INFLUENCE OF CURING ON THE PROPERTIES OF CONCRETES AND MORTARS IN HOT CLIMATES

by

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ABSTRACT

This investigation deals with the influence of initial curing periods and different curing environments, similar to those found in Middle Eastern countries, on the pore size distribution, permeability, water absorption and compressive strength of cement mortars and concretes made with and without pulverized fuel ash (pfa) and ground granulated blast-furnace slag (ggbs).

Three environments were chosen as follows: 1) 20°C+70%RH, 2) 35°C+70%RH, and 3) 45°C+30%RH. To simulate in-place casting, the initial mix temperatures were controlled to be as close as possible to that of the environment in which the mixes were to be kept and moisture loss was allowed to occur from only the top-as-cast face of the specimen. Durability of the mortar specimens was assessed using pore size distribution, oxygen permeability, air permeability and water absorption. In addition to strength, the following tests were carried out on the concrete specimens to assess durability: initial surface absorption (ISAT), water absorption, relative air permeability and porosity. All the tests carried out on all specimens were undertaken at an age of 28 days.

The test results showed that the durability properties of all specimens were significantly improved as curing periods increased. While curing durations had some significant effect on the strength of OPC/ggbs samples, the effects on OPC and OPC/pfa were in general only minimal. Furthermore, as to the effects on the pore size distribution and permeability, a critical curing duration (beyond which no further significant changes in these properties were observed) was seen to exist which depended on both curing environment and cement type.

Environments hotter than 20°C+70%RH adversely affected the durability properties of uncured samples of all mixes. Furthermore, the durability properties of plain OPC samples were adversely affected by the two hot environments when compared to 20°C+70%RH for all curing durations. On the other hand, while OPC/pfa and OPC/ggbs samples cured for one day or more at 35°C+70%RH showed similar or worse durability results compared with those cured at 20°C+70%RH, better results were obtained at 45°C+30%RH than in either of the other two environments. As to the effects on strength, for any given curing period, environments hotter than 20°C+70%RH adversely affected the OPC and OPC/ggbs samples but not those containing pfa.

AT 20°C+70%RH, the pfa specimens showed generally similar or worse durability results and weaker samples than plain OPC for all curing periods. This trend was reversed in the two hot environments. On the other hand, while OPC/ggbs samples showed similar or worse durability results at 20°C+70%RH and 35°C+70%RH compared to plain OPC, at 45°C+30%RH the slag specimens showed better durability results for curing periods of one day or more. The 28-day strength of OPC and OPC/ggbs concretes were similar to each other in all environments for all curing periods except for those which were uncured. The uncured OPC specimens were stronger than the slag specimens in all environments.

I wish to didicate this work to the memory of my eldest brother, RAHMAH, who died in a car accident. May ALLAH bless his soul and forgive his sins.

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ABBREVIATIONS

OPC = Ordinary Portland Cement

pfa = Pulverized-Fuel Ash

ggbs = Ground Granulated Blastfurnace Slag

PBFC = Portland Blastfurnace Cement

CaO = Calcium Oxide

C_3S = Tricalcium Silicate

C_2S = Dicalcium Silicate

C_4AF = Tetracalcium aluminoferrite

CH = $Ca(OH)_2$ = Calcium Hydroxide

APD = Average Pore Diameter

MPD-V = Median Pore Diameter by Pore volume

MPD-A = Median Pore Diameter by Pore surface Area

PSA = Pore Surface Area

MIP = Mercury Intrusion Porosimetry

ISAT = Initial Surface Absorption Test

CHAPTER ONE

INTRODUCTION

1.1 - General Introduction

Concrete has often been taken for granted in the Middle East without imposing suitable standards for quality control. Many concrete structures were built using either saline water or unwashed sea sand. Furthermore, no limits on water/cement ratios, cement contents or workabilities were set for small contractors to follow. Steel which had already corroded from leaving exposed for long periods was also used. Ordinary Portland cement (OPC) was imported from all over the world without any control checks. Curing of concrete has often been overlooked by some contractors who pay little attention to it and budget only a small amount of the total contract value for it.

The effort involved in controlling the quality of materials and production of the concrete can be negated if adequate curing is not carried out. The sensitivity of concrete to curing is influenced by the environment in which it is placed. Hot dry environments accelerate drying of the concrete and thus are far more harmful than cool damp environments. A properly designed concrete mix, carefully placed, compacted and cured will have adequate strength and will be durable. Strength is easy to define and relatively easy to control by means of standard cubes or cylinders. The strength from these standard specimens does not necessarily relate to the strength of the concrete in the structure; it merely gives a measure of the potential strength of the material. Durability on the other hand is not an intrinsic property of concrete and therefore it is not easy to define or to measure. Broadly speaking though, durability is an attribute of concrete which is related to its ability to resist attack from the environment in which it is placed, to maintain its appearance and to continue to function in the manner for which it was designed. Attack from the environment can take many forms but two of the most common are chloride ingress leading to corrosion of reinforcement , and sulphate attack.

Deterioration of reinforced concrete structures is mainly attributed to two factors; the quality of the concrete placed and the ambient conditions. To the author's knowledge, the main type of cement used in the Middle East in the 60's and the 70's was ordinary Portland. High ambient temperatures and the existence of aggressive salts are known to accelerate the deleterious reactions that take place within concretes, such as carbonation and steel corrosion, hence shortening the service life of the structures. When this is added to the fact that most concrete structures built in the last two decades were made of unsuitable materials, with inadequate specifications and by unskilled labour, the problems people see now are certainly understandable.

Middle East concreting has certainly come a long way. People can now produce better concrete than they did in the past. The service life of currently built concrete structures can be expected to be longer than those constructed in the past. However, it is still very difficult to produce a reinforced concrete as durable as, for example, that in Europe because of the factors described above. If it is desired to lengthen the service life of concrete structures in, for instance, the Gulf States, then a need exists to produce concretes that are less permeable and less absorptive than those in temperate environments. According to Kasai et al (48), the carbonation rates are greater for samples that are more permeable.

