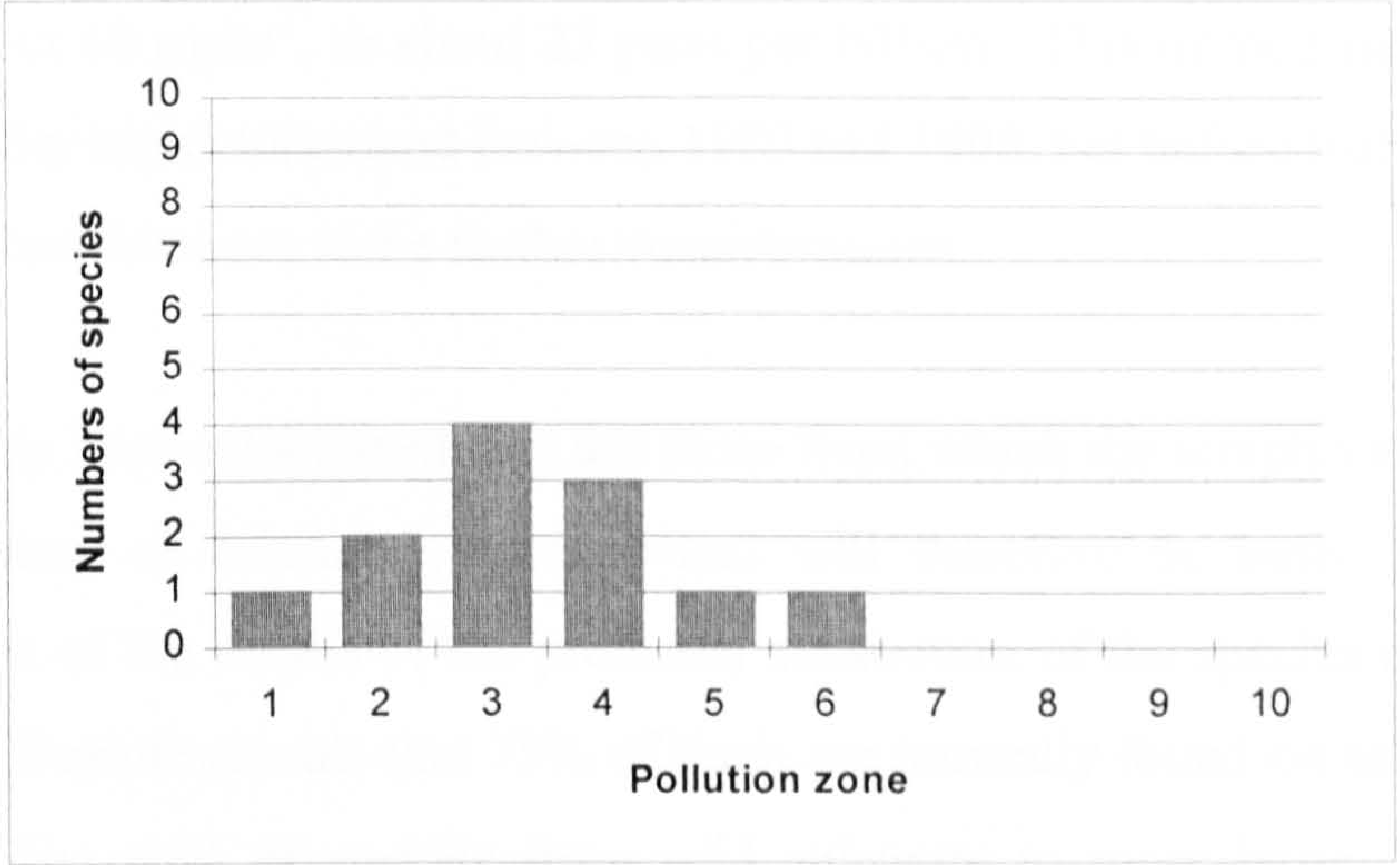


Figure 6.3 Tuscan Temple lichen survey: species and pollution tolerance

Although there were only twelve species recorded, it is evident from Figure 6.2 that there were more species tolerant to Zone 3 levels of pollution, on the Hawksworth and Rose scale, than any other. This indicates a mean winter sulphur dioxide level of about 125μg/m^3, or about 66 parts per billion. Figure 6.4, by comparison, shows the frequency distribution of the pollution tolerance of the woodland species recorded in 1989.

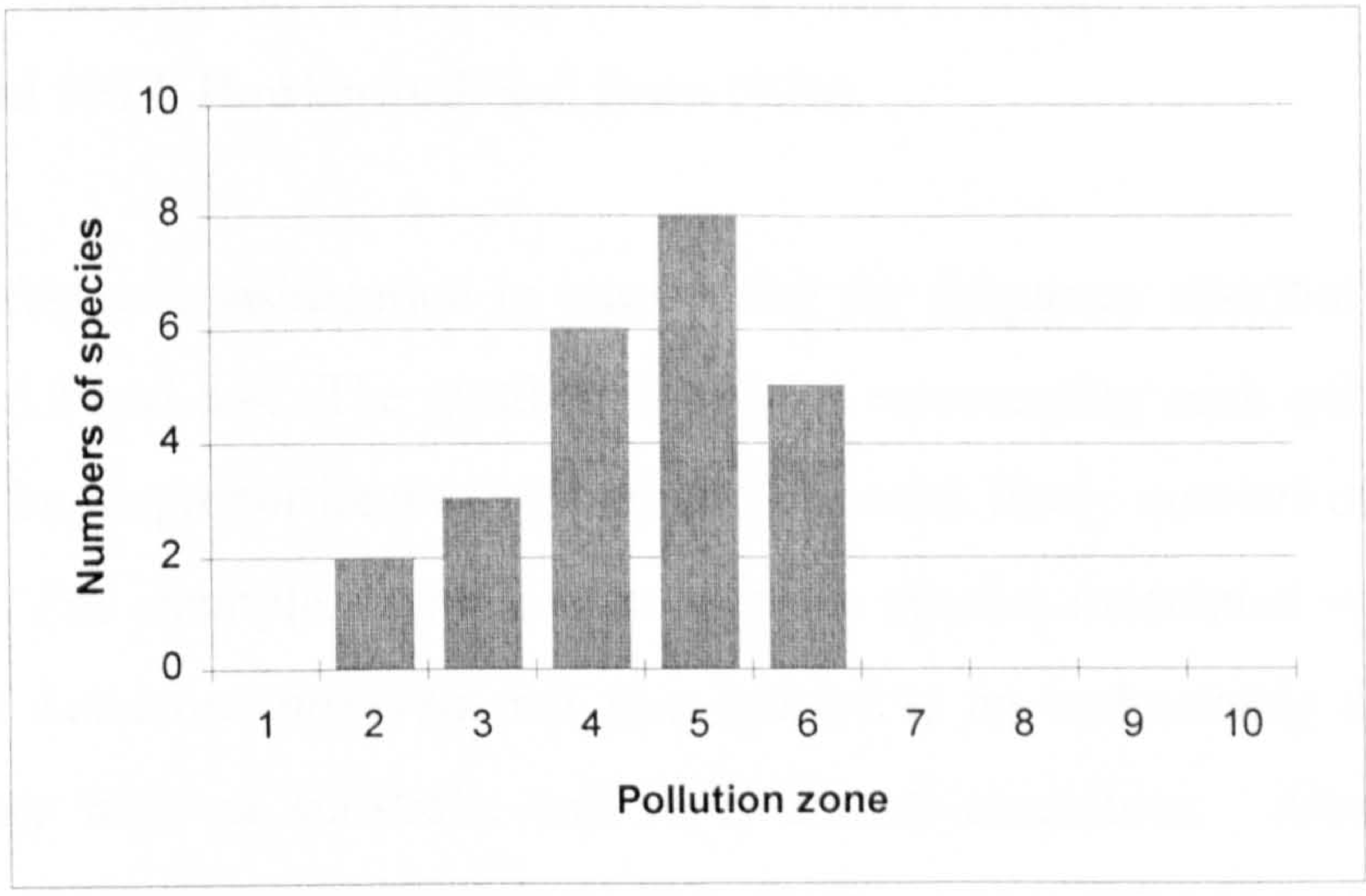


Figure 6.4 Duncombe Park woodland lichen survey: species and pollution tolerance

It is immediately apparent from Figure 6.4, despite the larger number of species recorded, that the mode value in this chart is at Zone 5, and only five species had tolerance to lower pollution levels. This represents a mean winter sulphur dioxide level of about 60 $\mu g/m^3$, or about 23 parts per billion. This immediately suggests that air quality has deteriorated between 1989 and 1998, but before that conclusion can be reached there are some further considerations.

It has already been established that the stone from which the temples are built has a high content of calcium carbonate and will therefore be basic to alkaline. Examination of the details of the preferred substratum of the species recorded on the Tuscan Temple reveals that 75% of them are normally found on acid rocks, or on trees. The shift of species from acid substrata to more basic, in polluted environments, is a well-recognised phenomenon. Several researchers have pointed out that as pollution levels rise the pollution-tolerant species tend to colonise substrata previously populated by pollution-sensitive species, and the pollution-sensitive species may colonise substrata with a higher buffering capacity than their normal habitat: species which normally live on tree bark or acid rocks tend to colonise more basic substrata, or may colonise substrata previously un-colonised. A typical example is the colonisation of concrete and asbestos-cement, surfaces with high pH, by *Lecanora muralis*. This species is often ubiquitous in some urban areas, and frequently represents a single-species colonisation due to the lack of competition in polluted environments (Richardson 1992; Brightman and Seaward 1977; Hawksworth and Rose 1976).

There is a further consideration in interpreting the frequency distributions shown in Figures 6.3 and 6.4. The number of species representing each pollution zone should not be disproportionate compared to the total likely number of species in each zone. For example, there is now only one species associated with Zone 1, and that is *Lecanora dispersa*, but this species is an enthusiastic coloniser of almost every form of substrate, and so is almost ubiquitous. Also, from the descriptions in Dobson, it can be seen that there are over fifty saxicolous species with Zone 6 pollution tolerance levels. So it may be expected that at any particular site there would be more Zone 6 species than species representing other zones. The interpretation of the pollution zone distributions needs, therefore, to be treated with some caution.

In this case study the difference in the indicated pollution tolerance between the species recorded in the woodland and the species recorded on the Tuscan Temple was analysed by subjecting the pollution tolerances of the two groups of species to significance testing. This determined if the difference suggested by the frequency distributions could be a chance difference, or not.

Mention has already been made that the starting point of this investigation was that air pollution is not implicated in the decay of the columns and this must provide the basis for the null hypothesis used in the significance test; therefore, the null hypothesis was that there is no difference in the pollution tolerance of the two groups of species. The alternative hypothesis is that there *is* a difference in their pollution tolerance and so a two-tail test was carried out. Since the data is in the form of ranks, the two groups are not related, and there are different numbers of species in each group, the Mann-Whitney test was used. The following table shows the output generated by *SPSS*.

Test Statistics

	Values	**Critical *Z***
Mann-Whitney U	76.500	
Wilcoxon W	154.500	
Z	**–2.317**	<–1.96
Asymp. Sig. (2-tailed)	0.021	
Exact Sig. [2*(1-tailed Sig.)]	0.022*	

* Not corrected for ties.

Table 6.7 Analysis of pollution tolerance of lichen species in 1989 and 1998

It can be seen from Table 6.7 that the calculated value of *Z* is less than the critical value and is significant at the 0.05 level for a two-tail test. So it can be concluded that the lichen species recorded on the Tuscan Temple in 1998 have significantly higher tolerance to atmospheric sulphur dioxide than the species recorded in adjacent woodland in 1989. This difference cannot be a chance occurrence and it suggests that air quality has declined in that period.

Discussion

This outcome confirms Senior's suggestion that acid rain may be implicated in the decay of the columns, although he provided no evidence to support his view other than the presence of coal-burning power stations in South Yorkshire (Senior 1996). The level of atmospheric sulphur dioxide indicated by the lichen species on the Tuscan Temple was compared to official figures and there appeared to be agreement between the two, but we need to be clear as to whether this agreement is real, or coincidental.

The Department of Environment Food and Rural Affairs website was accessed for the air pollution summary for rural areas of north-east England on 16 February 2002. The figure for that day was given as Index 2, which on their scale is equal to 89 to 176 $\mu g/m^3$, with forecast levels of Index 3, equal to 177 to 266 $\mu g/m^3$ (Department of Environment Food and Rural Affairs 2002c; 2002d). A comparison of the Hawksworth and Rose scale, and the DEFRA scale for sulphur dioxide is included in Appendix 8. It can be seen by comparing the two tables that there is a difference, in the methods of measurement, and in the range of levels which might be encountered. That is why the agreement between levels indicated by the lichen flora and that suggested by official statistics is little more than coincidence. There are two different scales of measurement and a disparity between expected ranges, but more importantly official statistics cannot detect local variations

The problem with official figures of air pollution levels is that they are collated from a national network of automatic monitoring stations, the nearest to Helmsley being Leeds, and Bradford, to the south, and Middlesborough and Sunderland to the North; therefore, local variations in air quality cannot be detected. This can be demonstrated in the pollution forecast figures on the day the website was accessed; the pollution forecast was Zone 3 for all ten regions of Britain. Clearly, local variations are not detectable, and so sulphur dioxide levels at Duncombe Park may be higher, or lower than the official figures suggest. It is, however, worth referring to the DEFRA *Summary of objectives of the National Air Quality*

Strategy, in which they say that mean winter sulphur dioxide levels, measured between 1 October and 31 March, should fall to 20μg/m^3 by 31 December 2000. They go on to say that 'These levels are adopted for the protection of vegetation and ecosystems...' but 'This objective only applies to sites remote from identified sources, including major industry and roads and urban agglomerations, and a concentration level higher than the limit does not necessarily imply that the objective has not been met' (Department of Environment Food and Rural Affairs 2002b). It is clear from this statement that either the standard has not been met in the area of Duncombe Park, or the official figures are inaccurate. The pollution levels suggested by the lichen flora are, in the writer's view, likely to give a more reliable indication of atmospheric sulphur dioxide levels at any particular rural location than Government statistics.

It could be argued that the method adopted here of detecting changes in air quality by comparing lichens on trees to lichens on stone is flawed. The argument would be that the analysis was carried out using data for lichens on different substrata and that a standardised substrate should have been used, perhaps by carrying out a further survey of the same areas of woodland as were surveyed in 1989. The answer to this lies in the work of Henderson and Seaward, who suggested that corticolous species tend to be an indication of past levels of air pollution, while saxicolous species, with their superior powers of re-colonisation, are more indicative of present levels (Henderson and Seaward, 1976. p.67), and more will be said about this aspect in the third case study.

There is another way to verify trends in air quality and that is to compare the results of the analysis of lichen flora pollution tolerance at this site to other nearby sites and with sites further afield. This will be one of the considerations in the two case studies which follow.

Summary

- Analysis of the lichen flora of the Tuscan Temple indicates that levels of atmospheric sulphur dioxide have increased over the period from 1989 to 1998;
- government statistics on air pollution do not have the resolution to detect local differences in air quality;
- it is likely that atmospheric sulphur dioxide is implicated in the decay of the stonework of the columns of the temples.

CASE STUDY 1 SUMMARY

- the data suggests that the botanical growths are inhibiting evaporation of absorbed moisture from the columns and the areas of decay are therefore associated with moisture gradients within the stone;
- Analysis of the lichen flora of the Tuscan Temple indicates that levels of atmospheric sulphur dioxide have increased over the period from 1989 to 1998;
- it is likely that atmospheric sulphur dioxide is implicated in the decay of the stonework of the columns of the temples.

PART 2 – RIEVAULX ABBEY

INTRODUCTION

The choice of Rievaulx Abbey as the second case study follows logically to some extent from the Duncombe Park temples. Rievaulx Abbey is also situated on the banks of the river Rye, some four kilometres to the north-west of the Tuscan Temple at Duncombe Park and is also located on Figure ap9.3, in Appendix 9. The stones from which the abbey was built are from the same geological sequence as the Duncombe Park temples and it might be expected that there would be similarities between the sites. Those similarities might include the pattern of lichen colonisation, the degree of associated weathering of the stone and the indicated air quality; however, none of those similarities are immediately apparent. In fact it is the differences which are most apparent. Those differences which are considered to be significant and which comprise the key aspects for this investigation are:

- Rievaulx Abbey occupies a relatively sheltered, valley-bottom, location with all the implications for micro-climate which that implies;
- it is constructed of several different stone types, each with their individual properties and weathering characteristics;
- it is a monument which has undergone considerable consolidation work and subsequent conservation since its 'rescue' in the early to mid-twentieth century and consequently there is little obvious sign of active weathering of the stone;
- it has a rich lichen flora.

Aims and Objectives

The aims:

- To locate the sources of stone used in the building of the abbey;
- to determine the physical properties of those stone types and their resistance to simulated weathering tests;
- to record the lichen flora of the ruins;
- to locate the sources of any previous lichen surveys of the area;

- to determine the abundance of lichen flora supported by the various stone types.

Objectives:

- to correlate the abundances of lichen flora on the different stone types to the physical properties of the stone and the likely influence on weathering;
- to determine if the lichen species composition on the monument and that of the surrounding woodland indicate the same levels of atmospheric sulphur dioxide;
- to determine if there is evidence in the lichen flora of changing air quality;

HISTORICAL OVERVIEW

Rievaulx Abbey is one of the most complete survivals of a Cistercian Abbey in Britain. It is typical of the Abbeys of that order, being sited in a secluded location and was begun in the mid twelfth century. The last of seven identified phases of construction dates from the fifteenth century. The abbey was surrendered to the Crown on 3 December 1538 and shortly afterwards became a ruin.

During the eighteenth century, the ruins acquired Picturesque value, and that value continued well into the nineteenth century. Rievaulx Terrace, similar in concept to the terrace at Duncombe Park, was laid out in 1757, with contrived views through trees down the steep valley sides to the ruins below and was described by Arthur Young in his account of a six-month tour of the North of England (Young 1771). The ruins were the subject of water-colours by the artist Dayes, in 1812, and by Turner in 1822. It was the subject of engravings by Henry Warren in the mid-nineteenth century, and illustrated by William Richardson for his book *Monastic Ruins of Yorkshire*, published in 1843 (Richarson and Churton 1843). One such illustration is reproduced in Appendix 9 – Figure ap9.14.

Many ruined abbeys were partly cleared of debris as early as the eighteenth century, including Byland Abbey and Fountains Abbey. The 'rescues' of the early twentieth century have already been mention in Chapter Two, but Rievaulx Abbey, taken into Guardianship in 1917 (Emerick in lit. 21 May 2002) but remained largely untouched until 1919. Work continued in the 1950s and the

1960s, by which time the plan had emerged with a high degree of completeness (Thompson 1981, p.37). The ruins are now a Scheduled Ancient Monument.

Repair history

The Office of Works, its successor the Ministry of Public Buildings and Works, and more recently, English Heritage, have between them carried out extensive reconstruction, consolidation and repairs. These have included radical interventions in the early 1920s such as the incorporation of ferro-cement ring beams to stabilise the walls of the nave of the Abbey Church. The standardised treatment of ancient monuments in guardianship in the early years of the twentieth century was applied to the remains of Rievaulx Abbey and that is the method of presentation which survives to the present day, illustrated in Figure ap9.15 in Appendix 9. The site is now the subject of a Conservation Plan, which addresses not only the conservation of the ruins, but also the conservation of the wider landscape including Rievaulx Village and Rievaulx Terrace and its temples (Caroe and Partners 2000).

LOCAL GEOLOGY

The stratigraphy of the Rye valley in the area of Rievaulx Abbey is similar to that at Duncombe Park. The stages and strata of the sequence, which forms part of the Callovian, the upper stages of the Middle Jurassic, and the Oxfordian Stage, or lowest stage of the Upper Jurassic, are shown in Table 6.8, below.

Stage	Strata	
Upper Oxfordian	Snape Sandstone Spaunton Sandstone Newbridge Member Coral Rag	Upper Calcareous Grit Formation
Middle Oxfordian	Malton Oolite Middle Calcareous Grit Hambleton Oolite Passage Beds	Coralline Oolite Formation
		Lower Calcareous Grits
Callovian	Kellaways Rock	Kellaways Sandstone

Table 6.8 The Callovian and Oxfordian Stages of the Middle and Upper Jurassic in Yorkshire.
(Hemingway in: Rayner and Hemingway 1974 p.212 Zones and Sub-zones omitted)

Senior (1999) identified the geological formations and the quarries from which those formations were exploited for the stone of the abbey and is shown in Table 6.9, below. But it should be noted that the Kellaways Sanstone is of the Upper Jurassic (Hemingway in: Rayner and Hemingway 1974, pp. 206-210) and not, as Senior states, of the Middle Jurassic.