Durability of concrete cannot be assessed by strength alone and there are many examples of reinforced concrete structures in existence today which substantiate this point. Few if any structures fail to perform adequately because of insufficient strength of the concrete. In the majority of cases the reason is lack of durability, leading very often to problems with corrosion of reinforcement. This lack of durability is a particular problem in countries such as the Gulf States where the hot arid environment combined with the presence of chlorides and sulphates (in both the aggregates and atmosphere) has resulted in a rapid and extensive deterioration of a large number of buildings (30,33,34,36). The ability of the concrete to resist ingress of any deleterious material is a good indication of its durability but it is unlikely that this can be linked to one single parameter. Porosity and permeability to air, water, water vapor, chlorides and sulphates are probably the more important parameters considered to have an influence on the durability.

The use of cement replacement materials like pulverized fuel ash (pfa) and ground granulated blastfurnace slag (ggbs) is quite common in Europe and North America. There are many technical advantages to be obtained when using pfa and ggbs particularly in terms of durability (58,19). Because, however, both materials are slower to react than the Portland cement which they replace,there are some doubts as to their performance in situations where the concrete is allowed to dry out rapidly immediately after placing (i.e. where little or no curing is applied in a hot arid environment). There is little documented evidence available on this particular problem.

1.2 - Hot Weather Factors:

Hot weather is characterized by high temperatures, low humidities and high solar radiation, see Fig. 1.1. The environment of the Arabian Gulf is, moreover, known for large daily fluctuations in both temperature and humidity and also for persistent winds.

1.2.1 - Temperature:

The temperature in the Arabian Gulf countries often rises to 50°C in coastal areas and more than this inland with May, June, July, and August being the hottest months of the year. The mean maximum temperature in the summer can be

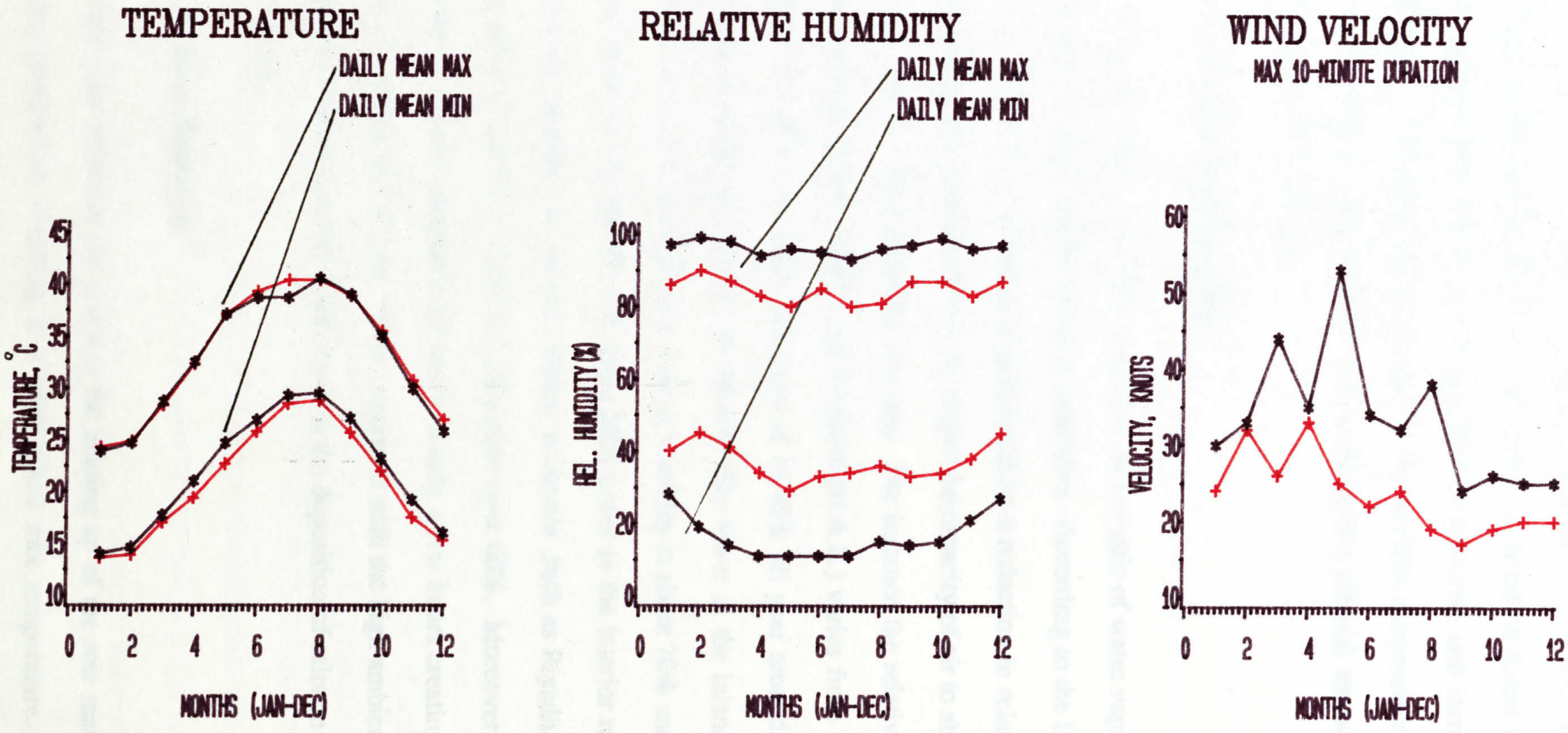


FIG. (1.1a) FIG. (1.1b) FIG. (1.1c)

FIG. (1.1) AMBIENT TEMPERATURES, RELATIVE HUMIDITIES AND WIND VELOCITIES IN THE UNITED ARAB EMIRATES (31).
***=DUBAI +++=ABU DHABI

as high as 45°C while the mean minimum ranges from 25 to 30°C. When this high ambient temperature is combined with about 11 hours of direct sunshine, it is understandable that the surface temperature of concrete and formwork can be much higher. Furthermore, a variation in the ambient temperature of up to 20°C can occur within 24-hours which may cause severe thermal stresses in concrete especially when it is young.

1.2.2 - Relative Humidity (RH):

The term relative humidity is defined as the ratio of water vapour available to the amount of water needed to reach saturation. According to the laws of nature, a rise in temperature is always accompanied by a reduction in relative humidity. The smaller the relative humidity, the higher the capacity of air to absorb moisture from available sources including concrete. For instance the relative humidity in coastal regions of the United Arab Emirates (U.A.E.) varies from a mean maximum of 85-100% to a mean minimum of 10-40% all year around, see Fig. 1.1. These mean values are seen to be considerably lower in the inland plains away from the Gulf. The average daily relative humidity is about 70% and 55% in winter and summer respectively and about 20% lower in the interior regions. Additionally, the interior parts of the Arabian peninsula ,such as Riyadh, have a much lower relative humidity where it hardly rises over 60%. Moreover, considerable variation in relative humidity can occur in only a few hours creating quite severe cycles of wetting and drying. When combined with the high ambient salinity that is common in the Gulf, this could result in the deposition of salts on the surface of the concrete.

1.2.3 - Solar Radiation:

High solar radiation can result in the heating up of the raw materials used in concrete production, resulting in a high initial mix temperature. Skies in the U.A.E. are generally always clear and so is the case in the other Gulf States. The mean daily sunshine hours are 7 to 8 in winter and 10 to 11.5 during the summer months (31).

1.2.4 - Winds:

The effects of persistent high winds on both fresh and hardened concretes should not be underestimated. An increase in wind speed results in an increase in the rate of evaporation of water, leading to a reduction in concrete workability and difficulty in compaction. It is estimated that the evaporation of water at 15 and 40 km/hour is 4 and 9 times that in still air respectively. The exposed surfaces of hardened concrete may also be attacked by salts deposited by the wind. Salts carried by winds can also be deposited on the aggregates and sand resulting in a high salt content within the concrete unless precautions are taken.

Winds in the Gulf countries are more persistent than in many parts of the world. Wind speeds of between 7.0 and 27.5 km/hour were observed for more than 75% of the time according to readings taken at 3 airports in the U.A.E. (31). Abu-Dhabi has a daily mean wind speed of about 16 km/hour all year around (31).

1.3 - Curing

Curing is the procedure by which water loss from concrete is prevented or minimized to allow sufficient hydration to take place. Loss of water from fresh and young concretes can result in detrimental effects on the properties of fresh and hardened concretes. Some of these problems such as plastic shrinkage cracks can be seen immediately , but others such as lack of durability and strength are not as obvious. The rate of this water loss is greatly accelerated by the environment of the Arabian Gulf States; i.e. low humidity ,high temperature and persistent winds.

The majority of water loss occurs in the top 30-50 mm of concrete, see Fig. 1.2. If water is not replaced or evaporation prevented, severe cracking could occur

(44). Continual water loss from young hardened concrete could also result in a rapid termination of hydration. According to Payne and Dransfield (44), if the relative humidity within the pores of the concrete drops to less than 80%, then no further significant hydration will take place. Tests have shown that the relative humidity drops to less than 80% in one day in the top 6mm under severe conditions and in the top 20mm within seven days (44). Powers (55) indicated that hydration ceases to take place if the vapour pressure in the capillary is not sufficiently high, i.e. about 0.8 of saturated pressure.