Quarry sites

Ref.	Quarry	Geological formation
		Upper Jurassic
1	Rievaulx Bank Quarry	Malton Oolite
2	Hollins Wood	Middle Calcareous Grit
3	Griffe Bank (Quarry Bank Wood)	Hambleton Oolite
4	unnamed quarry	Lower Calcareous Grit
5	Penny Piece Quarry	Kellaways Sandstone
		Middle Jurassic
6	Firth Bank Quarries	Saltwick Formation
7	Laskill Quarry	Saltwick Formation
8	Weathercote Quarry	Saltwick Formation

Table 6.9 Rievaulx Abbey: geology of stone types

(Based on Senior 1999, p.215, figure 178)

The following descriptions of the quarry sites and the mineralogy of the stone types is based upon Senior's account (Senior, in: Fergusson and Harrison 1999, pp.215-219), although Senior refers in part to the earlier work of Weatherill (Weatherill 1952-55, pp.333-354). There are several inaccuracies and inconsistencies in Senior's account which made the quarry sites difficult to locate, and these inaccuracies are highlighted in the descriptions which follow.

The Ordnance Survey grid references and place names, other than the quarry names, have been added by the writer and are from the Ordnance Survey 1:50,000 Ordnance Survey sheet 100 (Ordnance Survey 1979a). It has, however, only been possible to pinpoint some of the quarry sites by reference to the 1:10,000 series of Ordnance Survey maps (Ordnance Survey; 1981c; 1979b; 1977).

1. *Name*

   Rievaulx Bank

   Location

   Rievaulx Bank Quarry, by the roadside on Rievaulx Bank, 0.5km north-east of the Rievaulx Abbey complex.

   Grid ref. SE 579852

   Stone type

   Malton Oolite; Corallian Oolite; Upper Jurassic.

   Medium to coarse-grained oolite with micritic [chemically precipitated micro-crystalline] calcium carbonate cement; sometimes pisolithic [composed of large, irregular, ooliths], or shelly.

   Use

   Used extensively as rubble fill, and for rubble barrel vaults, relieving arches and vault webbing.

   Sample

   Samples were collected on 14 March 2000, 8 January and 17 February 2001.

2. *Name*

   Hollins Wood

   Location

   Uncertain

   Grid ref. SE565837? . There are several earth mounds, and wooden steps leading to a track above the tributary level in this wooded valley. Although not investigated in detail by the writer due to the difficult terrain, this could be a landscape formed by quarry waste. Senior points out that only one bed, up to 0.8m thick, was used.

   Stone type

   Middle Calcareous Grit; Coralline Oolite; Upper Jurassic.

   A calcareous marine sandstone, soft, fine to medium grained, slightly micaceous, largely fossil-free, cemented by micritic calcium carbonate. It is vulnerable to weathering by acid rain and air pollution as can be seen in the relief over the infirmary cloister entrance to the abbot's lodgings.

Use

Fine-detailed sculpture and ashlar

Sample

Notwithstanding the uncertain location of the source of this stone, a sample was collected on 18 November 2000. It subsequently became clear after preparing test cubes from this sample that it did not match Senior's description, and it is possible that the descriptions for the stone from this quarry and Quarry bank wood have become transposed in Senior's account.

3. *Name*

Griffe Bank

Location

Griffe Bank Quarries (also known as Quarry Bank Wood, and referred to by the latter name in this research).

Grid ref. SE582840 to SE583837

Stone type

Hambleton Oolite; Coralline Oolite; Upper Jurassic

A coarse-grained, shelly, oolite limestone with up to 20 per cent quartz, partly cemented by silica, partly by sparite. Always bioturbated, and because these areas are better cemented by silica, they stand slightly proud on weathering. Pale brown, but weathers to paper white.

Use

Used extensively in the refectory, St William's shrine, the infirmary chapel, and in the twelfth century rubble walls of the west range.

Sample

Samples were collected on 9 and 11 June, and 25 November 2000. There is doubt that the samples, although taken from several different areas of the quarry, match the above description; however, there is no doubt that the freestone in the lower beds of this quarry, accessible from the quarry floor and from where samples were taken, is not an oolite.

4. *Name*

Unnamed by Senior, but samples taken from this site are referred to in this research as from *Rievaulx Abbey Church quarry.*

Location

Described by Senior as 120 meters to the north of the church, but the 1:10,000 Ordnance Survey map, sheet SE 58 SE, shows a disused quarry to the south-east of the church at grid ref. SE 578851 (Ordnance Survey 1981c), just below the first temple on Rievaulx Terrace. On inspection of the two possible locations it became clear that the reference to 'the church' is the Abbey Church and not the church in Rievaulx village.

The grid reference is not SE577853, implied by Senior's description, but SE578851.

Stone type

Lower Calcareous Grit; Lower Oxfordian; Upper Jurassic.

A blue-hearted, slightly oolitic, tough siliceous rock (almost impossible to dress), with silicified microscopic *Rhaxella* algal bodies and a limited micrite cement. The rock is usually extensively bioturbated by characteristic *Thalassinoides* burrows [freshly deposited sediments are stirred up by sea-floor organisms such that bedding and lamination are disturbed]. Colour varies from white to pale brown.

Use

All stages of building for rough walling, or coarse rubble fill. Used on the lower courses of the Refectory.

Sample

Samples, with and without lichens, were collected on 8 January, and 17 February 2001.

5. *Name*

Penny Piece

Location

Penny Piece Quarry (also known as Bow Bridge Quarries), located just outside the west precinct wall, although the quarry face, illustrated in Senior's fig 18.1, could not be located during sample collection.

Grid reference of sample source: SE568858

Stone type

Kellaways Sandstone; Osgodby Formation; Middle Jurassic.

Fine-grained marine sandstone; yellowish-brown to reddish-brown; has undergone diegenetic decalcification and is often poorly cemented, with numerous carious holes after marine fossils, but is nevertheless difficult to dress.

Use

Dressed ashlar in most phases of building

Sample

Samples were collected on 25 November 2000, from a pile of semi-dressed stone, with moss growth, among mounds, probably formed by quarry waste.

6. ***Name***

Firth Bank, noted by Senior as a possible source.

Location

Firth Bank Quarries, described by Senior as being on the west side of Bilsdale, although Firth Bank is on the east side of Bilsdale at grid reference SE572922, just south of Hag End.

Grid ref. SE572921 to SE573924.

Stone type

Deltaic Sandstone; Saltwick Formation, although Senior's table on p.219 refers to 'Ravenscar Formation'; Middle Jurassic.

A medium grained, non-marine rock, pale brown to yellowish brown in colour; partly cemented by silica, partly by hydrated iron oxide (limonite) in characteristic swirling Liesegang patterns [nested bands, or rings produced by rhythmic precipitation within a fluid-saturated rock (Lapidus 1990)].

Use

Dressed ashlar in most stages of building

Sample

It was not possible to gain access to this quarry site because of restrictions due to the foot-and-mouth outbreak; access to this quarry site is over grazing land.

7. ***Name***

Laskill Quarry. Senior states that this is a possible source of stone.

Location

Laskill Grange

Grid ref. Laskill House: SE564908; quarry: SE565909. This quarry site is adjacent to the east side of the B1257 trunk road, which runs from Helmsley to Stokesley and so access for sampling was straightforward but risky, due to the large slabs of stone laying on the steep slopes of the quarry and to the overhanging nature and angle of dip of the quarry face.

Stone type

Deltaic Sandstone; Saltwick Formation; Middle Jurassic, all as noted in 1 above.

Use

As noted above

Sample

Collected 25 November 2000 and 17 February 2001, with, and without lichen growth.

8. ***Name***

Weathercote: a known source

Location

Weathercote Quarries (also known as Ventris Pits, or Helmhouse Quarries), 9km north of the Rievaulx Abbey, on the west side of Bilsdale.

Grid ref. Helm House: SE568932; quarries: SE563927 to SE563935

Stone type

Deltaic Sandstone; Saltwick Formation; Middle Jurassic, as noted in 1 above (at least 90,000 tons of stone have been quarried from this site)

Use

As noted above

Sample

It was not possible to gain access to this quarry site because of restrictions due to the foot-and-mouth outbreak; access to this quarry site is through farm property.

The locations of these quarries are illustrated in Figure ap9.16 in Appendix 9.

Sampling methods

The three criteria for sample selection adopted in the precious case study were also adopted here: samples should be easily transportable; they should match the descriptions of the stone types given for that particular quarry; they should be randomly selected.

Potential stone samples were matched to the descriptions given by Senior, as described above. Prospective samples, and quarry locations, were also cross-checked against descriptions given by Weatherill (Weatherill 1952-55), although these two sources often contain conflicting information.

Inevitably, at some of the quarry sites several beds of the geological sequence are exposed and consequently the quarry floor is littered with fragments from these beds. At Laskill Quarry for example, there are many large slabs which subsequent laboratory tests on a sample showed to be a dense hard limestone, probably from the upper levels of the sequence and which has been used for rough racking on many of the tops of the lower walls at Rievaulx, particularly the area of the Dorter and Novices Room. Samples of this stone have a characteristic, prismatic, brittle, fracture pattern which then reveals flakes of micrite. Samples of this stone type were also taken for further analysis. At Rievaulx Bank Quarry, the oolite is quite variable in density and sometimes shelly and so several samples were taken to reflect this variability, but not all of them were tested.

Some of the sites are within dense woodland, and this puts most of the quarry face and floor into deep shade. This results in many of the stone fragments on the quarry floor being covered in moss; therefore, the location of suitable moss-covered samples did not pose a problem but only the more leprose species of lichens such as *Lepraria incana*, or *Leproloma vouauxii* flourish under these conditions – but because of their powdery, or granular nature and their loose attachment to the stone, they are unsuitable for subjecting to laboratory tests. So suitable samples with lichens could only be collected from the sites with a more open aspect; consequently, it was only possible to obtain samples of some of the stone types with both moss and lichen growth. From that point of view the resulting sample groups with lichens are unavoidably biased towards particular stone types.

STONE CHARACTERISTICS

The results of the physical properties tests, and the simulated weathering tests, discussed in Chapter Five, have been consolidated and are given in Table 6.10 below.

Characteristics	Hollins Wood	Laskill Quarry	Penny Piece Quarry
Mean density	2.5g/cc	1.8g/cc	2.1g/cc
Mean open porosity	7.0%	17.0%	15.0%
Mean capillary rise time	72 hours	23 hours	0.4 hours
Pore volume <5µm	not tested	not tested	29%
Freeze/thaw resistance	Excellent	Good	Poor
Soluble salts resistance	Moderate	Good	Poor
Acid rain resistance	Poor	Moderate	Excellent

Characteristics	Rievaulx Abbey Church Quarry	Rievaulx Bank Quarry	Quarry Bank Wood
Mean density	2.5g/cc	2.5g/cc	2.3g/cc
Mean open porosity	3.0%	3.0%	11.5%
Mean capillary rise time	48 hours	30 hours	56 hours
Pore volume <5µm	not tested	not tested	not tested
Freeze/thaw resistance	Good	Excellent	Moderate
Soluble salts resistance	Moderate	Excellent	Moderate
Acid rain resistance	Poor	Good	Poor

Table 6.10 Rievaulx Abbey: stone properties and weathering characteristics

The resistance to the three simulated weathering tests, indicated in Table 5.12, in Chapter Five, as good, or poor, has been expanded in the above table to excellent, good, moderate and poor, based upon the percentage weight losses of the samples. The stone types with calcareous cements proved to have a poor resistance to the simulated acid rain test, although the oolite from Rievaulx Bank Quarry lost much less material in the test. Of the six stone types tested, only the samples from the Penny Piece quarry proved resistant to acid rain.

ABUNDANCE OF PLANT COLONISATION

It was shown in the last chapter that the degree to which stone is put at risk by plant colonisation, particularly by lichens, may be dependent upon the extent of cover. In order to determine the extent of cover at Rievaulx Abbey selected areas of the ruin were surveyed.

Method

The method adopted was to select a section of masonry with the greatest abundance of colonisation in each of the areas which had been surveyed for lichens. Details of the lichens survey method and the areas surveyed can be found in Appendix 8, and the results and analysis of the species recorded follows this sub-section. Miniature quadrats, of sizes 0.25 m^2 and 0.1 m^2 were used in order to determine the percentage cover. Each quadrat was sub-divided by wires into a grid of ten squares by ten squares. The quadrat was held against the wall, and the number of grid-squares in which lichen colonisation occurred was counted. This gave the percentage cover. The distance from ground level to the base of the quadrat was noted. In addition, the number of different species which occurred within the area of the quadrat was also recorded. The results are included in Appendix 8, and Table 6.11, which follows, summarises those results.

Survey area	Height above ground	Stone type/source	Maximum cover, %	Species count
1	0mm	Deltaic Sandstone/Laskill Quarry	100	3
2		This area was not accessible		
3	500mm	Deltaic Sandstone/Laskill Quarry	100	5
4	500mm	Deltaic Sandstone/Laskill Quarry	25	3
5	200mm	Hambleton Oolite?/Quarry Bank Wood	85	6
6		This area was not accessible		
7	150mm	Kellaways Sandstone/Penny Piece Quarry	10	3
8	500mm	Deltaic Sandstone/Laskill Quarry	24	5
9		This area was not accessible		
10	600mm	Deltaic Sandstone /Laskill Quarry	95	8
10a	0mm	Mixture of unidentified types	17	2
11	500mm	Kellaways Sandstone?	12	3
12	1500mm	Mix, including unidentified limestone	31	6
12a	1000mm	Hambleton Oolite?/Quarry Bank Wood	65	6
13	2000mm	Hambleton Oolite?/Quarry Bank Wood	79	7
13a	1000mm	Lower Calcareous Grit/Rievaulx Abbey Church Quarry	25	4
14	0mm	Kellaways Sandstone?/Penny Piece Quarry	5	2
15	500mm	Lower Calcareous Grit?/Rievaulx Abbey Church Quarry	15	4
16	1200mm	Mixture of RVX-C and QBW	15	4

Table 6.11 Rievaulx Abbey: stone types, lichen cover and abundances

The following bar chart, Figure 6.5 consolidates the information in Table 6.11, for the four stone types which were positively identified and indicates the maximum percentage cover in all the areas where that stone type was found, irrespective of aspect and orientation.

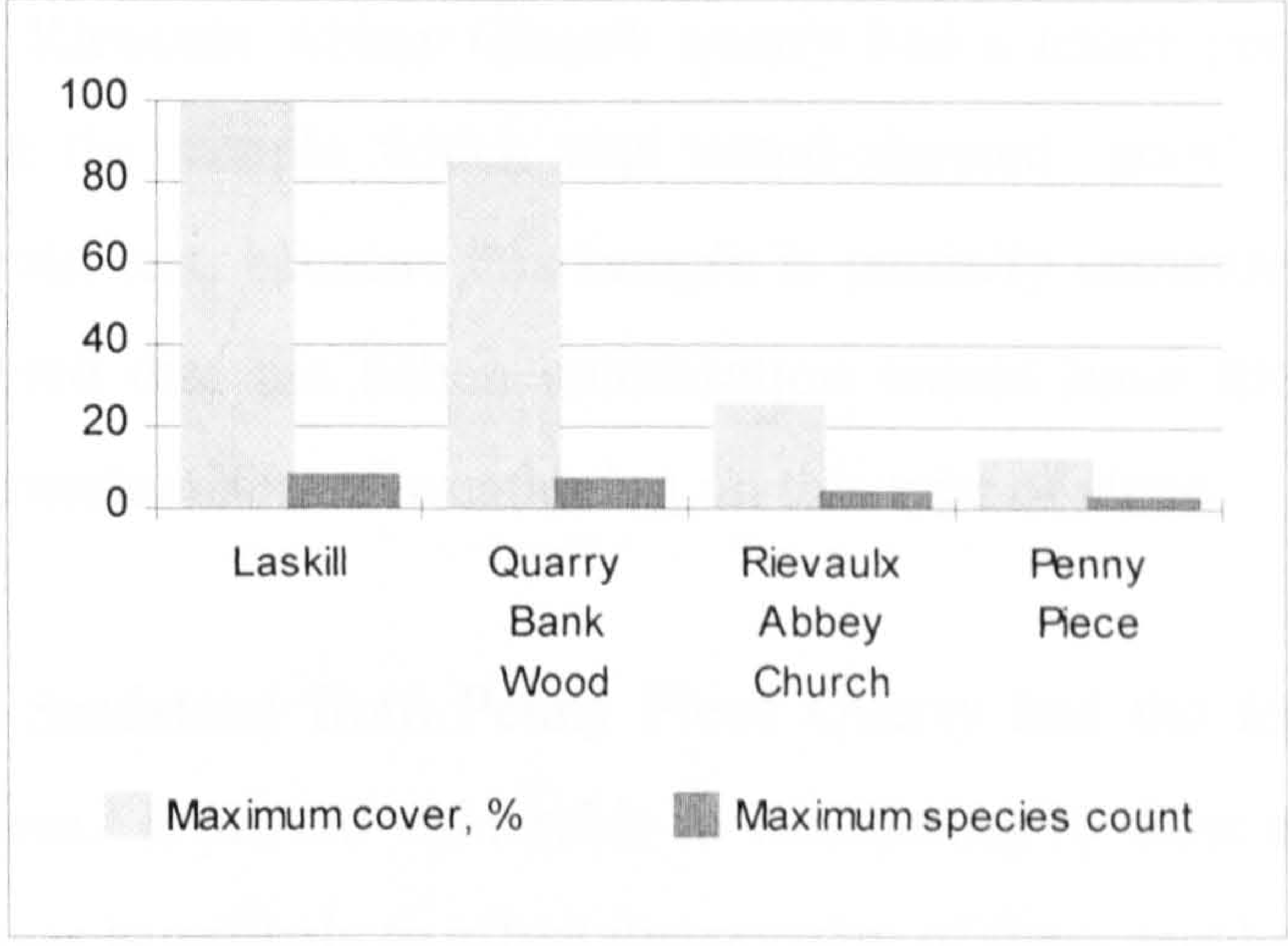


Figure 6.5 Rievaulx Abbey: Stone types and percentage lichen cover

Discussion

It should be noted that Senior ascribes the main source of the Deltaic Sandstone to Weathercote Quarries and only suggests Laskill Quarry as a possible source (Senior, in Fergusson and Harrison, 1999, p.216-217). Laskill Quarry was the only one of these two sources to which access was available and it is from there that the samples for laboratory tests were taken. Although these two sources are from the same geological strata, their properties may be slightly different. This stone type had the highest percentage lichen cover and the implication is that there is the maximum potential for that cover to potentiate other weathering mechanisms. From Table 6.10, it can be seen that the Laskill samples tested have 'good' resistance to weathering by frost and salts, but only 'moderate' resistance to the effects of acid rain.

The stone form Quarry Bank Wood, had a lower potential for colonisation, but had a 'poor' resistance to the effects of acid rain, because of the high calcium carbonate content. The capacity of the high percentage of lichen cover to potentiate this weathering mechanism, puts this stone type at high risk and the loss of detail on the bases of the columns in the Presbytery is witness to that process.

The stone from Rievaulx Abbey Church quarry had a lesser potential for lichen colonisation, but the sample which was tested showed 'poor' resistance to the simulated acid rain test, because this sample is partially cemented by micrite. It would be expected that the lichen colonisation would have little effect on the impact of other mechanisms of weathering on this type of stone.

The Kellaways Sandstone from Penny Piece Quarry had the least potential for lichen colonisation. It proved vulnerable to weathering by frost and salts, but the sparse lichen cover is unlikely to affect the severity of these mechanisms.

Summary

- Calcareous stones tend to attract the highest abundance of lichen cover; therefore, there is the greatest risk that the lichen cover can potentiate weathering mechanisms, including the effects of acid rain;
- siliceous stones tend to attract lesser degrees of colonisation and so the influence on other weathering mechanisms is likely to be minimal and they are resistant to acid rain.

RIEVAULX ABBEY LICHEN SURVEY

The aims and objectives of the examination of the lichen flora of Rievaulx Abbey were stated at the beginning of this case study. Details of the survey method, the areas surveyed and the reasons for the choice of those areas forms part of Appendix 8. The full lists of species recorded in each of the areas surveyed, along with descriptions of the characteristic appearance of the species, are also included in Appendix 8. Figure ap9.17 in Appendix 9 shows a plan of the abbey and the location of the survey areas. Figures ap9.18 to ap9.21 inclusive illustrate some of the species and their patterns of colonisation.