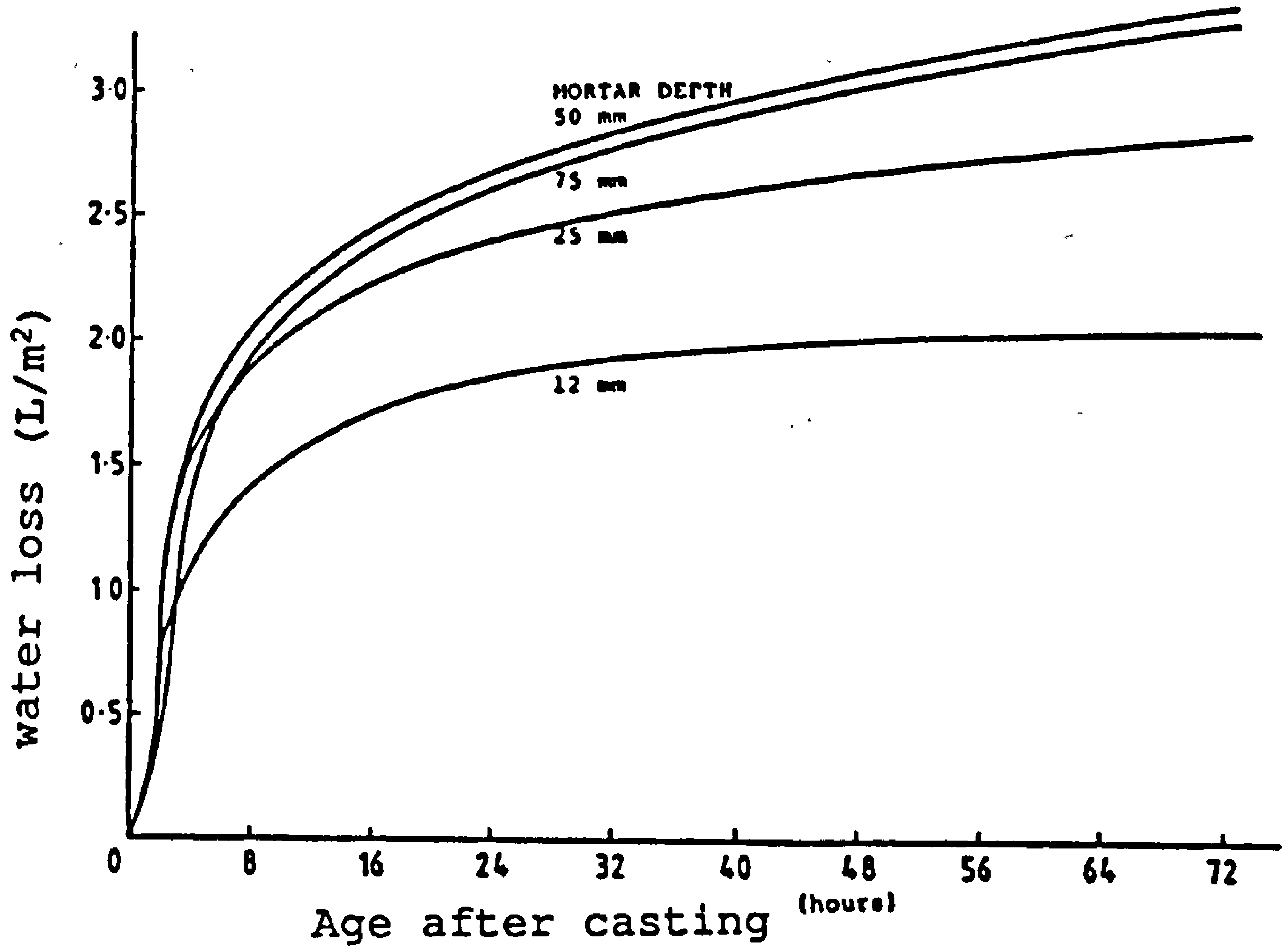


Fig. 1.2: Water loss with time and thickness of mortar in mould using B.S. proposed curing conditions (44).

Low permeability can only be achieved if the capillaries become either blocked or significantly narrowed and the time needed to reach this state depends largely on the initial water/cement (w/c) ratio, see Fig. 1.3. Senbetta and Scholer (22) attempted to measure the water absorption at various depths below the surface for concretes cured under different conditions and concluded that curing only influences the top few centimeters of concrete. It is however this few centimeters, the cover zone, that is instrumental in preventing ingress of deleterious materials.

The effect of curing on the relevant properties of concrete will be dealt with separately in reviewing each property.

Preventing or reducing water loss from concrete can be achieved in many ways. Application of additional water by ponding or wet hessian is widely used or alternatively, the use of coatings and membranes can help in reducing water loss. Fig. 1.4 (44) shows the effects of curing methods on the water absorption of cores taken from cubes during the construction of Jabal Ali port in Dubai.

1.4 - Hydration of Ordinary Portland Cement (OPC):

The hydration process of OPC has been investigated by many researchers and is very well documented (17,98). The main components of Portland cement, which are tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF), react with water to form complex hydrates. The end products of C_2S and C_3S phases can be presented approximately as follows:

$$C_2S + H \longrightarrow C\text{-}S\text{-}H + CH \quad \text{and}$$
$$C_3S + H \longrightarrow C\text{-}S\text{-}H + CH$$

where C-S-H is calcium silicate hydrate, CH is calcium hydroxide and H is water.

1.5 - Pulverized-Fuel Ash (pfa):

Pulverized fuel ash (pfa), which is also known as fly ash, is a by-product of burning coal in power stations for the generation of electricity. It is defined by British Standards (BS3892,1982) (79) as:

> '... the solid material extracted by electrostatic and mechanical means from the flue gases of boilers fired with the bituminous coal'

Pfa, which is considered as an artificial pozzolana, does not posses any cementitious properties on its own. Nevertheless, it will react with calcium

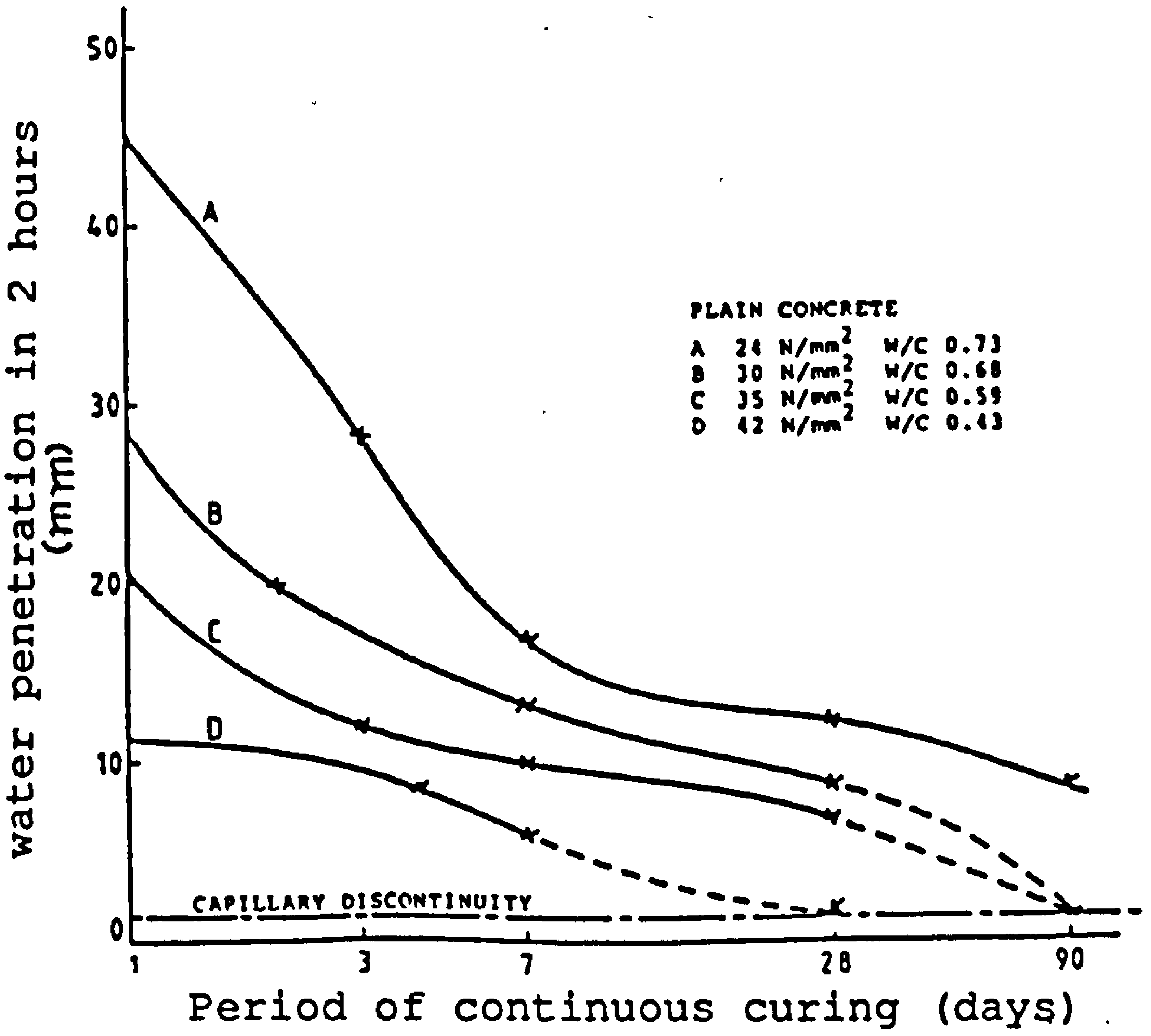
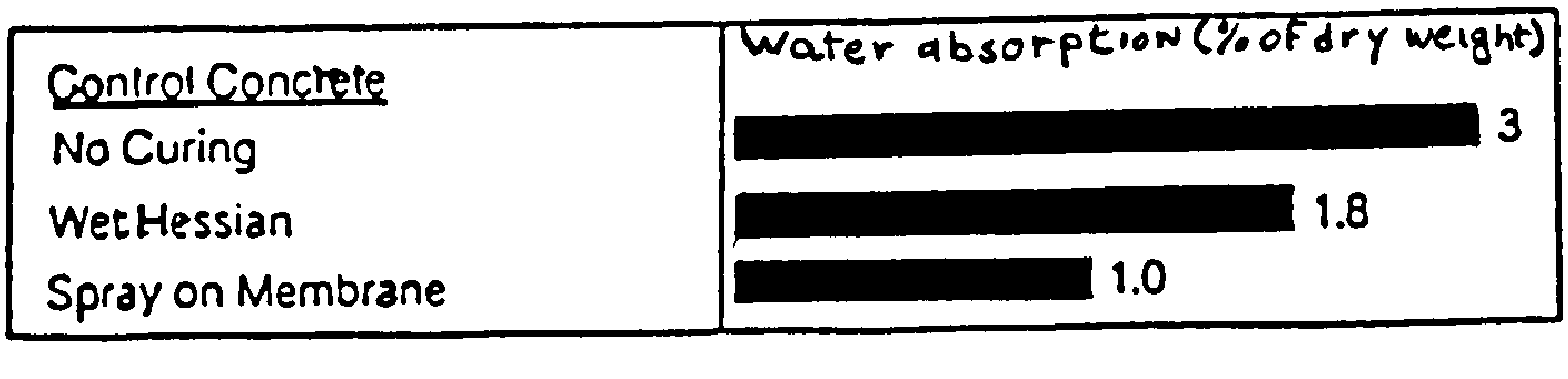


Fig. 1.3: The effects of continuous curing on the water penetration (44).



Concrete 340kg/m³ OPC

Fig. 1.4:Effects of curing on water absorption results(44).

hydroxide (lime) in the presence of moisture to form compounds possessing cementitious properties. The lime is usually provided by the reaction of the calcium oxide found in the OPC with water. Fly ash is now widely used in the construction industry in Europe, North America and Australia.

1.6 - Ground Granulated Blastfurnace Slag (ggbs):

The potential hydraulicity of glassy formed blastfurnace slag produced by rapidly quenching slag was first discovered in 1862 by Emil Langen. The presence of activators, such as solutions of alkalis and sulphates, are essential for the hydration of ggbs (19). For this reason, Portland cement is mixed with the ggbs to produce the needed alkalis and the mixture is called Portland-blastfurnace cement. The Portland blastfurnace cement (PBFC) is widely used in Europe, North America and Australia. According to Reeves (19), the countries of the European Cement Association produce 40 million tones per annum of PBFC, about 20% of the total cement production.

Ground granulated blastfurnace slag consists mainly of the oxides of calcium, silicon, aluminium and magnesium which amount to about 95% of the total constituents. The chemical composition of ggbs is closely related to that of Portland cement (19),

	lime	silica	alumina	magnesia
slag	34-44	34-39	8-14	6-10*
OPC	64-66	19-22	5-7	1-1.5*

* inductive ranges

and can therefore be used as a raw material for the production of Portland cement.

1.7 - Hydration of Pozzolanic Cements:

Pozzolanic materials possess little (if any) cementitious value in themselves when mixed with water. However, the pozzolanic reaction occurs between silicious or silicious aluminous fractions of the pozzolan with calcium hydroxide to form compounds with cementitious properties in the presence of moisture. The pozzolanic reaction can take place only when C_3S and C_2S have formed calcium hydroxide (lime). The main components involved in the pozzolanic reaction are SiO_2,Al_2O_3, Fe_2O_3 and CaO. Since the main components are similar to OPC, the main products are also similar to Portland cement hydration. These products are calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H). They are produced after the silica and alumina of the pozzolan react with calcium hydroxide.