Atmospheric sulphur dioxide pollution

The numbers of species recorded at Rievaulx Abbey and the pollution zones with which they are associated is shown in Figure 6.6, below. It would appear that the zone represented by the highest number of species is Zone 3, although there is also a peak in the bar chart for Zone 5 species. This might suggest a mean winter sulphur dioxide level of somewhere between about 60 and 125µg/m^3. This is a very broad spread, especially for a rural area and one value or the other may be the true figure, or it may lie somewhere between the two. A method of determining which is more likely needs to be found.

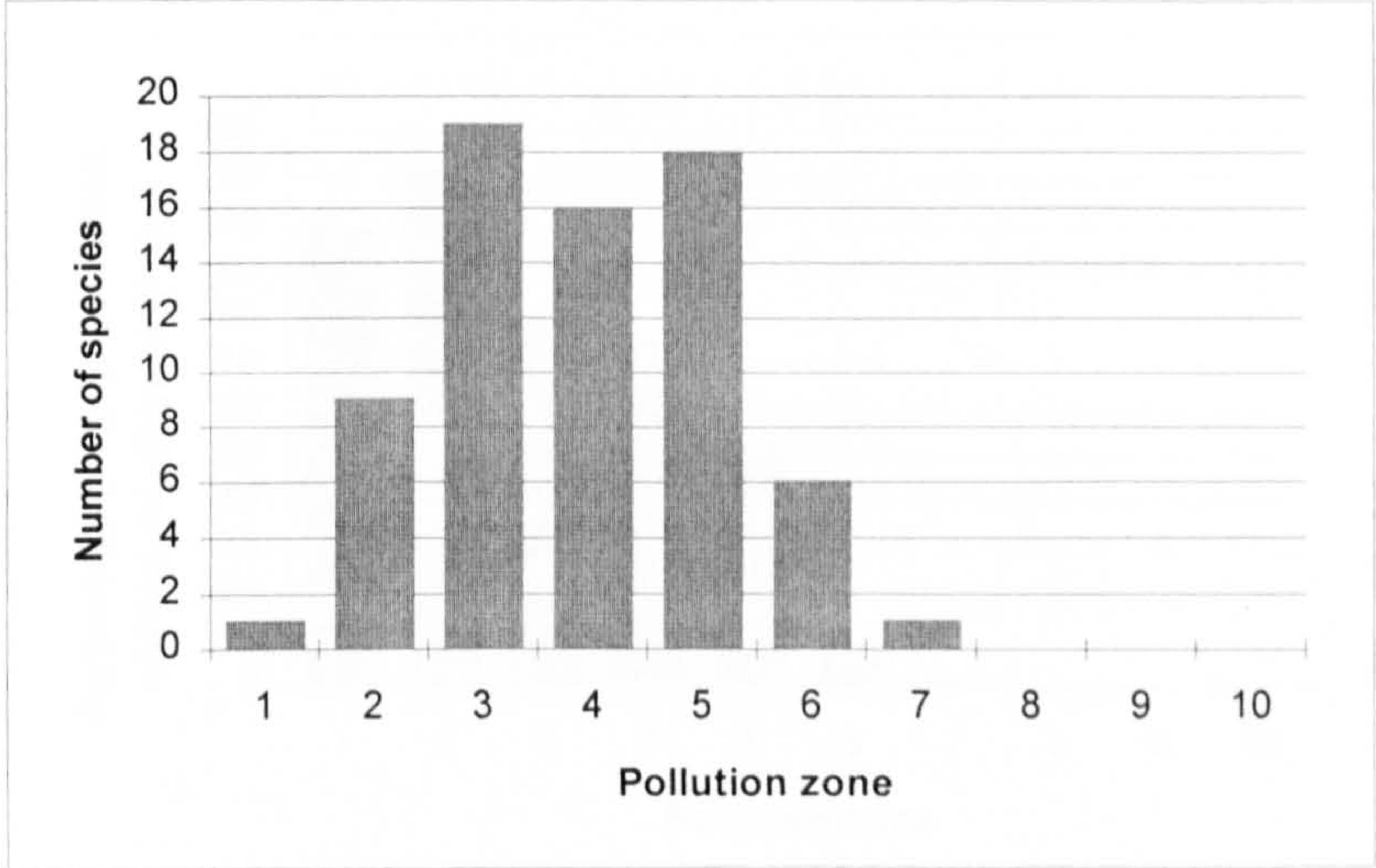


Figure 6.6 Rievaulx Abbey Lichen survey 2000: Species and pollution tolerance

The method of analysis, which plots numbers of species against their respective pollution zones, is only one way of looking at the data. In terms of providing an indication of the likely level of atmospheric sulphur dioxide, it may provide a somewhat distorted view. This is because it takes no account of all the species likely to be found at Rievaulx and their respective pollution tolerances.

Included in Appendix 8 are a series of bar charts which plot the frequencies of lichen species on the substratum on which they normally occur against their pollution tolerance. These bar charts were plotted from data extracted from Dobson (2000) where over 490 species have been associated with particular pollution zones, out of the 700 species described, illustrated and named by Dobson. This is from a total of the 1,700 or so lichen species of Britain (Dobson 2000, p.7). It can be seen from these bar charts that of species which are normally found on all types of rock, more species are associated with pollution Zones 5, 6 and 7 than any others. So at Rievaulx there might be a disproportionate number of species present representative of those zones. This is in fact what Figure 6.6 revealed.

Figure 6.7 shows the percentage of likely species in each pollution zone.

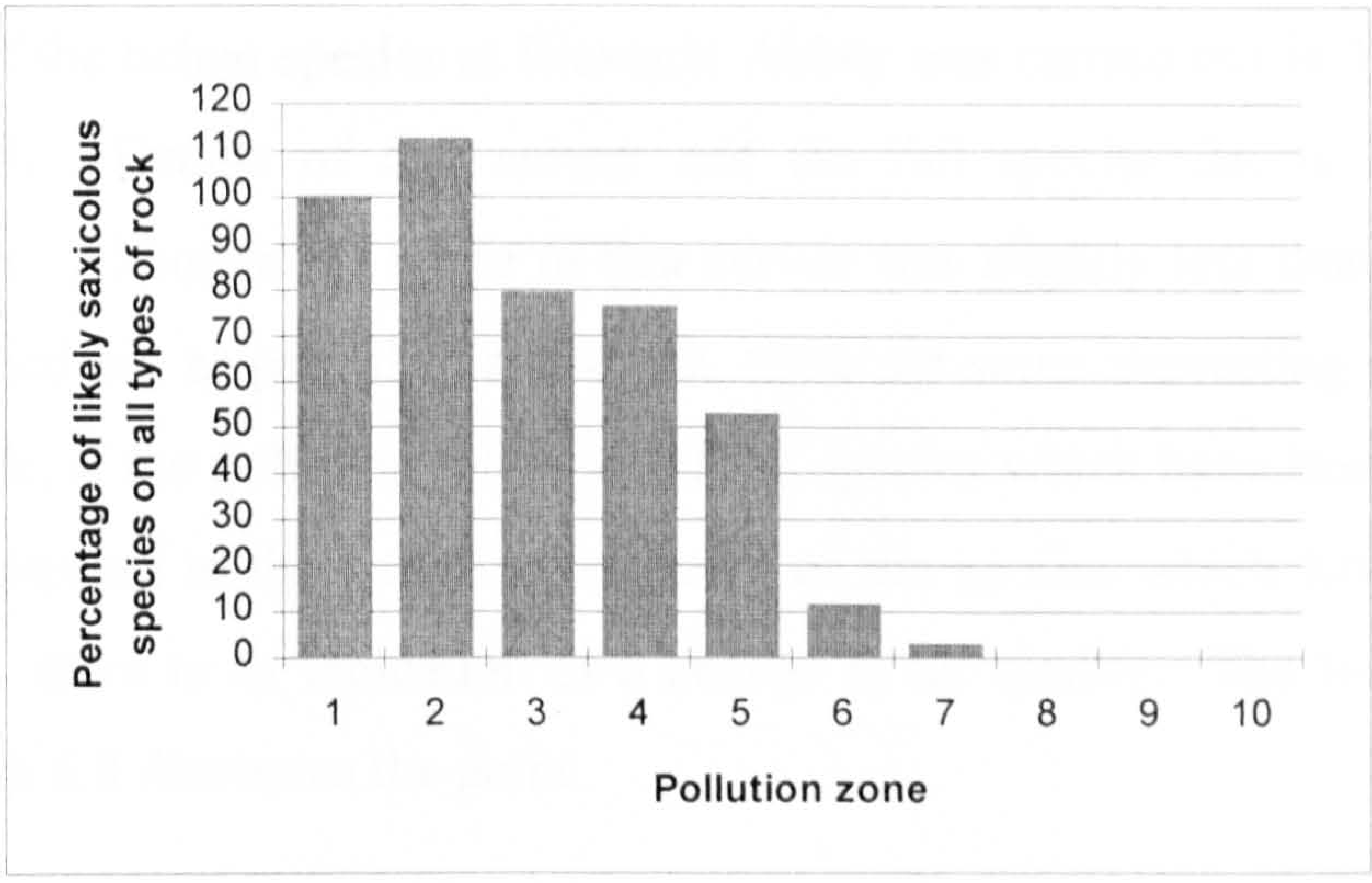


Figure 6.7 Rievaulx Abbey lichen survey 2000: Percentage of likely species, and pollution tolerance

Caution must still be exercised in interpreting the results, since only one species, *Lecanora dispersa*, is associated with Zone 1, and only eight saxicolous species area associated with Zone 2; therefore, it is possible that all those species might be present, but it would not necessarily indicate that a site is in Zone 1 or even Zone 2 because the species of these zones tend to be enthusiastic colonisers, particularly of basic substrata, no matter what the air quality. Caution must be exercised in the interpretation of these bar charts, but in the case of Rievaulx Abbey it is more likely that the Zone 3 species, of which 79% of the possible number were recorded, compared to only 53% of the Zone 5 species. It should be noted that 113% of the Group 2 species were recorded. A percentage over 100 was calculated because one species, *Lecanora expallens*, is normally associated with trees, but is also found on rocks (Dobson 2000, p.193).

Faced with the current levels of data, it is difficult to interpret the exact level of atmospheric sulphur dioxide which the lichen flora of Rievaulx Abbey alone suggest; however this can be achieved with more certainty by comparing the frequencies between sites and between surveys.

Comparison with previous surveys:

2000 survey and 1989 survey

A survey of the lichen species at Rievaulx Abbey was carried out in 1989 (Smith *et al.* 1989). Details of that survey and the full species list is included in Appendix 8. Although the scope of that survey was slightly less than that of the survey carried out as part of this research, there are some interesting differences. For example, if the pollution tolerance of the species which have been lost since 1989 is compared to the pollution tolerance of the species which have appeared since 1989, there is an indication of a change in air quality. The following bar chart, Figure 6.8 illustrates the point.

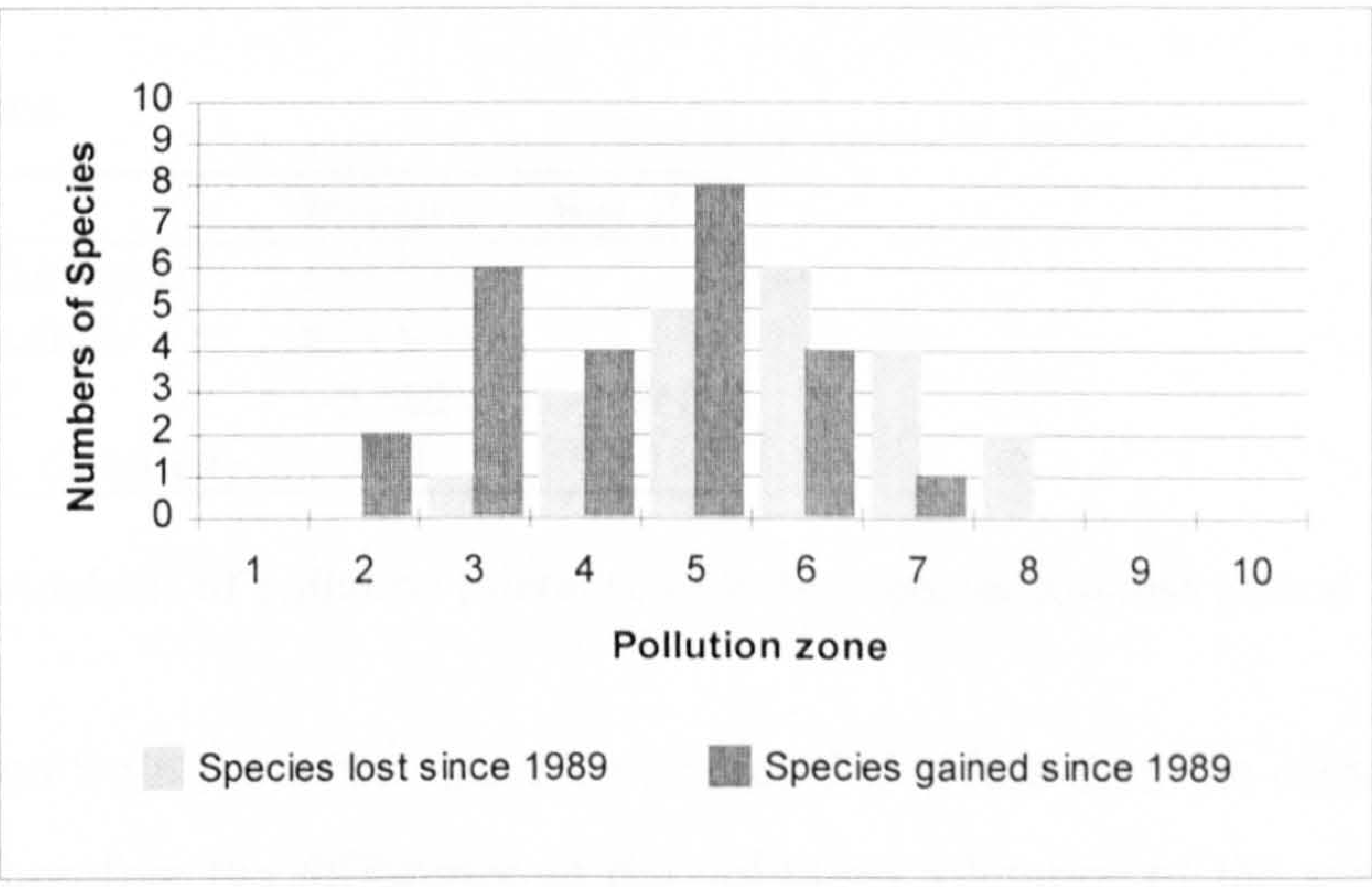


Figure 6.8 Rievaulx Abby lichen survey 1998 and 2000: Pollution tolerance of species lost and gained

The species which have been lost since 1989 are species associated with lower levels of sulphur dioxide than the species which have appeared since 1989. In any survey of lichens there is always room for error; species may be overlooked, particularly on large, complex sites such as Rievaulx Abbey. Don Smith, one of three lichenologists involved in the 1989 survey and, with the writer, involved in the 2000 survey, has commented 'It is interesting to see what has disappeared, particularly items that would be difficult to miss e.g. *Lecanora polytropa.*' (Smith, in lit. 2000). What Smith is suggesting is that it is unlikely that species recorded in 1989 would be overlooked in 2000 if they were still present, particularly as both surveys, from the analysis point of view, covered the same areas of the abbey.

A significance test can be applied to the frequency distributions of the two groups, to determine if the apparent difference in pollution tolerance is real, or if it could have occurred by chance. The null hypothesis was that there is no difference between the pollution tolerance of the two groups of species. The alternative hypothesis was that there *was* a difference. The test was, therefore, a two-tail test. Since the two groups are independent of each other, and there are different numbers of species in each group, the Mann-Whitney test was used to analyses the pollution zone numbers of the species in each group. Table 6.12 shows the output from *SPSS*.

Test Statistics

	Results	**Sig. *Z***
Mann-Whitney U	148.500	
Wilcoxon W	554.500	
Z	**–3.002**	<–1.960
Asymp. Sig. (2-tailed)	.003	

Table 6.12 Analysis of pollution tolerance of lichen species lost and gained

It can be seen from the table, that the calculated *Z* is less than the critical value of –1.96 and therefore the difference in the pollution tolerance of the species gained and lost is significant at the 0.05 level. The direction of the significance can be determined by reference to the average value of the pollution tolerance for each group. These values are, rounded to the nearest whole number, 4 and 6 for gains and losses, respectively. So it can be concluded that the species which have been lost from Rievaulx Abbey since 1989 have, as a group, significantly lower tolerance to atmospheric sulphur dioxide than the species which have appeared over the same period. This being so, changes in pollution levels might also be detectable in the tolerance of all the species, in each survey.

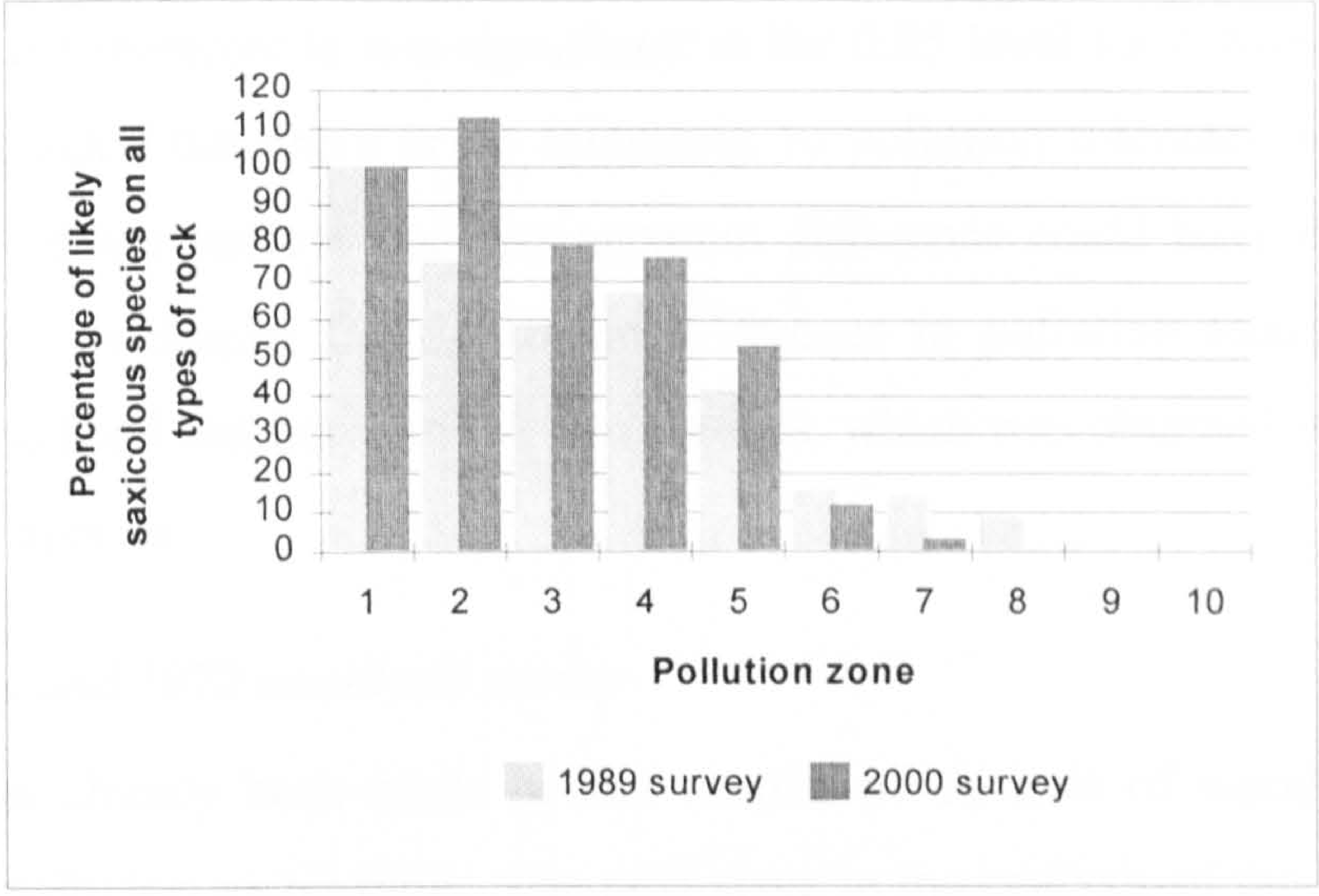


Figure 6.9 Rievaulx Abbey lichen surveys: Pollution tolerance of species recorded in 1989 and 2000

If the frequency distributions of the pollution tolerance of all the species recorded in 1989 and 2000 are compared, as shown in Figure 6.9, it can be seen that there has been a shift in the overall pollution tolerance from Zone 4 to Zone 3, discounting *Lecanora dispersa* of Zone 1, and species from Zone 2. A significance test can be carried out on the two frequency distributions, to determine if the difference between them is a chance occurrence, or not. It should be pointed out, however, that the distribution in Figure 6.9, and subsequent Figures in this section, show percentages of possible species per pollution zone, but the significance tests were performed on the raw data, from which, for example, Figure 6.8 was plotted. The null hypothesis was that there was no difference between the two distributions. The alternative hypothesis was that there was a difference between them, and so a two-tail test was conducted. Table 6.13, below, gives the output generated by *SPSS*.