CHAPTER TWO

LITERATURE REVIEW

THE EFFECT OF HOT WEATHER CONDITIONS ON THE PROPERTIES OF FRESH AND HARDENED CEMENT MIXES

2.1 - Fresh Concrete:

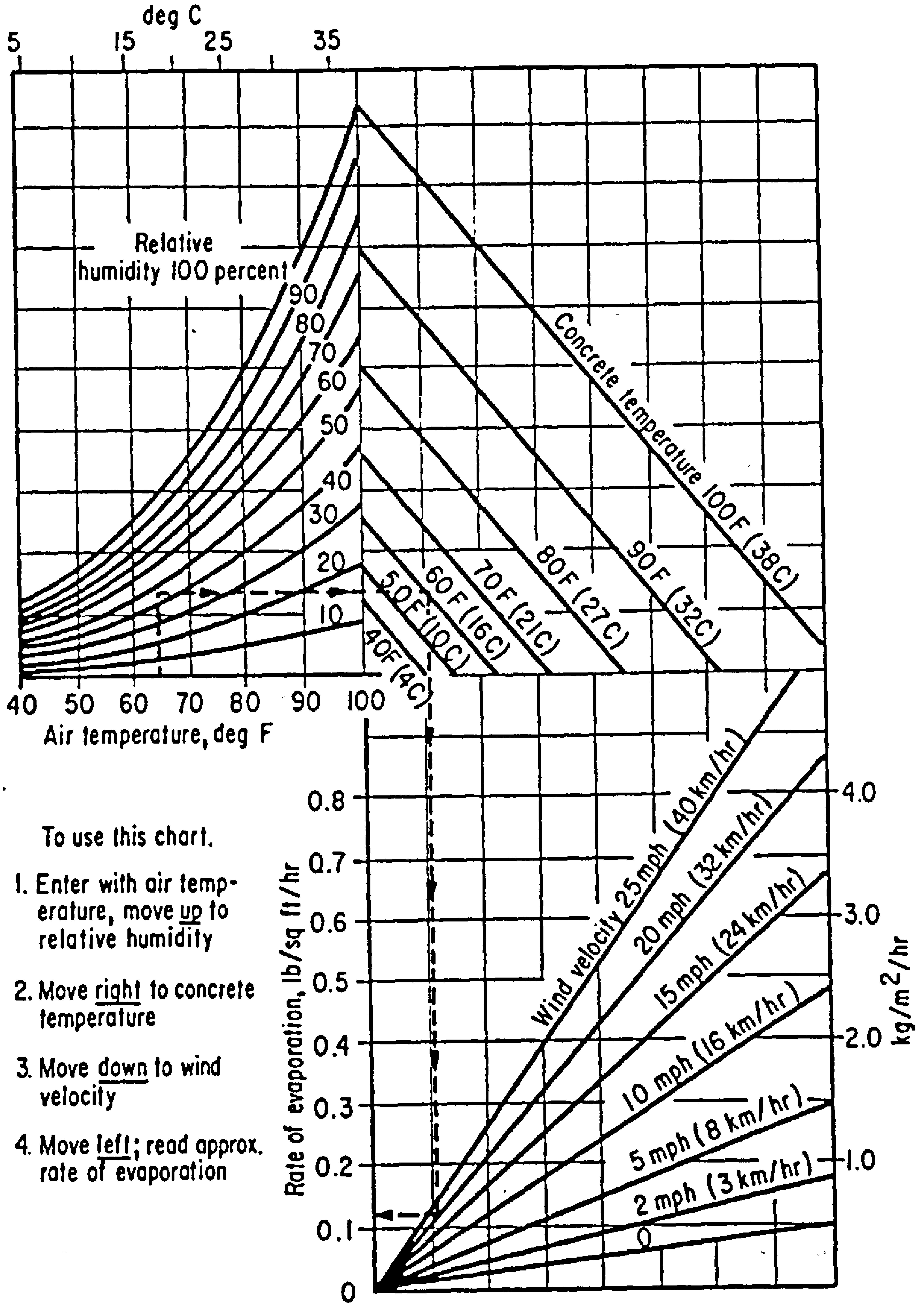
Hot weather conditions will influence the properties of fresh concrete in several ways including an increase in the rate of evaporation of water from the concrete, an acceleration in the rate of setting, and an increased water demand for constant workability.

2.1.1 - Rate of Evaporation:

Rate of evaporation of water from the concrete is enhanced by concrete temperature, high ambient air temperature, low relative humidity and high wind speeds (26), see Fig. 2.1. When the evaporation rate exceeds the bleeding rate, plastic shrinkage cracks are likely to occur (26). According to the American Concrete Institute (ACI), precautions should be taken when the rate of evaporation exceeds 1.0 kg/m^2/hour (26). Such precautions may include: casting at a lower environmental temperature (e.g. in the shade), erecting wind breakers, reducing the time between production and placement and providing adequate curing. If the water lost through evaporation is not replaced immediatly, hydration may cease resulting in an impairment in many of the short and long term properties of the concrete.

2.1.2 - Setting Time :

Cement hydration, like many chemical reactions, is accelerated by heat and the rate of hydration is likely to double for every 10°C increase in temperature



To use this chart.

1. Enter with air temperature, move up to relative humidity
2. Move right to concrete temperature
3. Move down to wind velocity
4. Move left; read approx. rate of evaporation

Fig. 2.1: Effects of concrete and air temperatures, relative humidity, wind velocity on the rate of evaporation of surface moisture from concrete. This chart provides a graphic method of estimating the loss of surface moisture for various weather conditions. To use the chart, follow the four steps outlined above (26).

(32). ACI reported results of the effect of temperature on the setting times of different cements and Fig. 2.2 shows that setting is significantly accelerated by high temperatures (26). It also shows that setting depends not only on temperature but also on cement type, particularly when set-retarding admixtures are used.

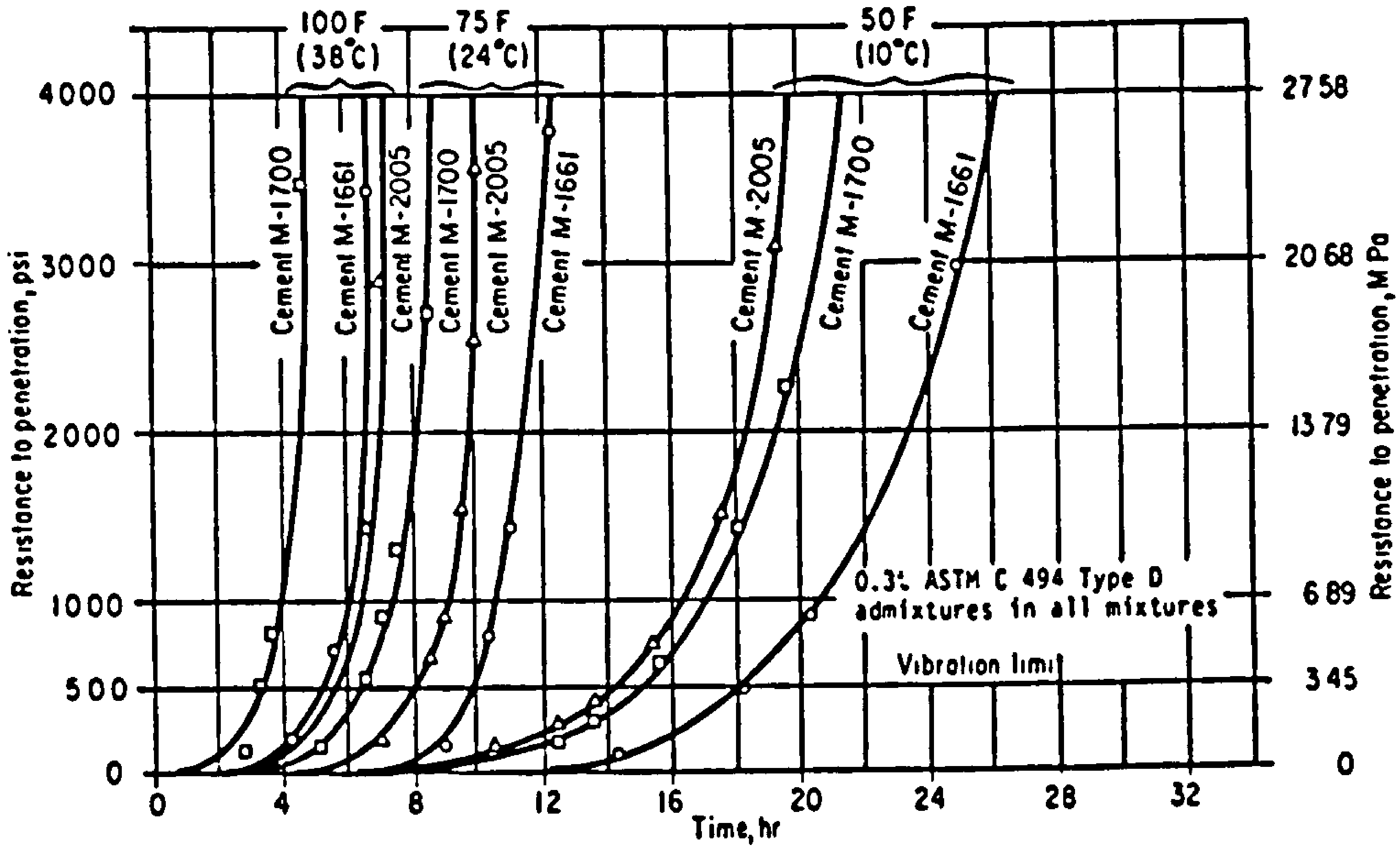


Fig. 2.2 : Temperature and brand of cement influence hardening characteristics of concrete mortars (26).

The influence of high temperature on the setting time of cements was confirmed by Berhane (28) who studied the effect of temperature on the heat of hydration. He found that the heat generated at early ages was greater at elevated temperatures than at normal temperatures and, since setting time and the heat of hydration are closely related, this agrees with the earlier findings of ACI. Moreover, elevated temperatures seem to decelerate the reaction at later stages (28).

2.1.3- Effects on Workability:

Due to the fact that the temperature and/or relative humidity greatly affect the evaporation rate of water and setting time of cements, the workability of the concrete is likely to be impaired in hot dry environments. The consequent loss in slump is normally compensated for by the use of additional water which results in an increase in water/cement ratio leading to a reduction in the strength, an increase in the capillary porosity and thus in the permeability (17). However, Burg (5) suggested that when trying to compensate for slump loss of ready mix concrete, an extra 8-10% of the total unit water can be added without any significant loss in strength.

The effect of concrete and ambient temperatures on the amount of water needed to increase the slump (which was measured immediately after mixing) by 25mm is shown by Klieger (77) in Fig. 2.3 for ASTM type I and II cements (normal and moderate sulphate resistant). At 50°C this amount was about 33% greater than that at 20°C. Moreover, Fig. 2.3 shows the effect of concrete temperature on slump, a reduction of about 40 mm was seen when the temperature was increased from 20°C to 50°C. It is important to note here that Klieger found the workability of ASTM type III cement (high early strength) mixes to be unaffected by high concrete and ambient temperatures. He could not explain the reason behind this behaviour.

Shalon and Ravina (38) examined the effect of concrete and ambient temperatures and relative humidity on the workability of ordinary Portland cement concretes as measured by the slump test in an actual desert area. Slump loss became significant only for concretes cast at temperatures above 50°C and at relative humidities below 20%. Additionally, they found that slump remained almost constant for about 20 minutes under the rather severe environmental conditions of 50°C and 40%RH. Their findings are in disagreement with those of Klieger. They nonetheless suggested that although they used a similar type of cement to that of Klieger, the cement composition, which is known to influence setting rate, could have been different. Sample size could be another factor in explaining such a behaviour. It is understood that Shalon and Ravina's samples (38) were bigger than those used by Klieger (77).