Test Statistics

	Results	**Critical *Z***
Mann-Whitney U	1884.000	
Wilcoxon W	4369.000	
Z	–1.620	<–1.960
Asymp. Sig. (2-tailed)	.105	

Table 6.13 Analysis of pollution tolerance of lichen species in 1989 and 2000 surveys

It can be seen from the table that the calculated Z is greater than the critical value of -1.960, and therefore is non-significant at the 0.05 level for a two-tail test. It can be concluded that there is no difference in pollution tolerance between the species in the two surveys and any apparent difference could have occurred by chance. This is despite the significant difference in pollution tolerance of the species gained and lost between the two surveys, which was obtained with smaller numbers of species.

1989 survey and 1970 woodland survey

Mention has already been made in this chapter of the role of woodland lichen surveys in pollution monitoring. The next stage in the analysis of the lichen flora of Rievaulx Abbey was to compare the pollution tolerance of the species in the two surveys considered so far with the pollution tolerance of species recorded in 1970 (Rose 1970) in woodland to the west of Ashberry Hill, located just to the west of Rievaulx Abbey. Details of this survey and the species list are included in Appendix 8. If there has been a change in levels of atmospheric sulphur dioxide in the Rye valley, then significant differences might be expected between the pollution tolerance of the species recorded in the woodland survey and the two surveys already discussed.

By comparing the frequency distributions of the pollution tolerance of the woodland species recorded in 1970, and those recorded on the abbey in 1989, as shown in Figure 6.10, it can be deduced that the likely level of atmospheric sulphur dioxide indicated by the woodland species, with a peak at Zone 3 is higher than indicated by the species recorded on the abbey which has a peak at Zone 4.

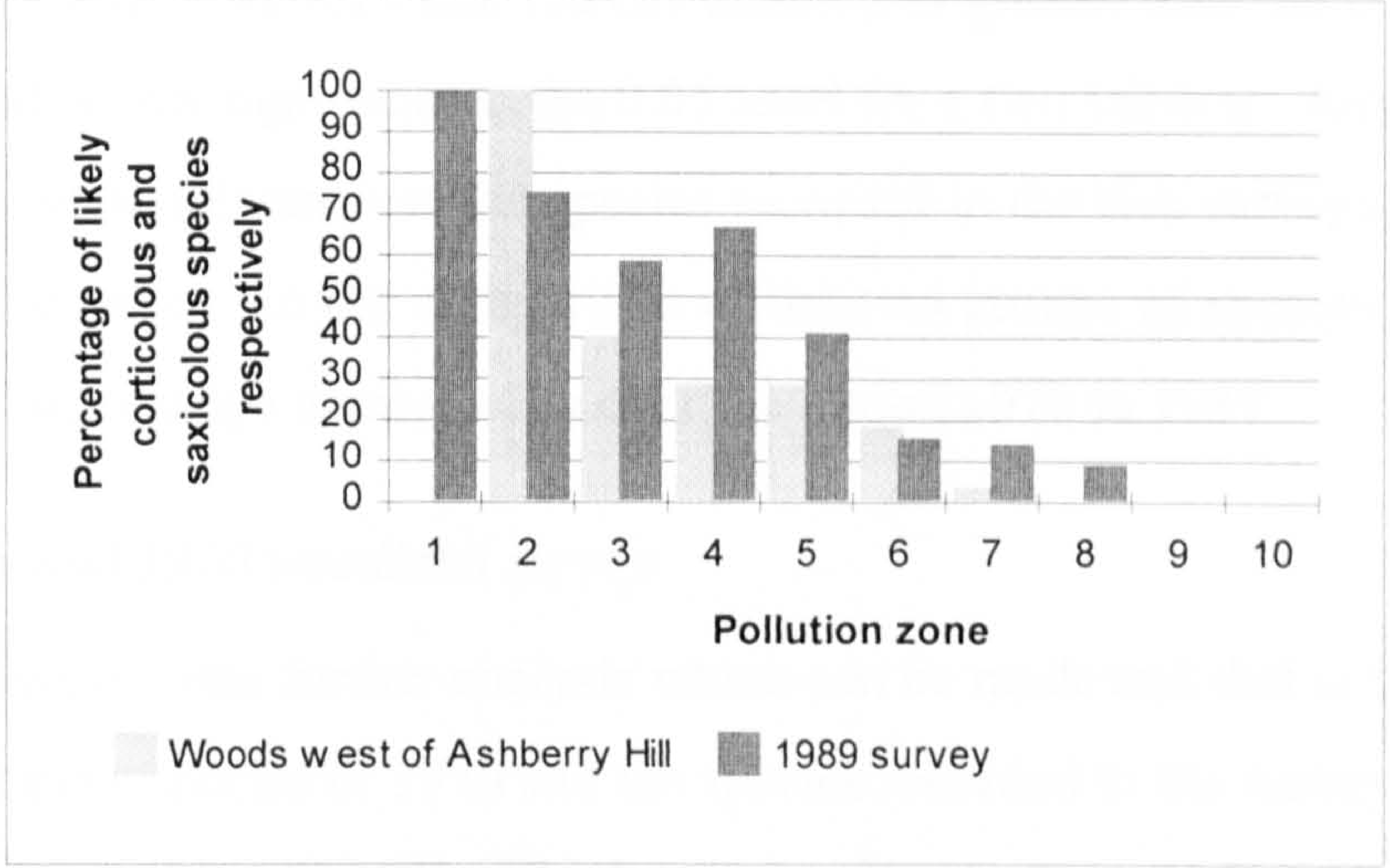


Figure 6.10 Rievaulx Abbey lichen surveys: Comparison of woodland and 1989 survey species

It should be noted that the 100% of Zone 2 species recorded in the woodland represents only three species. These species, according to the descriptions in Dobson (2000), have a preference for trees or bark although Richardson illustrates nine such species as 'indicator' species (Richardson 1992, plate 4); nevertheless, the method of analysis here is still valid. This is because no matter which species different authorities consider to be principally corticolous, or saxicolous, the numbers of each as calculated from Dobson's descriptions are used as the basis for analysis of all the lichen surveys considered in this research.

The differences in pollution tolerance between the species recorded in the 1970 woodland survey, and those recorded on Rievaulx Abbey in 1989 can also be subjected to significance testing, with the same null, and alternative hypotheses as used before. The output generated by *SPSS* is shown in Table 6.14, below.

Test Statistics

	Results	**Critical *Z***
Mann-Whitney U	626.500	
Wilcoxon W	2706.500	
Z	–0.780	<–1.960
Asymp. Sig. (2-tailed)	0.435	

Table 6.14 Analysis of pollution tolerance of lichen species recorded in the 1989 survey of Rievaulx Abbey and those recorded in 1970 in woods to the west of Ashberry Hill.

It is evident from Table 6.14 that the calculated Z is greater than the critical value of -1.96, and is non-significant at the 0.05 level for a two tail test. Any difference between pollution tolerance of the species recorded in the two surveys could have occurred by chance. So the comparison of the two groups of species provide no evidence of any change in air quality over the period 1970 to 1989.

2000 survey and 1970 woodland survey

There is, however, one further analysis which can be made and that is between the woodland survey species of 1970 and the species recorded in the survey conducted as part of this research, in 2000. The frequency distributions of the pollution tolerance of the lichens from each survey is illustrated in Figure 6.11.

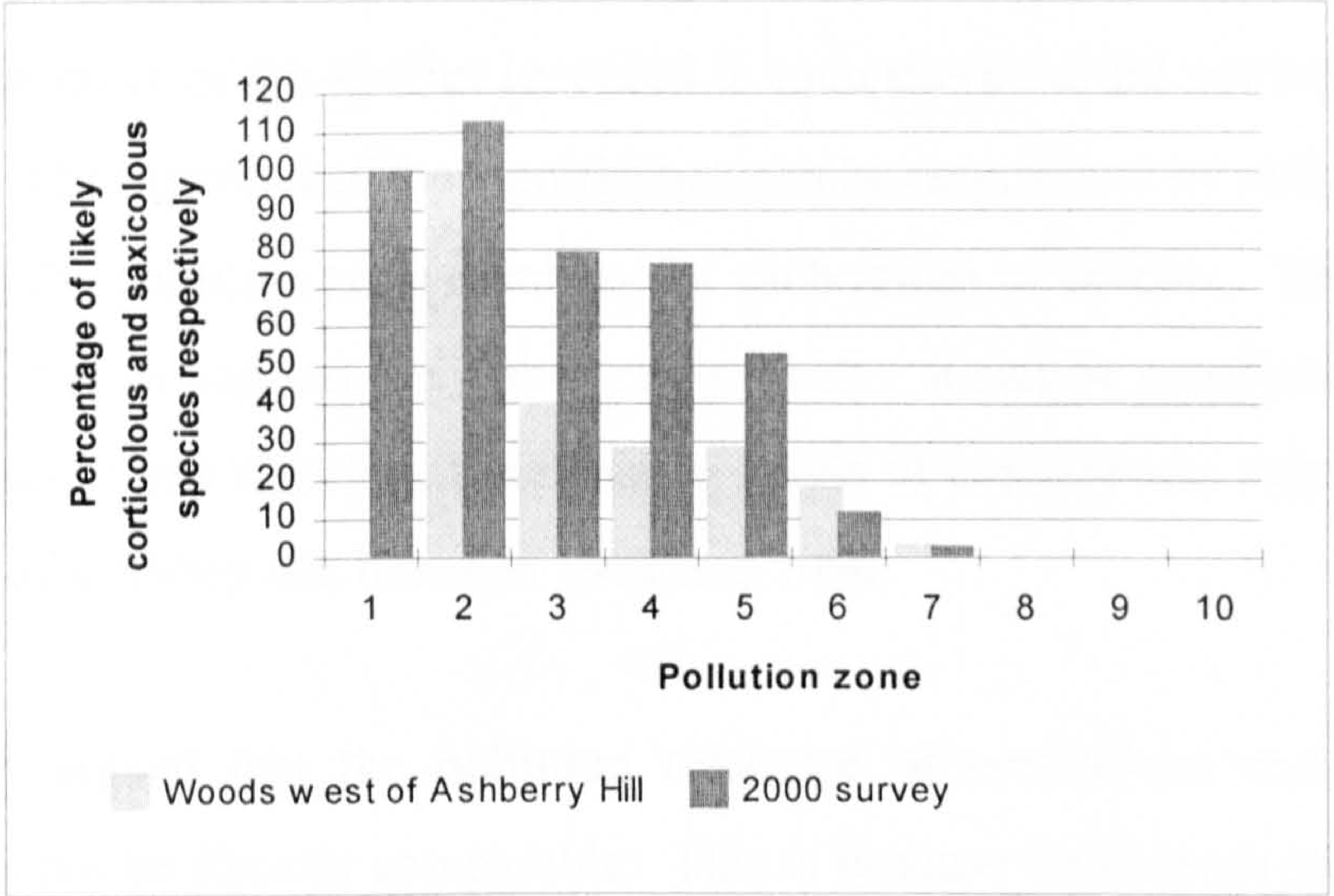


Figure 6.11 Rievaulx Abbey lichen surveys: Comparison between woodland and survey 2000 species

The distribution of the pollution tolerance of the two groups, discounting Zone 1 and 2 species are similar, although there is a greater percentage of likely species present for each zone in the 2000 survey than in the woodland survey despite there being a far greater number of likely corticolous species for each zone than saxicolous.

The significance of the differences in the pollution tolerance of the species in the two surveys was analysed as before, with the same null and alternative hypotheses. The output generated by *SPSS* is shown in Table 6.15.

Test Statistics

	Results	**Critical *Z***
Mann-Whitney U	547.000	
Wilcoxon W	3032.000	
Z	**–2.088**	–1.960
Asymp. Sig. (2-tailed)	.037	

Table 6.15 Analysis of pollution tolerance of lichen species recorded in the 2000 survey of Rievaulx Abbey and those recorded in 1970 in woods to the west of Ashberry Hill.

Table 6.15 shows that the calculated *Z* is less than the critical value of –1.960 at the 0.05 level of significance, for a two-tail test and therefore the difference in pollution tolerance of the species recorded in each survey could not have occurred by chance. The direction of the significance can be determined by reference to the averages of the pollution zone numbers for each group of species. These are 3.9, and 4.0, for the woods and the Abbey respectively. It can be concluded from this that there has been a significant increase in levels of atmospheric sulphur dioxide at the Rievaulx Abbey site between 1970 and 2000.

It could be argued that the pollution tolerance of corticolous and saxicolous species may not be directly comparable. This is because differences in substratum pH levels and the range of such levels will favour groups of species with different habitat preferences; however, the significance of this analysis is reinforced by the work of Henderson and Seaward, mentioned in the previous case study, who suggested that corticolous species tend to give an indication of past levels of air pollution, while saxicolous species, with their superior powers of re-colonization, are more indicative of present levels (Henderson and Seaward 1976, p.67). This is an aspect which will be discussed further in the next case study.

2000 survey and 2000 survey of the Tuscan Temple on Rievaulx Terrace

There is one final test which can be performed and that is to determine if there is any evidence of stratification of sulphur dioxide pollution levels in the Rye valley. This can be done by comparing the pollution tolerance of the lichen species recorded on the Abbey in 2000 and the pollution tolerance recorded on the Tuscan Temple on Rievaulx Terrace. The Terrace overlooks the ruins of Rievaulx Abbey and is some eighty-five meters higher than the valley floor.

The micro-climate of this part of the Rye valley has long been recognised for its potential as a frost pocket (Senior 1999, p.215), where cold winter air sinks and is trapped on the valley floor. During the winter months, when power station emissions are at a maximum, this air will be pollution-laden. It might be expected that there would be evidence in the lichen flora of the abbey, compared to the Tuscan Temple on the Terrace above, for stratification of air pollution levels. The analysis was conducted in the same way as previously.

The distributions of pollution tolerances shown in Figure 6.12, below, show a higher percentage of Zone 3 species at Rievaulx Abbey, discounting Zone 1 and 2 species, than for any other zone. By comparison, the species on the temple at Rievaulx Terrace although considerably fewer in number, show that the highest percentage of species is associated with Zone 5. This suggests that the level of atmospheric sulphur dioxide is considerably less at the level of Rievaulx Terrace than on the valley floor, although this difference will undoubtedly be seasonal, for the reasons given above.

Although the two distributions indicate a difference in pollution levels, significance testing will reveal whether these differences have occurred by chance, or not. The null hypothesis was that there was no difference in the two distributions; the alternative hypothesis was that there was a difference, and the direction of the difference was that indicated by the mode values of the two distributions and therefore a one-tail test was conducted. The conventional significance level of 0.05 was used. Table 6.16, below shows the output generated by *SPSS.*

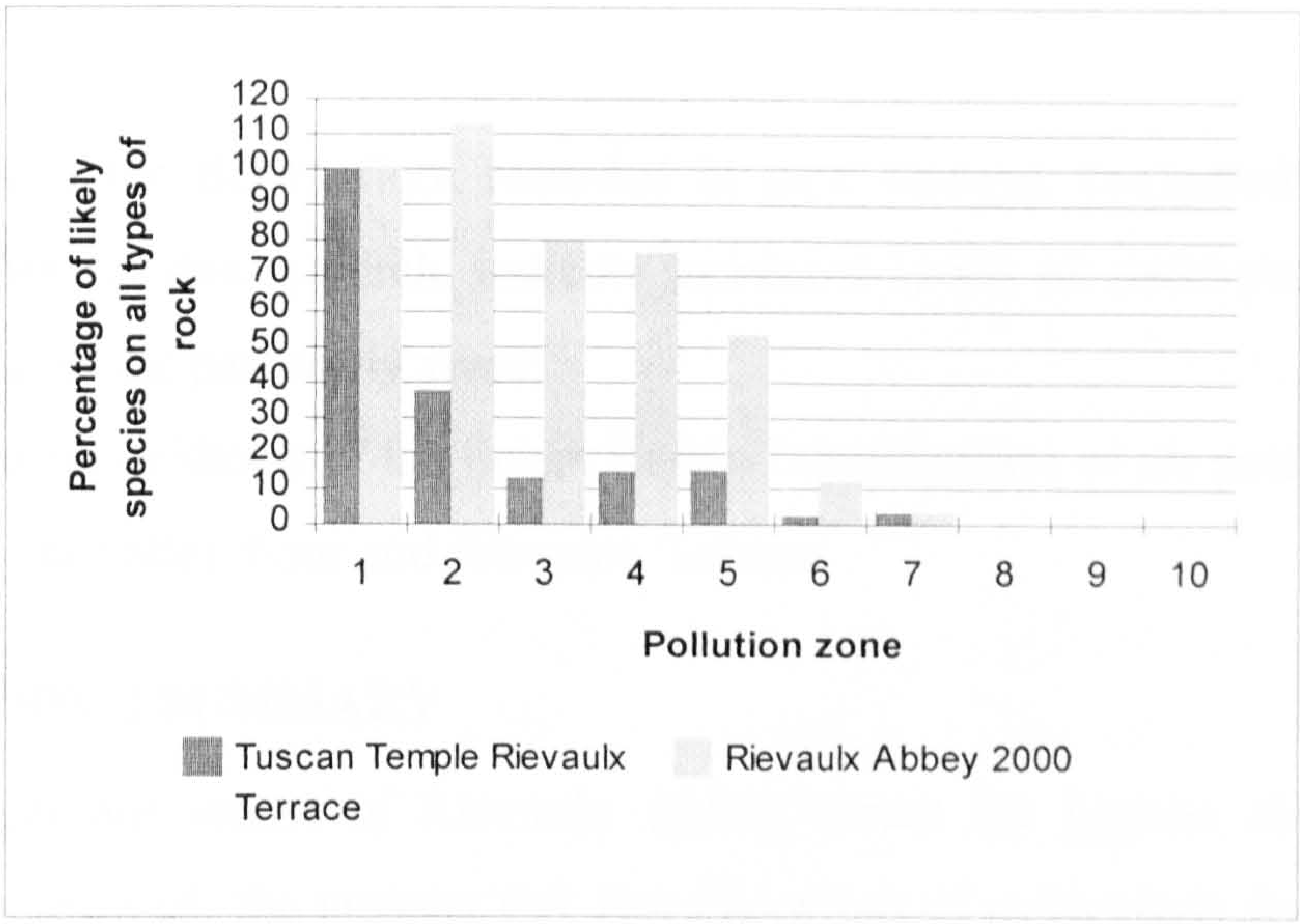


Figure 6.12 Tuscan Temple, Rievaulx Terrace and Rievaulx Abbey 2000 survey: lichen pollution tolerance

Test Statistics

	Results	Critical *Z*
Mann-Whitney U	592.000	
Wilcoxon W	745.000	
Z	–0.033	–1.645
Asymp. Sig. (2-tailed)	0.974	

Table 6.16 Analysis of pollution tolerance of lichen species recorded in the 2000 survey of Rievaulx Abbey and those recorded in the 2000 survey of the Tuscan Temple on Rievaulx Terrace.

It can be seen that the calculated value of *Z* is greater than the critical value of –1.645, and so is non-significant for a one-tail test at the 0.05 level. It can be concluded that, with this comparison, there is no evidence for stratification of sulphur dioxide levels in this area and the differences in the distributions shown in Figure 6.12 could have occurred by chance; they are, in effect, the same.

Summary

- Analysis of the lichen flora recorded in past surveys, compared to surveys carried out for this research, indicate increased levels of atmospheric sulphur dioxide over the past thirty years;
- there was no evidence in the lichen flora of stratification of air pollution levels between the valley floor and Rievaulx Terrace.

CASE STUDY 2 SUMMARY

- The calcareous stones of Rievaulx Abbey attract the highest abundance of lichen cover, with the greatest risk that the action of particularly frost and acid rain will be potentiated by the lichen cover;
- the siliceous stones are resistant to acid rain, attract lesser degrees of lichen colonisation and so the weathering risk to them is less;
- Analysis of the lichen flora indicates that levels of atmospheric sulphur dioxide has risen over the past thirty years and this confirms the finding of similar analyses conducted on the lichen flora of the Tuscan Temple at Duncombe Park, discussed earlier in this chapter;
- weathering by atmospheric sulphur dioxide must now be considered to be the dominant weathering mechanism at this site.

PART 3 – HAREWOOD CASTLE AND SLINGSBY CASTLE

INTRODUCTION

This case study is a comparative analysis of two castles which have many similarities, but also have significant differences.

The similarities are that they were both built on the site of former castles; they are now both ruins; they are both in private ownership; neither are accessible to the public; neither have had any major consolidation or conservation work since they became disused; they are both associated with country house Estates, although both pre-date the Estates and their designed landscapes; they are both the subject of draft Conservation Plans prepared within the past eighteen months.

The differences are that one was built in the seventeenth century, the other in the fourteenth; one is in rural North Yorkshire, while the other is only a short distance from a large industrial conurbation; one has a relatively rich lichen flora, the other has an impoverished lichen flora; one exhibits extensive weathering and physical damage to the building fabric, the other has neither. These two castles are Slingsby and Harewood castles, respectively. It is these differences, and their implications for the conservation of ruins, which will be investigated in this case study.

Geographical location

Harewood

Harewood Castle is located at Ordnance Survey grid reference SE 322457. It is situated about half a kilometre to the north of the village of Harewood, which is roughly equi-distant between Leeds and Harrogate, in the West Riding of Yorkshire. The castle is on an elevated site, overlooking the river Wharfe. In 1822, John Jewell wrote:

> 'This beautiful ruin is nearly all covered with ivy, and situated on the steep slope of a hill rising southwards, on the north side of the village, on Bondgate; it is about eighty yards from the Harrogate road, which winds gradually down the hill

> towards the vale of Wharfe; whose beautiful mazes may be traced to a considerable distance, which gives a softness and beauty to the scene; the eye wanders with infinite delight across a beautiful extent of country, twenty miles distant from York. On the other hand are prospects of unrivalled beauty, the vale itself opening to view the distant hills in Craven; ... causing an endless variety of picturesque beauties.'
>
> (Jewell, 1822, p.63-64)

The castle lies within the Harewood House Estate, which has been in the ownership of the Lascelles family since the early eighteenth century, but is now managed by the Harewood House Trust. Figure ap9.22 in Appendix 9 shows the location of Harewood Castle.

Slingsby

Slingsby Castle is located at Ordnance Survey grid reference SE 696749. It lies within the village of Slingsby which is situated in the Vale of Pickering, just beyond the northern limits of the Howardian Hills, about 15 kilometres south-east of Helmsley. Slingsby lies within the Castle Howard Estate, owned by the Howard family. Figure ap9.23 in Appendix 9 shows the location of Slingsby Castle.

AIMS AND OBJECTIVES

The aims

- To determine the source of the stone from which the two castles were built;
- to determine the physical properties and weathering characteristics of the respective stone types;
- to record and analyse the lichen flora of the two castles;

The objectives

- To compare the likely impact of lichen flora on the stone types of the two castles;
- to asses the relative botanical significance of the lichen flora on the two castles;
- to compare the likely levels of atmospheric sulphur dioxide, based on the lichen record;

- to draw some conclusions as to the implications of the findings for the management of plants on ruins.

HISTORICAL OVERVIEW

Harewood Castle

The castle is thought to have been completed, by Sir William de Aldburgh, in about 1327 (Jewell 1822, p.65). It is believed that this castle stands on the site of an earlier structure (see Moorhouse 1989) and may have been a remodelling of that earlier structure (Goodchild 2000, p.6).

After passing through several families by inheritance, the castle was eventually sold in 1600 to discharge the debts of the Ryther family (Goodchild 2000). It is after that date that the castle ceased to be a main residence, and soon became a ruin. The subsequent owner was obliged to sell the castle in 1656, by which time it had already become a ruin, and was advertised as a source of building stone (Goodchild 2000, p.7). It was the purchaser, Sir John Cutler, who is reputed to have reduced a great part of the castle to ruins by using the stone and timber to build farm houses, barns and walls (Jewell 1822, p.68).

After the death of Sir John Cutler in 1693, the castle and the estate of Harewood and Gawthorpe passed through the family until 1738, when it was sold to pay family debts, and was purchased by Henry Lascelles (Jones 1859; Goodchild 2000). It was the son of Henry, Edwin Lascelles, who was responsible for the building of Harewood House designed by John Carr and begun in 1758 (Summerson 1993, p.349). It was also Edwin Lascelles who commissioned Lancelot 'Capability' Brown to transform the landscape setting for the new house (Goodchild 2000), but it was Edwin's son, the 1st Earl of Harewood, who instigated the incorporation of the ruins of the castle into the pleasure grounds of the house. This was done in 1813 so that the ruins would be seen as a 'rustic picturesque', more fashionable, element in what had up until then been a 'polite picturesque' designed landscape. Certainly the views of Harewood Castle painted by JMW Turner in 1798 and 1808 are in the genre of the former (Goodchild 2000).

Repair history

Little is known about the repair history of Harewood Castle and it can not be said with any certainty whether it received active maintenance to preserve its 'rustic picturesque' appearance during the nineteenth century. What has happened to the castle in the years since the 1940s, when the present plantation was established, is not documented but, from personal memories in the 1950s it was a prominent feature overlooking the river Wharfe. It was visible from many parts of the surrounding countryside, including the equally prominent geological feature of Almsciffe Crag, but has now become 'lost', surrounded and obscured by a forest of mature coniferous trees.

The castle is now a scheduled Ancient Monument and is listed Grade I, although its condition has deteriorated through lack of maintenance. In 1998 concern was raised both by the Harewood Estate regarding its condition, and by English Heritage, who placed the castle on the Buildings at Risk register and noted its condition to be 'At immediate risk of rapid further deterioration or loss of fabric; no solution agreed.' (English Heritage 1998, p.123). Ed Dennison Archaeological Services were commissioned to prepare a condition survey and a Conservation Plan, to provide a pre-intervention record, to make recommendations regarding a phased programme of consolidation works and repairs and to make recommendations for its future long-term management (Dennison 1999). That Conservation Plan was completed in 2000, although the castle still remains on the Buildings at Risk register, but now noted as 'Slow decay; no solution agreed.' (English Heritage 2001, p.110). The castle in its present condition is illustrated in Figure ap9.24 in Appendix 9.

Slingsby Castle

There was a castle or manor at Slingsby, of sufficient importance to require a Royal licence in 1216 and a licence to crenellate was granted in 1344 (Brook 1904). During the period of the Wars of the Roses, which began in the mid fifteenth century (Trevelyan 1987, p.198) the castle was much strengthened by Lord Hastings, probably because the neighbouring Pickering Castle was Lancastrian, so by then the castle was not only crenellated but had an outer defensive wall with corner turrets and a moat (Brook 1904, p.141-143).

The original castle was presented to the Cavendishes, probably to Sir Charles Cavendish, although what became of it thereafter is unclear. It was Sir Charles Cavendish who is thought to have begun the present castle, or house, in about 1640 (Brook 1904, p.146). A more probable date of 1620 has been suggested by Pevsner (Pevsner 1992), bearing in mind the political unrest in England and Scotland in the 1640s.

It is probable that the house was never completed, not only because Sir Charles Cavendish died in 1653, but also the builders may have been called to take up arms in the Civil Wars and building work abandoned (Brook 1904, p.146). In any event, contemporary documentary evidence shows that the castle was in ruins by 1749 to such an extent that it must have been abandoned for some considerable time (Brook 1904, p.146). It is probable that after the Civil Wars, stone from the castle was reused for local building work, because there is evidence that stone taken from the castle was used to build the cellar of Slingsby rectory, as well as many of the neighbouring cottages (Brook 1904, p.150-151).

From a stylistic point of view the castle has much in common with Hardwick Hall, Derbyshire, which was built between 1590 and 1597 (Summerson 1993, p.66) and there are similarities between Hardwick Hall and the slightly earlier Wollaton Hall (Brook 1904; Summerson 1993). Wollaton and Hardwick were both built by Robert Smythson for the Cavendish family; Elizabeth Hardwick was the grandmother Sir Charles Cavendish, and the design for Slingsby is believed to be by either Robert Smythson's son John Smythson (Pevsner 1992), or by John's son Huntingdon Smythson (Girouard 1966; Brook 1904).

Repair history

If this castle was never completed, as Brook suggests (Brook 1904), then there may never have been repairs to the standing masonry. It is evident from an examination of what remains that this represents only a fragment of what was originally built, because the ground plan is complete and some masonry still stands almost to the original eaves height. It is known from the photographs in Brook that, by the beginning of the twentieth century, the fourth and fifth bay upper-storey windows and masonry on the east elevation were intact (Brook 1904, frontispiece). This section of the masonry was still intact when photographed in the early 1960s and illustrated in Girouard (Girouard 1966, illustration 173; see also Girouard 1983, p.190). By 1982 there had been considerable losses of masonry, particularly to the east elevation, which prompted Castle Howard Estates Ltd. to commission a condition report, subsequently carried out by Alan Moody with Douglas Wise and Partners (Moody 1984). Since then there seems to have been no action, until 2001 when Ed Dennison Archaeological Services was commissioned to prepare a condition report and Conservation Plan. This Plan is still in preparation. Slingsby Castle in its present condition is illustrated in Figure ap9.25, in Appendix 9.

LOCAL GEOLOGY

The area in which Harewood Castle is situated is one of Gritstone. The castle is built from Almscliffe Grit, and Almscliffe Crag, from which it takes its name, is an outcrop of this rock which forms a prominent landscape feature just over six kilometres to the north-west. The Almscliffe Grits come from the Pendelian stage of the Namurian Series. This forms the lowest and oldest phase of the Silesian Subsystem of the Upper Carboniferous (Ramsbottom *et al.*, in: Rayner and Hemingway, 1974, p.45; pp.76-79), and has extensive coverage in this area on both sides of the river Wharfe, as well as further south and to the west.

The geology of the Slingsby area, and of the Hambleton Hills, is of the Callovian and Middle Oxfordian Stage of the Upper Jurassic (Hemingway in: Rayner and Hemingway 1974, p.206-213). The sequence is comparable to that in the area of the River Rye and Rievaulx Abbey and it can be determined from the Geological

Survey 1" to 1 mile series, sheet 53 (British Geological Survey 1909) that the lowest strata is the Coralline Oolite Formation. It is most probable that the ollite for the dressing of the castle masonry is from either the Hambleton Oolite strata or the Malton Oolite strata, and the stone for the ashlar from the Middle Calcareous Grit strata which lies between the two. All three strata are of the Coralline Oolite Formation.

Sampling methods

Stone samples were taken from discarded rubble at both sites. At Harewood, the site is strewn with boulders and stones of all sizes and every suitable-sized stone which was examined proved to be the same stone type and matched the stone of the castle. It is thought that the stone was quarried locally, but there is little evidence to be seen of disused quarry sites; however, the 6" to 1 mile Ordnance Survey sheet SE 34 NW, which covers this area, shows a disused quarry site at grid reference 321455, only 250 yards south-west of the castle, and deep within the area of the plantation (Ordnance Survey 1956). A cluster of five further disused quarry sites are also shown, some 1,200 yards west-south-west of the castle, but the closest site would seem to be the most probable source.

There is the possibility that the stone for Slingsby castle originated from a quarry, now disused, just half a kilometre to the south, named on the Ordnance Survey 1:10,000 sheet SE 67 SE as 'Slingsby quarry' (Ordnance Survey 1981b). Brook, however, suggests the quarry site lies within Slingsby Banks Wood, about 1 kilometre further south (Brook 1904), although this site was not investigated by the writer because it was inaccessible at the time samples were required, due of the foot-and-mouth outbreak. Commercial quarrying is still carried out at three sites between Slingsby and Hovingham, 3 kilometres to the west, but mainly for hardcore for building and roads work. Suitable samples were sought in the discarded rubble from the castle site itself.

The castle is built from two types of stone. An oolite was used for the plinth courses, strings, window dressings, mullions, transoms and quoins and a calcareous sandstone was used for the ashlar walling. These two stone types have their characteristic appearances and any potential samples from the discarded rubble on the site were easily identifiable. Some of the samples were taken from rubble exposed after the undergrowth had been cleared in preparation of a photogrametric survey, undertaken in the spring of 2001 by Ed Dennison Archaeological Services. Other samples were taken from piles of rubble in the cellar beneath the south-east tower. No suitable samples with mosses or lichen colonisation could be found.

Stone characteristics

Table 6.17 below summarises the key characteristics of the Carboniferous Millstone Grit, used at Harewood Castle, and the two Jurassic stone types used at Slingsby Castle, based on the results of the laboratory tests discussed in Chapter Five.

Characteristics	Harewood Grit	Slingsby sandstone	Slingsby oolite
Mean density	2.2g/cc	1.9g/cc	2.4g/cc
Mean open porosity	12%	18%	10.5%
Mean capillary rise time	0.58 hours	24 hours	5 hours
Pore volume <5µm	44%	81%	95%
Freeze/thaw resistance	Good	Moderate	Poor
Soluble salts resistance	Good	Moderate	Moderate
Acid rain resistance	Excellent	Excellent	Moderate

Table 6.17 Harewood and Slingsby: stone properties and weathering characteristics

The Harewood Gritstone had the highest capillary rise time, but more than half of its pore volume was greater than five microns wide. As a consequence, this stone type had good resistance to frost and to the action of soluble salts. The quartz grains of this stone are not cemented with calcium carbonate and so it has a high degree of resistance to acid rain.

Eighty-one percent of the pore volume of the Slingsby sandstone was found to be less than five microns wide; consequently, it has only moderate resistance to frost and to the action of soluble salts. It has only a small calcium carbonate content and so has a high degree of resistance to acid rain.

The Slingsby oolite has a higher density and a lower porosity, but 95% of the pore volume was found to be less than five microns wide; consequently, this stone type proved to be vulnerable to the action of both frost and salts. The resistance to acid rain was only moderate because, with time, it will be completely dissolved in an acidic atmosphere, although in the short term the formation a calcium sulphate 'skin' may afford some protection.

Laboratory tests do not necessarily provide reliable indications of weathering characteristics; nevertheless, they are a good starting point and from the foregoing it would appear that the choice of the Coralline oolite for the weathering elements at Slingsby may have been a bad choice. There is little visible evidence of any differential weathering of the ashlar, but it is well recognised that gypsum resulting from rainwater run-off from calcareous stones can initiate weathering of non-calcareous stones below. Only laboratory tests on samples of ashlar would confirm whether this mechanism is implicated in weathering at Slingsby.

THE LICHEN SURVEYS

Details of the method adopted for these two lichen surveys, along with the species lists, consolidated species lists and associated data, can be found in Appendix 8. Plans and elevations of each castle, on which are indicated the location of the lichen species, are included in Appendix 9 along with illustrations of some of the lichen species. The plans, elevations and lichen illustrations constitute Figures ap9.26 to 39 inclusive.

Lichen distribution in Yorkshire

In assessing the significance of lichen flora at historic sites, it is useful to know how the species composition relates to the species in the surrounding areas. Data compiled by Seaward to map lichen distribution in Yorkshire (Seaward 1994), has enabled a comparison to be made between the species recorded at these two sites and their wider distribution. Seaward's data is in the form of the number of 10 kilometre grid-squares in which each species has been recorded. There are 195 such grid-squares covering Yorkshire. By plotting the numbers of species recorded at these two sites against the number of grid-squares in which they have previously been recorded, an insight can be gained into their wider distribution, and this is shown in Figure 6.13, below.

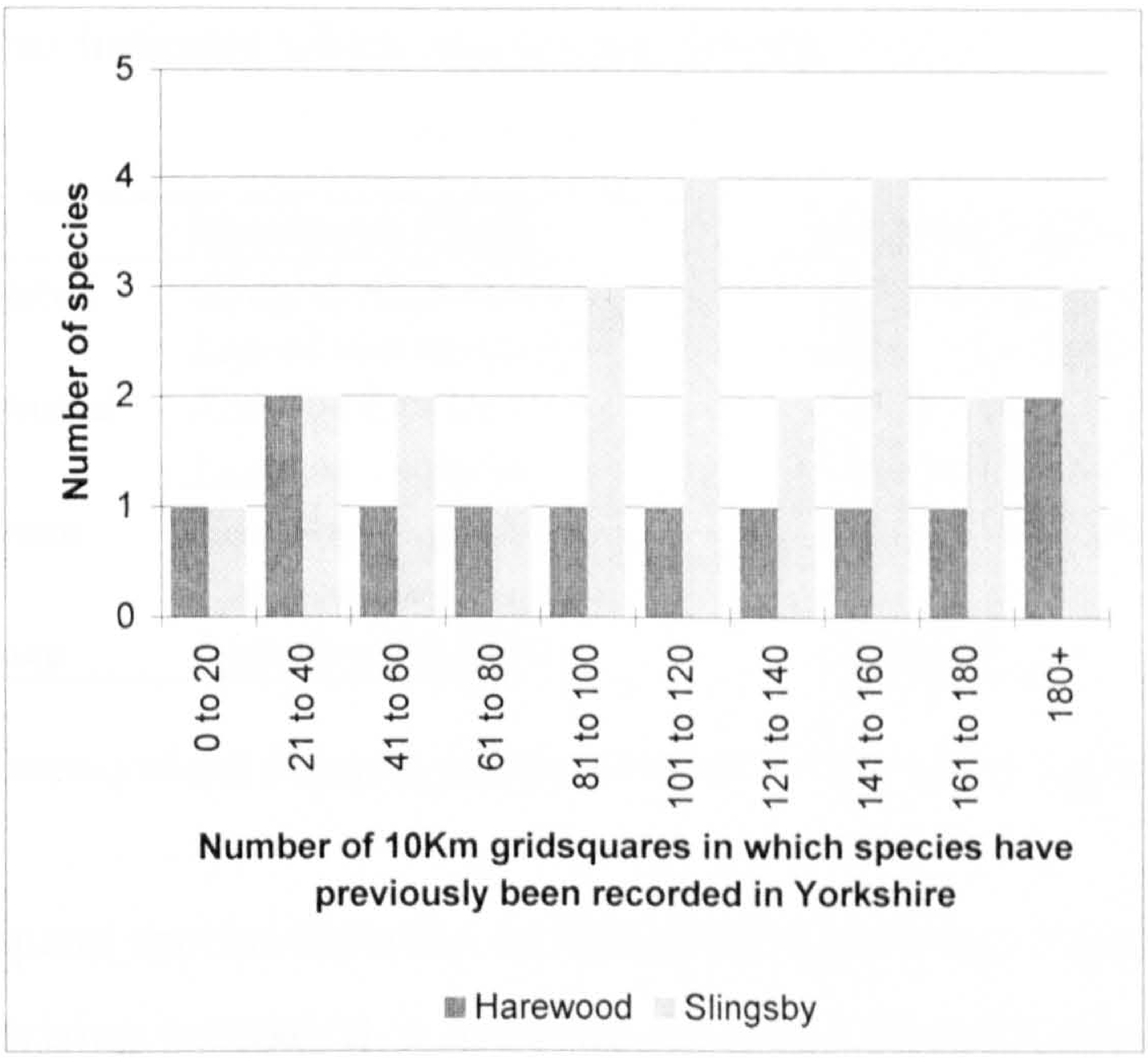


Figure 6.13 Harewood and Slingsby: lichen species recorded and their distribution in Yorkshire

It can be seen from the Figure 6.13 that both sites provide habitat for species which are represented throughout the county, including species which are commonly encountered and species which are relatively infrequent.

The species which are under or over represented at these two sites can be determined by comparing their frequencies with their frequency in Yorkshire. In order to achieve this all the frequencies were transposed to the frequency scale of one to four, used at Harewood Castle. The results are shown in Figure ap7.1 included in Appendix 8.

By comparing these distributions it is possible to determine the extent to which these ruins provide an unique habitat for lichens. Seaward's frequencies are geographical distributions and are all-inclusive with respect to substratum types. The frequencies recorded at Harewood relate to the siliceous stone from which the castle was built, while the frequencies at Slingsby relate to calcareous stone. It would be surprising if there were any similarities between the three distributions. The important matter is to determine where the differences lie and their implications. Table 6.18 below lists the species which are most notably under, or over represented at the two sites compared to their distribution in Yorkshire. Table 6.18 also indicates which species are notably present, or absent from these sites.

	Harewood Castle	**Slingsby Castle**
Over-represented	*Opegrapha calcaria* *Leproloma vouauxii*	*Caloplaca flavescens* *Xanthoria candelaria*
Under represented	*Xanthoria calcicola* *Lecania erysebe*	*Xanthoria parietina* *Lecanora dispersa*
Notable presence	*Xanthoria calcicola* *Opegrapha calcaria*	*Candelariella mediens*
Notable absence	*Lecanora dispersa*	*Lepraia incana*

Table 6.18 Harewood and Slingsby Castle: Over and under represented lichens

The most frequent species recorded on Harewood Castle was *Opegrapha calcaria*, which is surprising because it is a species of damp, shaded *calcareous* substrata (Dobson 2000, p.250). *Leproloma vouauxii*, also a species of shaded rocks and walls (Dobson 2000, p. 214), thrived at this site, undoubtedly because of the dense tree planting in the immediate vicinity of the castle. *Xanthoria calcicola*, only exceptionally found on acid rock (Dobson 2000, p. 411) was represented by only one occurrence at Harewood. *Lecania erysebe*, also one of the least frequent species at Harewood, is noted as being common in cracks on calcareous substrates and a notable and ubiquitous urban species (Dobson 2000, p.182). *Lecanora dispersa* with one of the highest frequencies in Yorkshire and with high pollution resistance, is not represented at Harewood at all because it is principally a lichen of nutrient-rich basic substrates.

At Slingsby, *Canelariella mediens* was one of the five most frequent species, despite it being rare on natural calcareous substrates (Dobson 2000, p.102). *Xanthoria candelaria*, a species of horizontal rock and bird-perching sites (Dobson 2000, p.411), was over represented at Slingsby, but *Xanthoria Parietina*, with its similar substratum preferences and a greater resistance to air pollution (Dobson 2000, p.413) was under represented. Also, more notably under-represented, was *Lecanora dispersa.* Although it was the dominant species at Harewood, *Lepraria incana* was absent from Slingsby, despite it being one of the most frequently recorded species in Eastern Britain. This is undoubtedly because it is a species of shaded, acid rocks (Dobson 2000, p.211).

The above is a very polarised way of examining the species compositions, but it can be taken a stage further by examining the extent to which the species have capitalised on niche substratum habitats provided by the two castles.

Habitat and substratum

Mention has been made of substratum preferences for lichen species and perhaps this matter should be expanded upon. Limestones and calcareous sandstones as used at Slingsby tend to have a higher surface pH than, for example, gritstone used at Harewood Castle. Lichens are known to be sensitive to substratum pH levels (Dobson 2000; Gilbert 2000; Baron 1999; Smith 1921). Some prefer alkali surfaces and others prefer, or tolerate, a more acidic environment. Lichens will grow on a variety of substrata, including trees, shrubs, mosses, soil, and, rocks and stone. Of the species which normally colonise stone, some will thrive on sandstone and others on limestone. This is so provided that other critical factors, such as air quality and illumination levels, are at an optimum for the species concerned. This data contained in the consolidated species lists in Appendix 8 has been used to produce Figure 6.14.

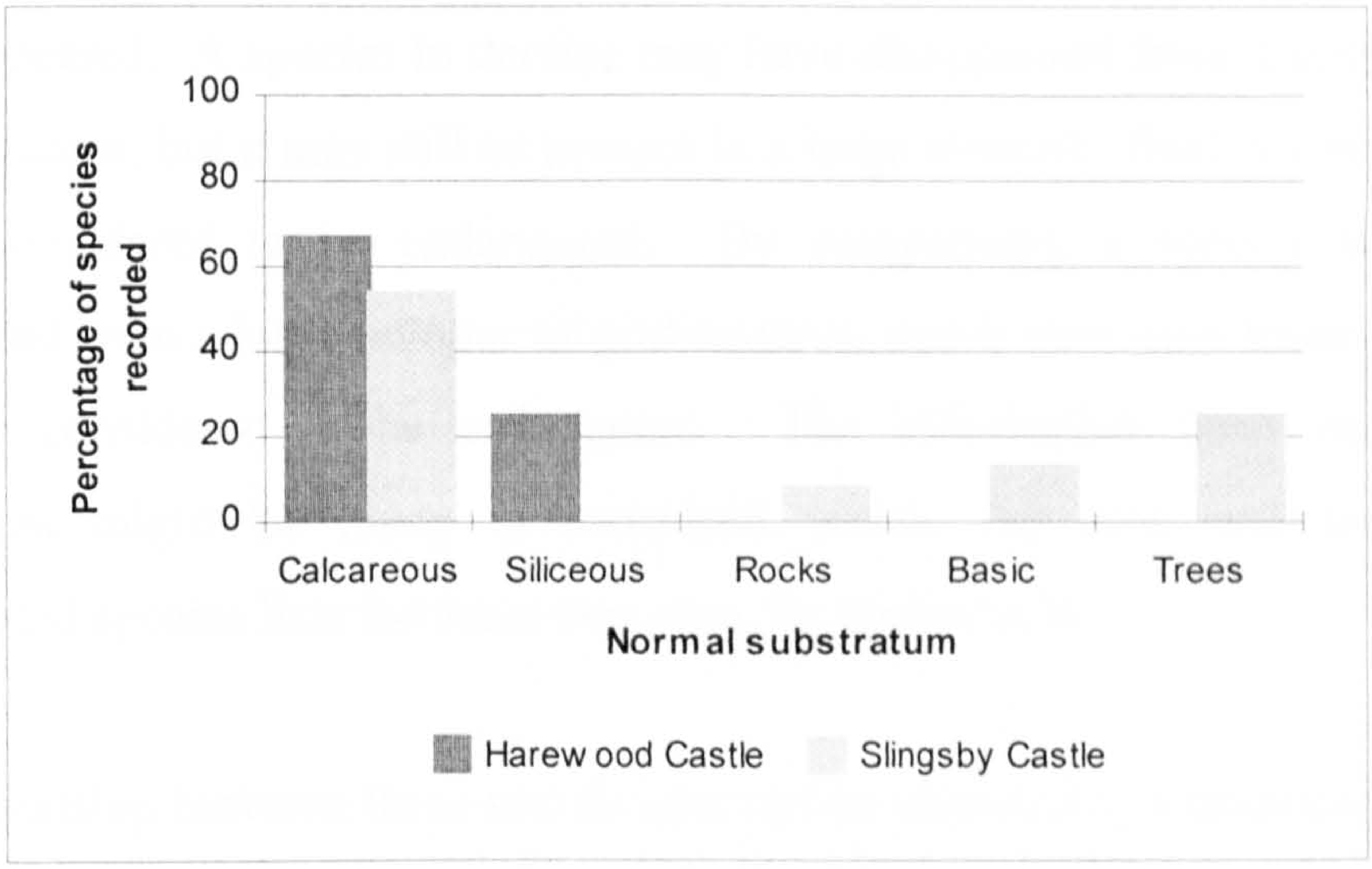


Figure 6.14 Substratum preferences

It can be seen from Figure 6.14 that over 60% of the Harewood Castle species are normally found on calcareous substrata. Only two, *Baeomyces rufus* and *Lepraria incana*, are normally associated with acidic substrata. In the absence of pH level measurements for the stone of Harewood Castle, the probable explanation is that the natural acidity of the stone has been neutralised by run-off from the lime mortar used to bed and joint the stone. Lime mortar 'cures' back to calcium carbonate which binds the aggregate in the mortar. Calcium carbonate is relatively soluble in water (Drever 1994) compared to other rock-forming minerals and in solution, can be absorbed into the pore-spaces of the sandstone. A brief summary of the chemistry involved in this process is described later under the heading 'Air quality and weathering of the monument'. The result is that Harewood Castle provides habitat for species of lichens which would not be expected to be found on naturally occurring rock and stone in that region.

Species stability

There are several factors which affect the stability of species communities at historic sites and some of those will be discussed shortly. But first, the stability of the species on a regional scale must be examined, to determine whether they are in decline, rare, endangered or protected by statute. The important consideration is not the number of grid-squares in which a particular species has been recorded, but the relationship between those and the number of grid-squares from which it has disappeared. A species in decline may have disappeared from a large number of grid-squares, but it may still be present in a large number. Such a species could not be considered to be endangered. By comparison, a species which has disappeared from a large number of grid-squares, and is now only found in a few, could be considered to be endangered. The information from which such judgements might be made is contained within the data included in the consolidated species lists for these two sites, in Appendix 8.

The relationship between these two factors can be revealed by expressing one as a percentage of the other. The result is shown in Figure 6.15, below.

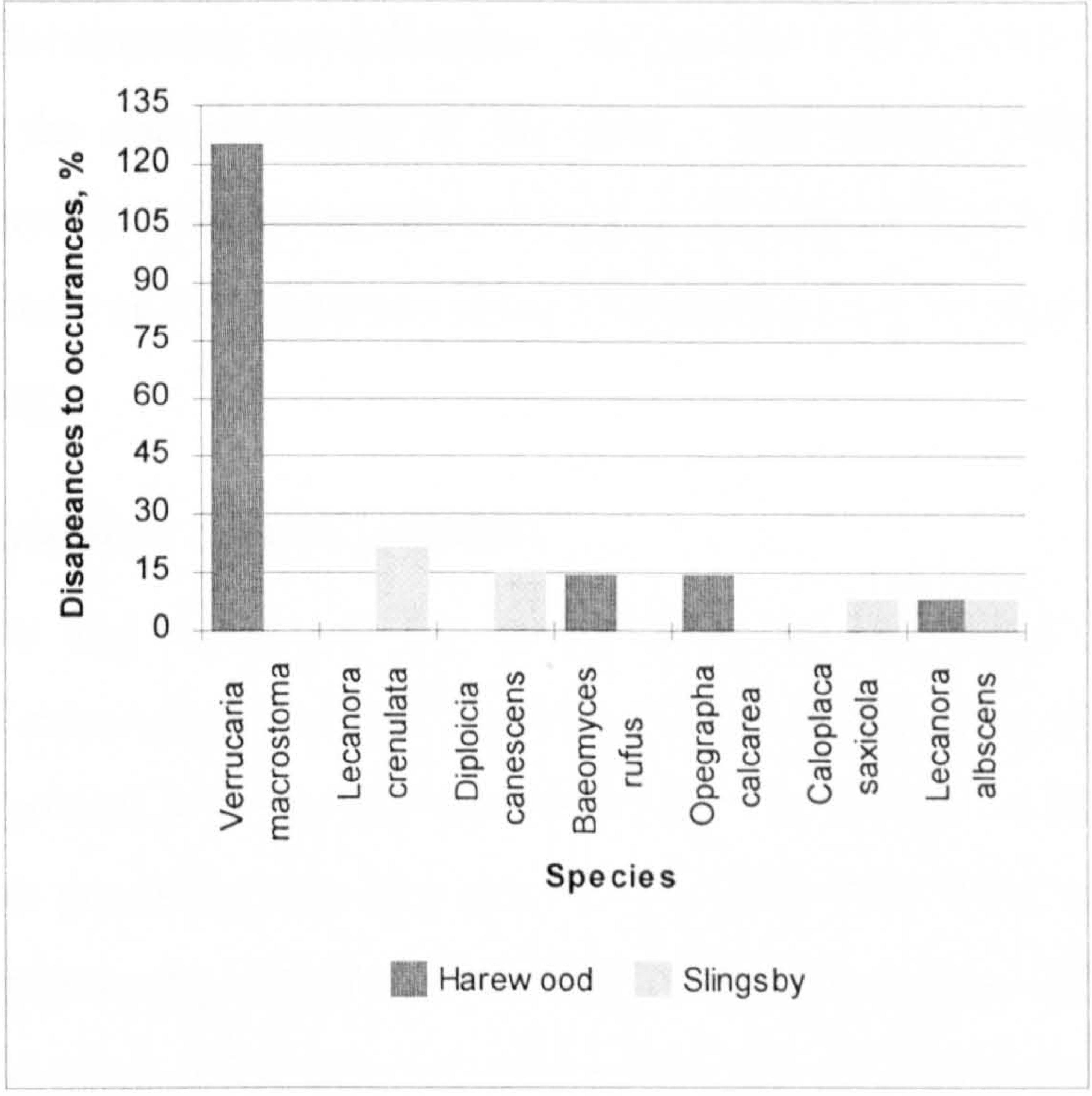


Figure 6.15 Number of grid-squares from which species have disappeared, as a percentage of grid-squares in which they are now found

Figure 6.15 shows that of all the species recorded at these two sites, *Verrucaria macrostoma*, on the plinth of the east elevation of Harewood Castle, is the rarest occurrence in Yorkshire; it has disappeared from more grid-squares than grid-squares in which it is now found. The second rarest is *Lecanora crenulata*, represented by one occurrence on the north-west tower of Slingsby Castle. It should be noted that although these species are relatively rare in Yorkshire, neither are considered to be nationally scarce, since neither are Red Data Book species (Church *et al.* 1996).

Influences on species stability at a more local level can be associated with site management, and monument conservation. There is no doubt that the forest planting, carried out around Harewood Castle in the mid-1950s, has over time caused a change in the lichen species on the castle, because of a gradual reduction in illumination levels at the ruin. Undoubtedly the species composition will change again as a result of tree-felling in the area, when the castle is made available to the public. There may be a further change in species if lime mortar is used in the forthcoming consolidation and repairs which may cause further reductions in the natural acidity of the stone. But undoubtedly there is one overriding factor which has caused a change at Harewood Castle and that is the reduction in levels of atmospheric sulphur dioxide from the industry and homes of the West Riding.

Atmospheric sulphur dioxide pollution

There are two key aspects in the interpretation of the lichen flora for the monitoring of atmospheric sulphur dioxide pollution at any particular site. These are the likely present level and the interpretation to determine the direction of any change. In the preceding two case studies, the former has been investigated by analysis of the frequency distributions of the pollution tolerances of all the species present and the work of Henderson and Seaward has already been mentioned in that context (Henderson and Seaward, 1976). These authors concluded that atmospheric levels of sulphur dioxide at Harewood had declined since the Clean Air Acts of 1956 and 1968 were introduced. They reached their conclusions by analysis of the dominant lichen species. So it is worth investigating how Henderson and Seaward arrived at their conclusions, because it seems that there are limitations both in their method and in the method adopted in the previous two case studies, particularly in assessing the direction of change. This is pertinent to this case study, because their conclusions were drawn from the analysis of the lichen species recorded on the Harewood Estate, including the castle and surrounding areas.

Harewood has long been influenced by air pollution emanating from the industry of Leeds. Henderson and Seaward made their assessment of the direction of change in atmospheric sulphur dioxide levels at Harewood from recorded levels from six national survey gauges sited in the northern suburbs of Leeds. These recordings showed a dramatic fall over the period 1962 to 1965 and a less significant fall thereafter (Henderson and Seaward, 1976, p.67). The analysis of the lichen species was based on the tolerance of the dominant corticolous and saxicolous species recorded in 1976. They found that the corticolous species indicated a much higher level of pollution than did the saxicolous species. This led them to the conclusion that the corticolous species were indicative of past levels, while the saxicolous species, with superior powers of re-colonisation, were more indicative of present levels of pollution.

While Henderson and Seaward's conclusions support the findings of the direction of change at the preceding two case studies, it would appear that a method of analysis which relies on dominant species is fundamentally flawed because many other factors, in addition to air quality, can influence the dominant species composition. These include: illumination levels, which are dependent on aspect and orientation; patterns of water inundation of the substratum, which determines the moisture content of the substratum; the degree of nitrogen enrichment of the substratum and competition from other species. The more traditional method involves the identification of 'indicator' species, which have been associated with specific levels of sulphur dioxide pollution, but this method is more usually carried out by identifying species on trees. The method of analysing frequency distributions of pollution tolerance of species, used in the previous two case studies, is a radical departure from accepted methods. This method is an improvement on the dominant species method, but it also has its limitations because it does not take into account other variables which might influence species composition.

In the preceding case study a method was used in which current sulphur dioxide levels could be assessed by considering the pollution tolerance of the species and also the potential numbers of species on any particular substrate and their regional distribution. So the purpose of this sub-section is to investigate how a method might be developed to assess the direction of change of sulphur dioxide levels, which takes into consideration the complexities of lichen communities at historic sites. But before that step is taken, it is worth investigating briefly whether the findings of Henderson and Seaward are statistically significant by analysing their data using the method adopted so far in this research.

The species lists and associated data can be found in Appendix 8 and the frequency distributions of the pollution tolerances of the corticolous and saxicolous species are shown in Figure 6.16, below.

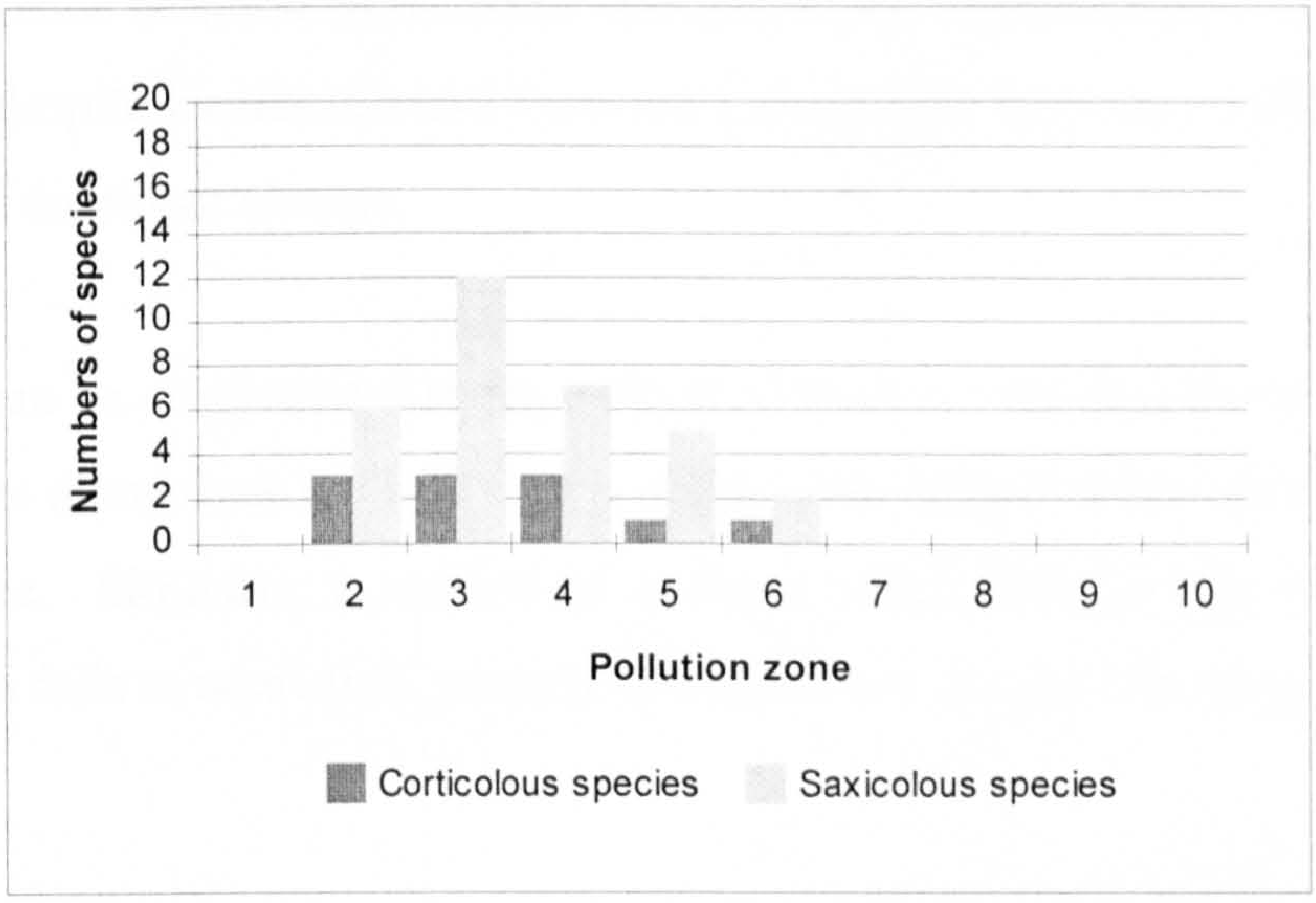


Figure 6.16 Harewood Estate 1976: corticolous and saxicolous lichen species pollution tolerance

These frequency distributions were analysed using *SPSS*, the output form which is shown in Table 6.19. The null hypothesis was that there was no difference in the two distributions. The alternative hypothesis was that there was a difference because that is what had previously been concluded; the corticolous species had a higher pollution tolerance than the saxicous species. Under these circumstances a one-tail test was used, with the standard level of significance of 0.05.

Test Statistics

	Results	Critical Z
Mann-Whitney U	168.000	
Wilcoxon W	234.000	
Z	−0.231	<−1.645
Asymp. Sig. (2-tailed)	0.818	
Exact Sig. [2*(1-tailed Sig.)]	0.837[1]	

[1] Not corrected for ties.

Table 6.19 Harewood Estate 1976: analysis of frequency distribution of pollution tolerances of saxicolous and corticolous lichen species.

The calculated value of Z is less than the critical value and is therefore non-significant. It can be concluded that the difference in the distributions of the pollution tolerance of the two groups of species could have occurred by chance. The mean values of the pollution tolerances were calculated to be 3.445 and 3.531, for the corticolous species and the saxicolous species respectively. The small difference between them, when rounded to the nearest integer, results in no difference despite Henderson and Seaward's claim that there *was* a difference, on the basis of dominant species.

And so it can be concluded that the method of analysis which relies on frequency distributions alone does not take into account other factors which could influence the outcome. Similarly, a method of analysis which relies solely on dominant species also fails to take other, potentially significant, factors into account.

Development of method of assessing the direction of change of atmospheric sulphur dioxide levels using lichen flora at historic sites

The first consideration is the pollution tolerance of all the species recorded at a particular site and not just the dominant species. In this way the pollution tolerance of non-dominant species can also be taken into account. The first step in the design of a more all-embracing analysis method is to calculate the product of the species pollution tolerance and the species frequency. If the pollution zone number is simply multiplied by the species frequency, there would clearly be situations where low frequencies of a pollution-sensitive species would produce the same numerical value as high frequencies of more tolerant species. In order to obtain a series of values which, numerically, reflects the pollution tolerance levels, the reciprocal of the pollution zone number for each species can be used. This, when multiplied by the species frequency, gives the first part of a formula: $\frac{1}{Z} \times F$, where Z is the pollution zone number, and F is the recorded frequency of one species associated with that zone. The critical element in this part of the final formula is F, because if comparative analyses are to be made between sites, or between current and historical data, then the method of calculating the frequency and the counting system used, needs to be consistent, or capable of transformation into a consistent format.

The next step in the development of a formula is to calculate the cumulative value of $\frac{1}{Z} \times F$ for all the species in each pollution zone:

$\left(\frac{1}{Z_1} \times F_1\right) + \left(\frac{1}{Z_1} \times F_2\right) + \left(\frac{1}{Z_1} \times F_n\right)$, where Z_1 is the pollution zone, and F_1 is the frequency of the first zone 1 species, and so on. So now we have a calculated value of $\sum\left(\frac{1}{Z} \times F\right)$ for each pollution zone.

The next step is to consider how the numbers of species recorded in any particular survey, associated with each pollution zone, might affect the outcome of the above formula. The magnitude of the values which the formula produces so far are partly a function of the number of species representing each pollution zone. In order to compensate for this, the value of $\sum\left(\frac{1}{Z} \times F\right)$ for each zone can be divided by the number of species recorded, associated with each zone. The formula for each pollution zone then becomes: $\frac{\sum\left(\frac{1}{Z} \times F\right)}{N}$ where N is the recorded number of species associated with each zone.

The final step in the development of a formula is to take into account the total number of potential species on the type of substratum at a particular site. Mention has already been made that there are, for example, over 50 Zone 6 species which are normally associated with rock, but less than ten species associated with Zone 2. Those Zone 2 species are also likely to be found in less polluted environments, but their presence does not necessarily indicate that the pollution level is Zone 2. Also, there is a higher chance of encountering Zone 6 species, because there are five times more of them. So the proportion of species representative of each zone is an important factor. This can be considered to be the 'probability' factor *P*, and it can be dealt with in the same way as in the previous case study: by calculating the percentage of potential species which the recorded number of species represents, for each pollution zone. The formula above can be multiplied by the percentage values of *P*, to take account of the probability of any particular species being present.

If the values calculated are called the site zone indices, or SZI, a final formula for each of the ten pollution zones on the Hawksworth and Rose scale becomes:

$$SZI = \left(\frac{\sum\left(\frac{1}{Z} \times F\right)}{N} \right) \times P\%$$

This formula for calculating the values of the ten pollution zone indices for a particular site takes account of the following:

- The pollution tolerance of each species recorded, including the dominant species;
- the frequency of each species recorded;
- the total number of species recorded, associated with each pollution zone;
- the number of species recorded compared to the number of likely species on that particular substratum, taking account of regional distributions of species.

The ten Site Zone Indices can then be compared between sites and the distributions analysed using the Mann-Whitney test to detect differences in the mean values. There are, however, two drawbacks to this method. The values which the formula produces are small and a precision of at least four decimal places is required in order to make reliable comparisons, although it could be argued that this is not permissible to claim higher levels of precision than that of the original data. The second drawback is that the number of values in the resulting distributions is small; consequently, large differences between pairs of indices are required before significant differences can be detected.

Data from Henderson and Seaward's 1976 lichen survey of Harewood were then inserted into the above formula, for corticolous and saxicolous species. The following bar chart, Figure 6.17, shows the frequency distributions for the Site Zone Indices for each group of species.

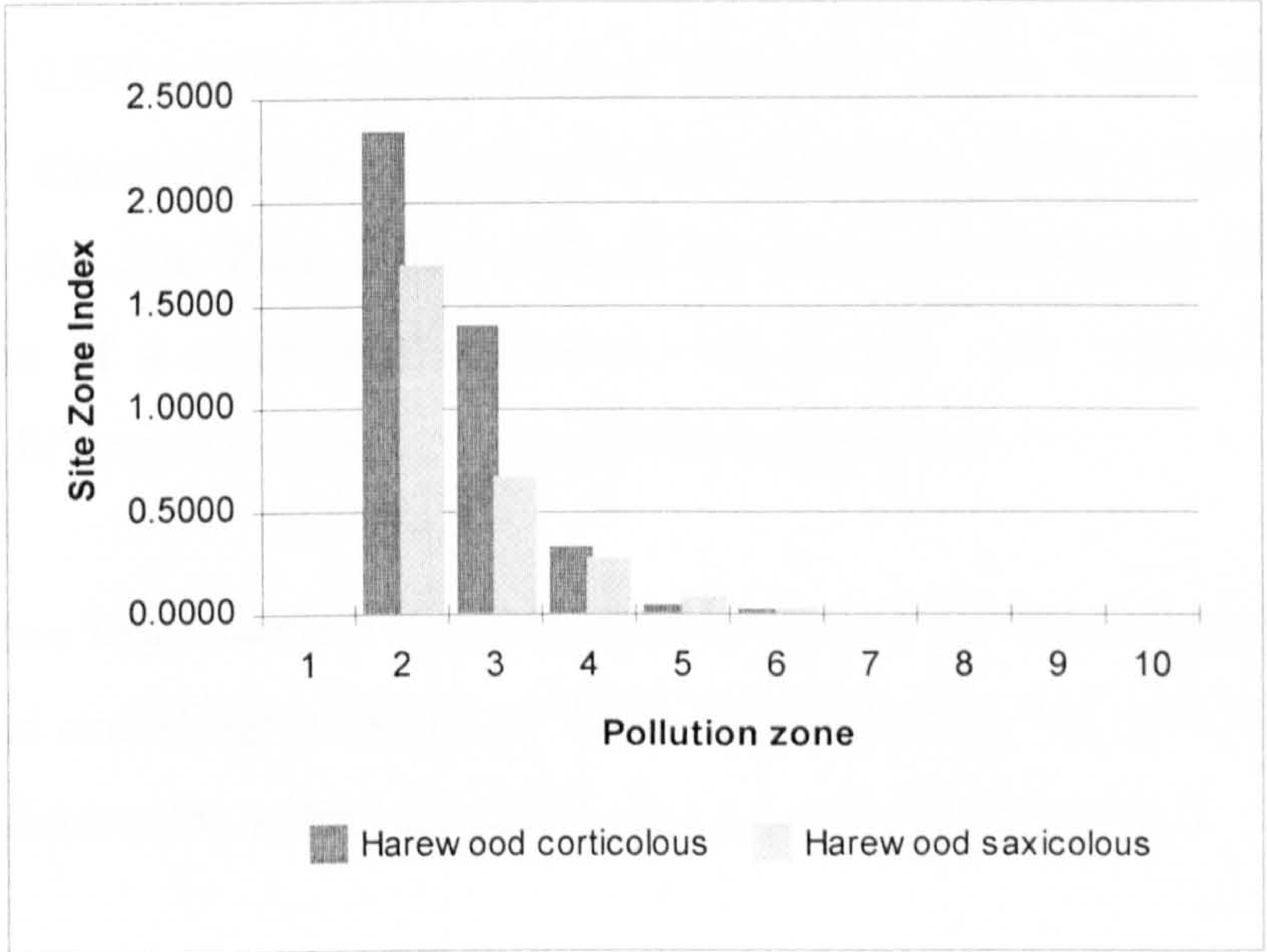


Figure 6.17 Harewood Estate lichen survey 1976: Site Zone Indices for corticolous and saxicolous species

These two distributions were then subjected to significance testing using the Mann-Whitney test. The assumptions of the test are as before. The output generated by *SPSS* is shown in Table 6.20.

Test Statistics

	Results	**Critical *Z***
Mann-Whitney U	49.500	
Wilcoxon W	104.500	
Z	–0.040	<–1.645
Asymp. Sig. (2-tailed)	0.968	
Exact Sig. [2*(1-tailed Sig.)]	0.971[1]	

[1] Not corrected for ties.

Table 6.20 Harewood Estate lichen survey 1976: analysis of corticolous and saxicolous species based on analysis of Site Zone Indices

It can be seen from Table 6.20 that the calculated value of *Z* is greater than the critical value and is therefore non-significant within the parameters of the test. It can also be seen by comparing this *Z* value with the value calculated using frequency distributions of zone numbers that the *Z* value has increased from –0.231 to –0.040; it has moved further from the critical value and although statisticians discourage the analysis of trends (Coolidge 2000, p.103) it is worth noting that the Site Zone Index method, far from providing the basis for the confirmation of a significant difference, has in this case resulted in a non-significant difference becoming even more non-significant.

The Site Zone Index method was then used to analyse the lichen species recorded at Harewood and Slingsby castles in 2000. The following bar chart, Figure 6.18, shows the distribution of the calculated zone numbers for each site.

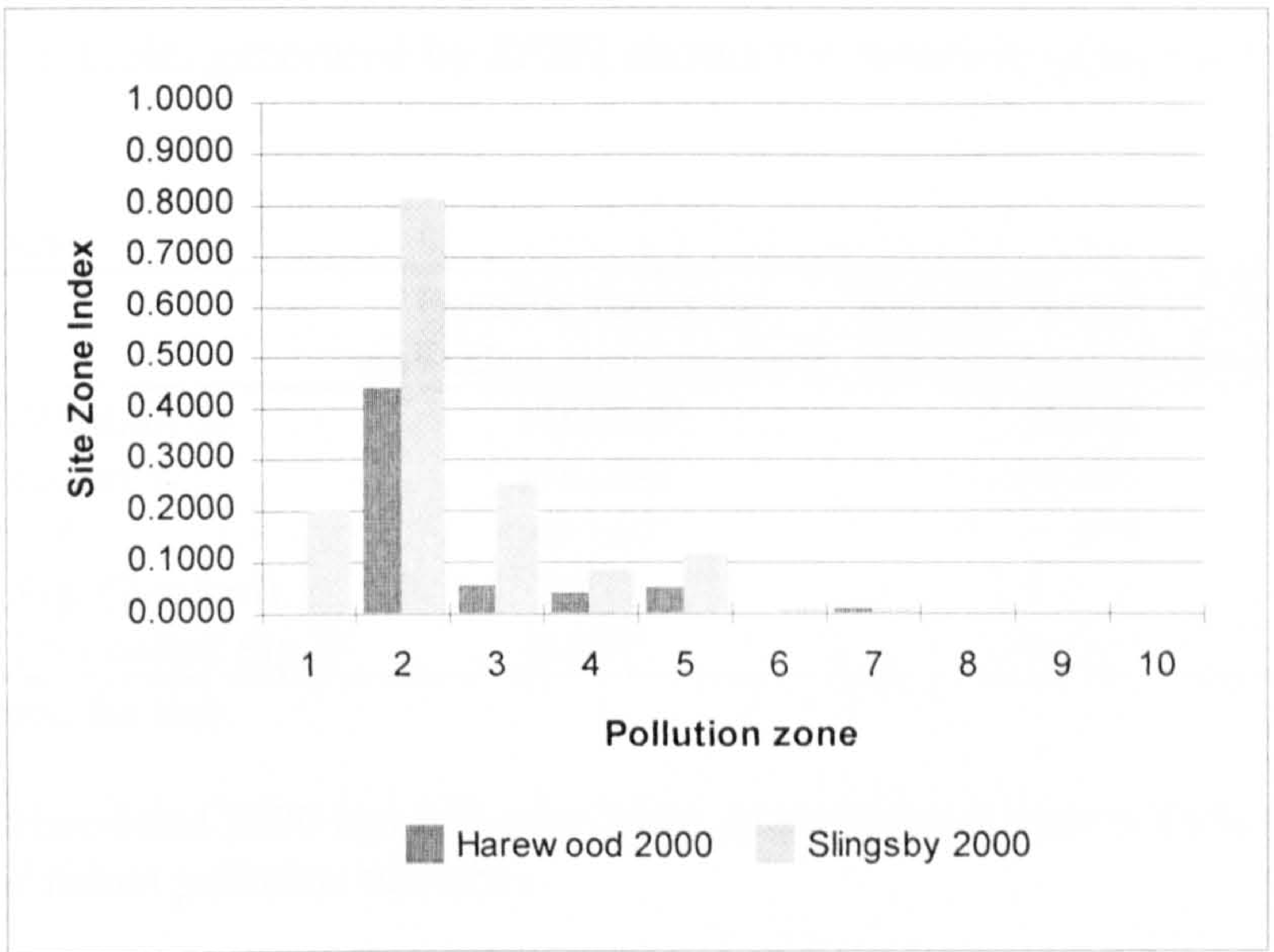


Figure 6.18 Harewood and Slingsby castles: comparison of lichen pollution tolerance using the Site Zone Index method

It can be seen from Figure 6.18 that Slingsby Castle has higher Site Zone Indices for zones 1, 2, 3, 4 and 5, compared to Harewood Castle. Also, the Zone 2 Index for Slingsby is almost twice that of Harewood. This appears to indicates that atmospheric sulphur dioxide levels at Slingsby Castle are higher than at Harewood. The mean value of the distribution for Harewood Castle was calculated to be 0.0583, compared to a value of 0.1472 for Slingsby and because of the way the Site Zone Index formula was designed, these values are proportional to the levels of pollution.

These findings confirm published accounts of the relationship between urban and rural levels of air pollution and thus to some extent validates the formula. With the introduction of the Clean Air Acts (HMSO 1956; 1968) and the adoption of the 'high stack' policy for dealing with power station emissions, levels of urban air pollution have tended to fall, while rural levels have tended to rise (Henderson and Seaward 1976; Gilbert 2000).

The two distributions shown in Figure 6.18 can be subjected to significance testing, using the Mann-Whitney test. The results can then be compared with those obtained from the corresponding distributions of pollution zone numbers. The following table, generated by *SPSS*, shows the outcome of that comparison.

Test Statistics

	Results, based on pollution zone method	**Results, based on Site Zone Index method**	**Critical *Z***
Mann-Whitney U	116.500	36.000	
Wilcoxon W	416.500	91.000	
Z	–0.567	–1.094	<–1.960
Asymp. Sig. (2-tailed)	0.571	0.274	
Exact Sig. [2*(1-tailed Sig.)]	0.587[1]	0.315[1]	

[1] Not corrected for ties.

Table 6.21 Harewood 2000 and Slingsby 2000: comparison of results from two methods of analysis of lichen pollution tolerance

Neither of the *Z* scores were below the critical values for either a two, or a one-tail test, but the results show that the Site Zone Index method produced a value closer to the critical value for a two-tail test. This indicates that in the analysis of pollution zone frequency distributions, adopted in the two previous case studies, it is more difficult to detect significant differences; consequently, significant differences which *were* detected were more robust; however, it has not yet been determined whether the analysis of distributions produced by the Site Zone Index method will detect significant differences where such differences exist.

Air quality and weathering of the monuments

The results of the laboratory tests have shown that the stone from which Harewood Castle is built is the most durable of those tested, and despite high levels of air pollution in the past the masonry is generally in good condition. The most notable weathering is to the mortar which, in the lower levels of the masonry, is virtually absent. There are several possible reasons why this has occurred, and these include dissolution of the mortar by rising groundwater, the action of frost or salts, or as a result of the action of acid rain due to past high levels of air pollution. It is most probable that it is due to a combination of all four mechanisms acting together, but the action of acid rain might be expected to be the most severe.

Sulphur dioxide, either wind-blown, or in the form of acid rain, can react with calcium carbonate, in this case in the mortar joints, to form gypsum. Calcium sulphate is more soluble in water than calcium carbonate and can migrate into the pore structure of sandstone where the expansive forces exerted as it crystallises can exceed the tensile strength of the stone (Price 1994). Examples of such damage to sandstone can often be seen where rainwater run-off occurs from limestone onto sandstone below. Paradoxically, this is also the process, touched on earlier, which can alter the pH of the stone and provide a less acidic substrata. At Harewood Castle this has enabled *Opegrapha calcarea,* one of the two dominant species at this site, to flourish.

At Slingsby, however, the ruin is much more vulnerable. The laboratory tests showed the two types of stone to be vulnerable to frost, salts and acid rain, in varying degrees. If air quality has declined at this site, as the lichen record suggests for the two case study sites further north, then the processes of weathering of the Calcareous grit, by salts produced from the reaction between acid rain and mortars and limestone dressings, as outlined above, will continue. The dissolution of the limestone will also continue and so the cycle of gypsum production, absorption and crystallisation becomes self-perpetuating, until either the air quality improves, or there is no further soluble material left to dissolve.

Lichens as part of the complex weathering model

There is the potential for lichens to cause direct weathering and also to influence other weathering mechanisms. In Chapter Three, the ways in which lichens cause direct weathering were discussed. In Chapter Five, the analysis of the saturation and drying test results suggested that there was a potential for lichens to influence the severity of weathering by frost, salts and acid rain, by inhibiting drying. This potential appeared to be dependent on the degree of plant cover; the more extensive the cover, the greater the potential for influencing rates of drying.

The implications for the three stone types at these two sites can be summarised as follows:

- Harewood Castle – sparse lichen cover – durable stone – low probability that lichens will potentiate weathering processes

- Slingsby Castle – extensive lichen cover – vulnerable stone types – high probability that lichens will potentiate weathering processes.

Summary

- Harewood Castle has a relatively impoverished lichen flora, compared to Slingsby Castle;
- the masonry of the two castles provides habitat for some lichen species which are common in the region and for some which are relatively scarce or are in decline (although not endangered), including the dominant species at Harewood and one occurrence at Slingsby;
- the masonry of Harewood Castle provides habitat for species which are unlikely to be found in the surrounding countryside – this is because the pH of the masonry has been increased as a result of weathering of the mortar joints;
- analysis of the frequency distributions of the air pollution tolerance of lichen species recorded in 1976 failed to confirm the conclusions reached by Henderson and Seaward, at that time;
- it has been shown that a method of analysing the pollution tolerance of lichen flora, which takes into account several variables, may provide a more reliable method of determining the relative levels of atmospheric sulphur dioxide at two sites and also the direction of change at any particular site;
- there was no difference in levels of atmospheric sulphur dioxide at the two sites;
- the lichen flora of Slingsby Castle is more likely to potentiate weathering of the masonry that that at Harewood, because at Slingsby the lichen flora is more abundant and the stone types are less durable.

CASE STUDY 3 SUMMARY

- Harewood Castle has a relatively impoverished lichen flora compared to Slingsby Castle, but they both provide habitat for species which are scarce and in decline in Yorkshire;
- the masonry of Harewood provides habitat for lichen species unlikely to be found on natural rock outcrops in the area;

- analysis of the frequency distributions of the air pollution tolerance of the lichen species recorded in 1976 at Harewood did not confirm the conclusions reached by researchers at that time;
- a Site Zone Index method of analysing the pollution tolerance of lichens has been proposed as a more reliable method of determining likely levels of atmospheric sulphur dioxide than determining dominant species or analysing frequency distributions of pollution tolerance;
- the lichen flora of Slingsby Castle is more likely to potentiate weathering of the masonry that that at Harewood, because at Slingsby the lichen flora is more abundant, and the stone types are less durable.

CHAPTER SEVEN

CONCLUSIONS

INTRODUCTION

This final chapter brings together the main points which have emerged from each of the preceding chapters. The extent to which the aims and objectives of the research have been met will be discussed, and an assessment will be made as to whether the results of the research have provided adequate answers to the research questions and how these answers contribute to existing knowledge. In addition, the areas where the research methods can be developed further will be discussed and areas for future research will be explored.

THE KEY FINDINGS

The way in which monuments are managed in England is changing. Most significantly it is becoming increasingly common for flora to be retained. It is not the intention that picturesque values, as discussed and analysed by Hussey (1927), Hipple (1957), Ousby (1990) or Barrell (1992) be restored to the ruins of Britain but it is because the ecological and nature conservation value of flora is increasingly acknowledged. These changes in management practice are evident by comparing the work of Thompson (1981), in which he recalls the ways in which ruins were managed in the early decades of the twentieth-century, with the work of Thomas and Wells (1997; 1998). These changes in management practice are taking place in the absence of adequate research into the consequences for weathering of monuments.

Two plant groups have been identified in this research as important to the weathering of stone. They are the endoliths and epiliths. Endoliths and epiliths, such as lichens and mosses, are important because they conceal historic surfaces and so alter the appearance of monuments in subtle yet distinctive ways. Climbing plants such as ivy, although not studied in this research, are important because they are highly conspicuous and because historically they are the group of plants which have been associated with those past picturesque value of ruins which featured in the contemporary writings of Burke (1757), Gilpin (1795), Payne-Knight (1795) and many others. It is only in the relatively recent past that writers including Macaulay (1977), Felmingham and Graham (1972) and Mostafavi and Leatherbarrow (1993) have commented on the absence of any sense of the Picturesque in the way ruins are presented. This too conveniently overlooks the realities of the weathering potential of plants, especially ivy, but of mosses and lichens as well.

Three weathering mechanisms have been identified as important in an industrialised country with a maritime climate. They are the effects of cyclical freezing and thawing of water, on which the seminal work is that of Everett (1961), the effect of soluble salts which has been the subject of extensive research, including that of Price (1978; 1994) and Goudie and Viles (1997) and the effects of acid rain, investigated by Cooke and Gibbs (1993). In the real world, these three mechanism are unlikely to act in isolation, but invariably operate in combination. Those combinations of action, or complex weathering interactions, which were highlighted in Chapter Three and which was acknowledged by Viles (1997) are an area of research which has been seriously neglected.

There are methods by which the action of those three weathering mechanisms can be investigated in the laboratory, and they have been identified in Chapter Four. Also, the direct weathering of stone caused by the three plant groups under investigation has also been investigated by many researchers, and that aspect was discussed in Chapter Three. But the ways in which those weathering mechanisms are influenced by those plant groups is an unexplored area of research. One of the challenges of this research was to develop test methods which would enable this aspect to be investigated. An account of the development of these methods was given in Chapter Four and in Chapter Six, but the results of those test are not easily obtained. Far from providing protection to stone, as had previously been suggested by researchers including Mottershead and Lucas (2000) and Vile and Pentecost (1994), the plant groups tested have been shown to be capable of potentiating the three weathering mechanisms studied. This is in addition to any direct weathering action, particularly by lichens, such as that identified by Bachman (1990), or Syers and Iskandar (1973), which were discussed in Chapter Three.

The results of the laboratory tests laid the foundation upon which the case study investigations were built. At Duncombe Park, it was shown that the decay of the columns of the temples has been caused by a combination of factors, including the ability of the botanical colonisation to inhibit water evaporation from stone. The other important factor which had been identified by Senior (1996), but not proved, is that atmospheric pollution and the consequent acid rain, are key factors in the decay. The analysis of the lichen flora species composition showed that levels of atmospheric sulphur dioxide are increasing in North Yorkshire, and this is contrary to that which Government statistics would lead us to believe.

The trend towards increasing levels of air pollution in rural North Yorkshire was further confirmed by the analysis of the lichen flora at Rievaulx Abbey. In addition, the percentage coverage of lichens on the masonry of selected areas, combined with the results of the simulated weathering tests conducted in the laboratory, gave an indication as to which of the stone types were most vulnerable to weathering under the influence of plants.

In the comparative analysis of Harewood and Slingsby Castles, the relative importance of their lichen flora was investigated. It was demonstrated that both castles provide habitat for species which are regionally relatively scarce and at Harewood the species were shown to provide a record of weathering in a previously polluted atmosphere. It was also possible, based on the results of the simulated weathering tests and assessment of the abundance of lichen flora of both castles, to predict which of the stone types is most vulnerable to the three weathering mechanisms in the presence of lichens. A method of demonstrating how lichen flora could be analysed to determine changing levels of atmospheric sulphur dioxide was further developed, which would take into account multiple variables, including the regional distribution of species.

The following subsections demonstrate particular aspects of this research:

- The extent to which the findings of this research, summarised above, satisfy the aims and objectives stated in Chapter One;
- whether the findings provide adequate answers to the research questions;
- the ways in which the findings contribute to existing knowledge.

THE AIMS AND OBJECTIVES

The aims of this research, stated in Chapter One, are embedded within the chapter structure of this research. The extent to which the objectives of the research have been achieved is described below.

The relative impact of various weathering agents

The results of this research have shown the relationship between the three key weathering mechanisms and the physical properties and weathering characteristics of the eleven stone types tested. It has also been shown that the relative impact of three key weathering mechanisms can be ranked in order of the severity of their effects on those stone types. For instance, weathering by freeze/thaw cycles is a seasonal phenomenon in Britain, but salts are a persistent cause. Air pollution and the consequent acid rain are also persistent causes and many of the Jurassic sandstones which were tested were calcareous stones which are highly vulnerable to weathering by acid rain. In the case study area, despite its rural location, atmospheric sulphur dioxide can be considered to pose the greatest threat to many of our monuments.

The development of a model of complex weathering

Implicit within the concept of what is generally understood as weathering of stone, there is a complex series of interactions which here have been called complex weathering. Within those complex interactions it is now apparent that there are further hierarchies of complexity provided by the plant groups which have been studied. They have their own micro-scale levels of weathering and they also have been shown to influence weathering on the macro-scale. The former is generally considered to be on a near-geological time-scale, but macro-scale weathering by plants is likely to be much more severe, because it potentiates already potent weathering processes. It was the intention to produce a diagrammatic model of complex weathering, but the review of the literature has shown that the level of understanding of some of the more commonly identified weathering processes is not fully understood and the ways in which they act in combination is still little studied. To add the role of plants to an already incomplete model would be an addition based more on supposition than on empirical data, and so a detailed analysis of the macro-scale weathering influence of plants has been limited.

Nevertheless, it is possible to identify the relative risks which the three plant groups pose to differing stone types. An indication of how a matrix can be developed is given in Appendix 10. It relates the physical properties and weathering characteristics of the stone types which have been studied here, to the three weathering mechanisms studied and the influence of the plant groups. Also included is an indication of how this matrix could be extended to include other stone types and how the plant groups could be subdivided to produce a risk-assessment model of macro-scale weathering by plants. As well as its application to ruins, this method of risk-assessment is also applicable to gravestones, obelisks and stone statuary.

A conservation philosophy for flora and ruins

There should be an increased awareness amongst conservators that ruins have multiple levels of meaning. That has not generally been recognised in the past. Plants on ruins have had, and still have, significant value from several points of view:

- They act as a memory of the past;
- they represent time passing;
- they symbolise continuity of existence;
- they are a metaphor for life.

In addition, and more pragmatically:

- They have ecological significance;

- they have nature conservation value;
- some provide a record of past environmental conditions;
- they are capable of active weathering;
- they are capable of potentiating weathering.

Any conservation philosophy which concerns plants on ruins should recognise both sets of attributes listed above and weigh the advantages and disadvantages of each. For much of the twentieth century, it is clear that none of the 'emotional' aspects were given credence, nor were any of the pragmatic aspects recognised other than the ability of plants to cause direct weathering and structural disruption. A future philosophy ought to embrace the 'emotional' aspects, because it is clear from the passages quoted in Chapter Two, that those aspects, although abstract, are the ones with which people can most closely identify. A future philosophy should also carefully weigh the relative importance of the more pragmatic aspects. This is because an undercurrent of this research has been the paradox posed by an advocacy for a greater tolerance of all genera of plants on ruins and the unfolding realisation that the weathering impact of plants on masonry is greater than had previously been believed. That is the paradox which a philosophy towards plants on ruins should resolve.

The management of flora on historic building fabric

The paradox mentioned above can be resolved. It was shown in the case studies how a simple form of weathering risk assessment can be made, particularly in relation to endolithic and epilithic plant species by identifying the following:

- The physical properties and weathering characteristics of the stone types from which the monument is built – this will reveal the weathering vulnerability of the stone;
- the plant species which are present – this will reveal which species are regionally or nationally scarce, in decline, or unique to a particular site;
- mapping the coverage and distribution of the plant species – this will indicate the extent to which they will potentiate other weathering mechanisms;
- the predominant weathering mechanisms – this will enable the risk to the masonry to be assessed.

This simple form of weathering risk assessment can only be considered to be a beginning in the understanding of the role of plants in complex weathering. There are many factors which determine the degree of botanical colonisation of stone, including the aspect, exposure and orientation of a stone structure, the mineralogy of the stone and hence its surface pH, its surface roughness and the materials used for bedding, jointing and pointing, as well as the presence or absence of decayed organic matter. In addition, there are many mechanisms which can cause weathering of stone and they are often inter-dependent processes. There is clearly a complexity of factors at work, and it has been possible to investigate just a few of them in this research.

THE RESEARCH QUESTIONS

Management trends

During a period of more than 400 years, the imperceptible changes which the ruins of Britain underwent by natural processes have symbolised many things to many people. In the late nineteenth, and early twentieth centuries, many of those ruins came into public ownership and were consolidated and made accessible. They were valued as historical evidence and that is how they were, and still are, presented to the public. No other layers of meaning were permissible and that has been a cause of comment, debate, and criticism for nearly sixty years.

However, there is a trend to conserve ruins as ‘green’ ruins, and it is based upon an increasing awareness of the ecological importance of historic sites. This trend is gathering momentum without the benefit of appropriate research into the consequences. Much of the evidence of weathering and damage by plants, which might have been useful from the past, has been largely destroyed at the expense of preserving the historical evidence of the monument; furthermore, the systematic recording of relevant evidence of damage, or weathering by plants, on extant ruins which have not been conserved, is largely absent from the conservation agenda. There is clearly a risk involved in this trend, but it is little recognised.

The influence of plants on weathering

It has been shown that the weathering of stone by plants can take place on the micro-scale, and on the macro-scale. Micro-scale weathering takes place at the granular or crystalline level, dependent upon the stone type. Macro-scale weathering also takes place at the granular or crystalline level but because more potent mechanisms are involved, it results in much more rapid weathering than might otherwise be expected.

Mosses

In most accounts of stone weathering due to mosses, the common perception is that mosses hold large volumes of water against the stone surface and this influences the potential for weathering by frost and salts. It is clear from the results of laboratory test conducted in this research that mosses *do* inhibit drying of saturated stone and absorbed water is only gradually lost, even under optimum drying conditions. But in assessing the implications of this for the weathering of stone there is one important factor to consider – the conditions under which mosses flourish.

Mosses are likely to have colonised stone which is perpetually damp and therefore already highly vulnerable to weathering by frost and acid rain and by mineral dissolution. Damp stone, in the presence of mosses, is not due to the mosses, it is due to the prevailing environmental conditions; mosses, including the species subjected to tests in this research, flourish where there is moisture – they are not the cause of the moisture. That is an important fact and it is one which is commonly misunderstood. The consequences are that mosses are unlikely to influence the weathering action of frost and acid rain, but they may provide a degree of indirect protection against the action of soluble salts by stabilising what is often an already damp environment.

Lichens

It was shown in Chapter Three that two aspects of the action of lichens are generally considered. The first is their ability to cause direct weathering of stone. The second is their alleged ability to provide protection to stone. This research accepts that lichens cause direct weathering, but found no evidence to support the view that they provide any protection to stone from weathering mechanisms which involve water. The results discussed in Chapter Five showed clearly, that with the samples tested, lichens had a minimal effect on rates of water absorption of stone. Under drying conditions, however, they had a significant influence, extending drying times by over 16%. The consequences are that lichens have the capacity to potentiate the action of frost, salts and acid rain, by inhibiting water evaporation.

Lichens, in contrast to mosses, tend to colonise stone surfaces which frequently dry completely after inundation. There are two consequences to this. The first is that salts, mobilised during saturation, will crystallise during drying and in the presence of lichens the crystals may be larger and the weathering effect greater. The second consequence is that after complete drying, salts may change state to the anhydrous form and subsequently cause weathering as they re-hydrate. These processes are not possible in stones which are permanently damp and it has already been highlighted in Chapter Three that salts are considered by some to be a major cause of weathering, because they tend to be persistent; whereas, weathering by frost action in Britain is seasonal.

Summary

It is concluded that, based on the analysis of the laboratory test data, mosses and lichens influence the weathering of stone by slowing the evaporation of absorbed water. The effect of this is threefold: it increases the risk of weathering by frost, because stone retains absorbed water for longer; it enhances the effects of weathering by soluble salts because there will be more time for crystal growth, resulting in larger crystals; it increases the weathering effect of acid rain, because low pH water is retained in the stone for longer than it would had the plants not been present.

The degree to which the three weathering mechanisms are potentiated by plants is dependent on the stone types and the plant groups. It is important, therefore, to understand the weathering characteristics of the stone types, as well as the habitat preferences of the plant groups under consideration.

The degree to which plants can potentiate weathering depend upon four factors:

- The plant genus and species;
- the physical properties and weathering characteristics of the stone;
- the surface area to volume ratio of the masonry units under consideration;
- the dominant weathering mechanism.

The use of plants as a diagnostic tool

The analysis of lichen flora to predict changes in levels of atmospheric sulphur dioxide was demonstrated in Chapter Six. As far as can be determined from the literature, the analysis of lichens flora has never before been used to determine a cause of weathering of historic buildings. Indeed, the systematic recording of lichen flora has only recently been acknowledged as an important consideration in determining the ecological value of historic sites.

The method adopted in this research, in the analysis of lichen species composition has not been that traditionally adopted by lichenologists. It is a method which uses statistical techniques and it has developed during the course of the research to enable many of the variables which influence species composition to be taken into account. It has been shown to be capable of detecting changes in air quality at the case study sites and has provided an indication that atmospheric sulphur dioxide may be the most potent weathering agent in rural North Yorkshire, despite official indications to the contrary.

It was shown in Chapter Two that lichens are sensitive to many pollutants, including nitrates from agrochemicals and oxides of nitrogen from vehicle emissions. Both of these compounds have in the past been implicated in masonry weathering and there is no reason why the use of lichens as predictors could not be extended to these two groups of compounds; however, much of the necessary groundwork has still to be addressed.

Cultural significance

The Burra Charter defines cultural significance as '...aesthetic, historic, scientific or social value for the past, present or future generations.' (Australia ICOMOS

1999). The extent to which plants on ruins fulfil those criteria is a matter of debate; however, the following is the view which has developed during the course of this research.

The lichen communities at historic sites are the result of a number of factors. Those factors have been shown to include the type of substratum which is available, the levels of illumination, the patterns of inundation, levels of nitrification and the levels of atmospheric pollution. All these factors are influenced by human activity at a local, regional and national level. It was argued in Chapter Two that the flora on historic masonry fabric is an important component of monuments and the appearance of many monuments in Britain is to a greater or lesser degree a direct result of that plant colonisation. This is irrespective of the Genus or species, and irrespective of how rigorously that flora has been discouraged in the recent past. There is no doubt that the flora of ruins, despite the paradox which it represents, should be considered to be part of the cultural significance of the cultural heritage of Britain. In the context of historic building conservation plants undoubtedly have '...aesthetic, historic, scientific and social value...', for all the reasons which have been highlighted in the preceding chapters, but that has yet to be fully recognised.

CONTRIBUTION TO KNOWLEDGE

There are five main areas where this research has contributed to existing knowledge:

- The physical properties and weathering characteristics of the stone types from the case study sites have been determined;
- it has been demonstrated that plants, as well as their micro-scale weathering effects on stone, are also capable of macro-scale effects, by potentiating other more potent weathering mechanisms through their indirect action;
- the lichen flora on historic masonry surfaces can be used to the same effect as lichens on trees, in the prediction of levels of atmospheric sulphur dioxide; furthermore, sophisticated analysis methods can be developed to provide more reliable results;

- the analysis of the lichen flora at the case study sites has provided evidence to support the view that levels of atmospheric sulphur dioxide, whilst they may have fallen over the past thirty years in urban areas, have increased in rural North Yorkshire – and that should be a matter of concern for those charged with the care of ancient monuments in that area.
- the lichen surveys which have been carried out for this research will contribute to the ecological and nature conservation value assessments of those sites and the species lists, when entered into the national database, will contribute to the knowledge of lichen distribution both in Yorkshire and in Britain.

HOW THE RESEARCH METHODS COULD BE REFINED FOR FUTURE APPLICATION

There are inevitably areas of this research where refinements to the methods can be made, particularly regarding the saturation and drying tests. It is immediately tempting to suggest that the tests should be conducted with larger sample sizes. Robson (1994), quoted at the beginning of Chapter Four, highlighted the fact that it becomes more difficult to prove significant relationships the smaller the sample size; therefore, the significant findings in this research are robust findings and there would be no advantage in larger sample sizes, but there are areas where sample sizes should be modified in any future research:

- The saturation and drying tests on samples with plants should be divided into two distinct sub-groups of samples with mosses and with lichens, with fifteen samples in each sub-group. This would enable the relative influence of each plant group to be more clearly identified by statistical techniques than was possible with the small sub-groups resulting from the sample sizes used in this research;
- if the tests are conducted in an environmental chamber, some of the uncontrolled variables will be eliminated and so many of the steps in the subsequent analysis will be unnecessary;
- porosimetry tests should be conducted on all stone types subjected to saturation and drying tests and this will render the use of a separate capillary rise test redundant, although both test methods have been shown to have their limitations.

AREAS WHERE FURTHER RESEARCH IS REQUIRED

- This research has been carried out in a previously neglected area of study. The findings are irrespective of any of the known direct weathering effects of plants. It has highlighted that there is still an incomplete understanding of the interactions between the varying weathering mechanism and that the development of a complete model of complex weathering is still somewhat elusive; nevertheless, the results of this research have helped to fill some of the gaps, but have been limited by both time and resources. There is clearly scope for further investigation in this subject in two distinct areas. The first is the verification of the results of the saturation and drying tests. This can be achieved by repeating the tests on the same stone types, and this should involve further investigation into the relationship between extended drying times due to mosses and lichens, to determine whether the relationship is linear. The second area is the extension of this research beyond North and West Yorkshire. This should involve the following:
- Conducting saturation and drying tests on further stone types, with similar and with different lichen and moss species.
- analysis of lichen species composition on ruins and pollution tolerance of those species from other parts of England and from Scotland, for comparison with the results of this research;
- extend the pioneering work of Gilbert, and Hawksworth and Rose, to lichen species tolerance to nitrates, which is relevant to agricultural sources of soluble nitrates, and to species tolerance of oxides of nitrogen, which has relevance to acid rain originating from vehicle exhaust emission;
- develop further and refine the risk-assessment method.

There are also some more general areas of concern which should also be addressed:

- It should become policy that damage and weathering to masonry by plants, and other factors, should be recorded and analysed at historic sites, particularly at sites still in private ownership where rigorous consolidation and repair of masonry has yet to be undertaken. Such recording should be considered of equal importance to any historical or archaeological analysis of extant remains at such sites;

- in order to monitor changes in air quality, irrespective of indications from Government statistics, all the sites which were surveyed for lichens in this research should be re-surveyed every ten years. Lichenologists working in other areas of the country should be encouraged to be far more rigorous in the survey methods they adopt, so that it is clear to those who follow in later years exactly which areas of a site were surveyed, what species were recorded in each area with details of the method of assessing the frequency of each species. The frequency scale should be standardised to facilitate analysis of current and historical data at any particular site;
- the use of lichen surveys to monitor pollution at historic sites could be made redundant if monitoring stations were established at, say, Fountains Abbey or Rievaulx Abbey. Data from such stations in rural areas would provide invaluable additional evidence that cultural heritage is at risk. Armed with such data, conservation professionals could form an effective lobby to try to persuade the Government to take its environmental responsibilities, in the wider international context of pollution control, more seriously. It is not just for public health and ecological reasons that air quality should reach and exceed present targets, but it is also for the benefit of our cultural heritage.

CONCLUSION

The passage from GW Francis, which was quoted at the beginning of Chapter One, although perceptive in its time, was somewhat simplistic in content, because it did not recognise that plants, including lichens, have more than one level of influence on the weathering of stone. This research has demonstrated that the indirect level of influence has the potential to be far more powerful than any direct weathering implied by Frances's account. The crucial aspect which this research has revealed is that not all stone types are equal and neither are all plant types in this context. That is an important consideration in assessing any risk posed by plants to historic masonry and only when that consideration is properly addressed can we begin safely to restore multiple levels of meaning to our heritage of ruined monuments; however, the great paradox which has emerged from this research is that plants are part of the problem and they are also part of the solution.