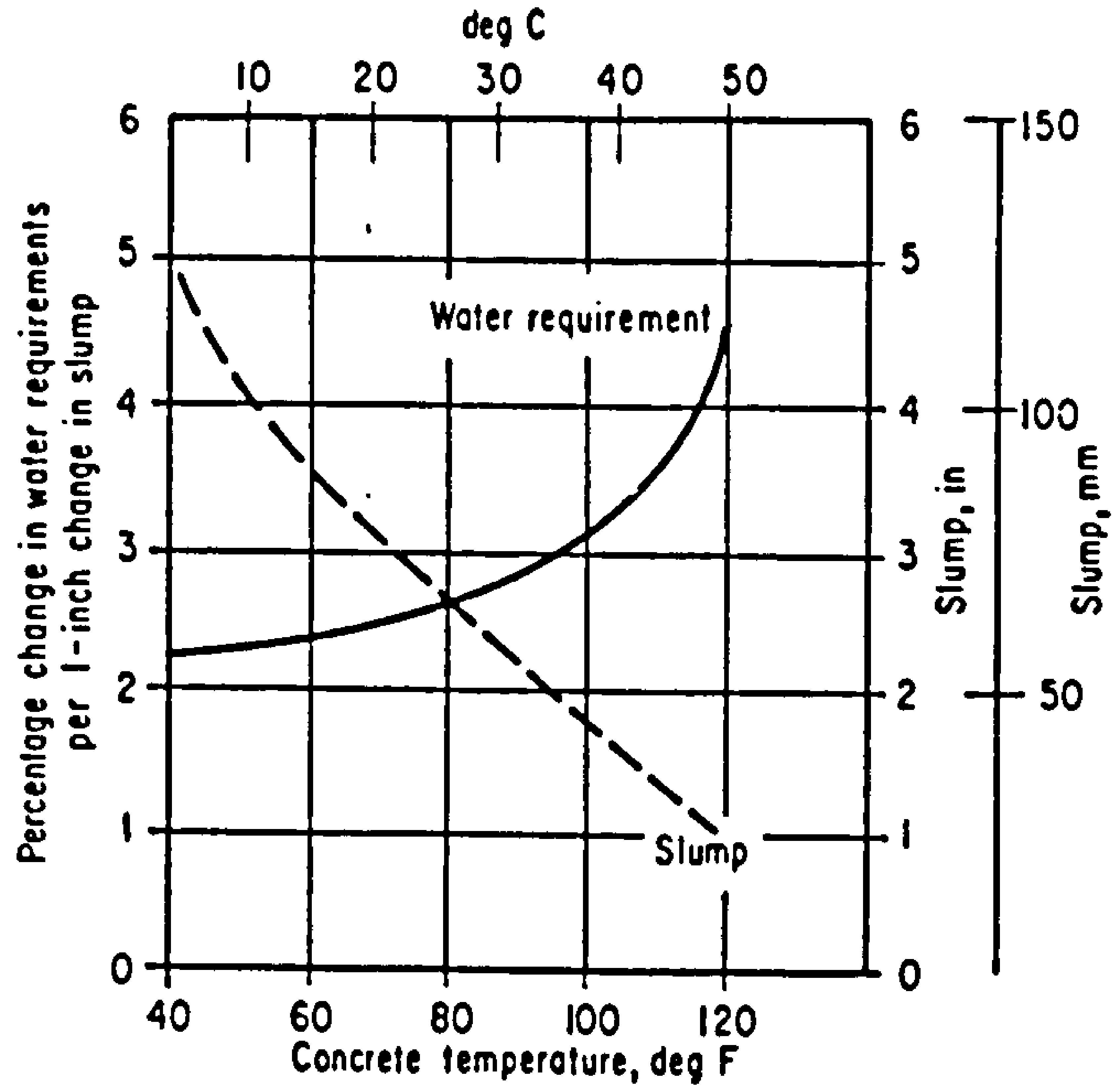


Fig. 2.3 : Effects of concrete temperature on slump and water required to change slump. Cement content=307 kg/m^3; 4.5% air; maximum size of aggregate 38 mm; average of data for Types I and II cements (normal and moderate sulphate resistant) (77).

The inclusion of pulverized fuel ash (pfa) in concrete is known to lead to an increase in the workability or alternatively to a reduction in water/cement ratio in order to maintain the same workability (18,58,111). The level of reduction in water/cement ratio depends on both the level of replacement and on the source of pfa. Ramazamianpour (18) found a reduction of about 10% when 30% of the OPC was replaced by pfa from Drax Power Station in West Yorkshire. On the other hand, the effect of the inclusion of ground granulated blastfurnace slag (ggbs) on workability is known to be slight and a reduction in the water/cement ratio of no more than 5% can be expected if workability is to remain constant (19).

2.2 - Hardened Concrete:

The influence of hot weather conditions on the properties of the fresh concrete may also be reflected in such properties of hardened concrete as compressive strength and durability. Strength, permeability, water absorption, pore structure and many other properties may be permanently impaired if adequate precautions are not taken.

2.2.1 - Compressive Strength:

Although compressive strength may give little indication as to the durability of concrete, it is a test used worldwide as a means of compliance and quality control. In this review, mention will only be made of the effects of hot weather conditions on the compressive strength of the concrete.

Plain OPC Mixes

There is agreement among researchers that an increase in curing temperature results in an increase in the early age compressive strength of the concrete. Fig. 2.4 shows the effect of curing temperature on the one-day compressive strength of OPC concretes (26). As the temperature increased, there was a consequent increase in the one-day compressive strength. It was also shown by Byfors (39) that the rate of strength development was significantly increased by higher temperatures at early ages, a trend also confirmed by Price (112).

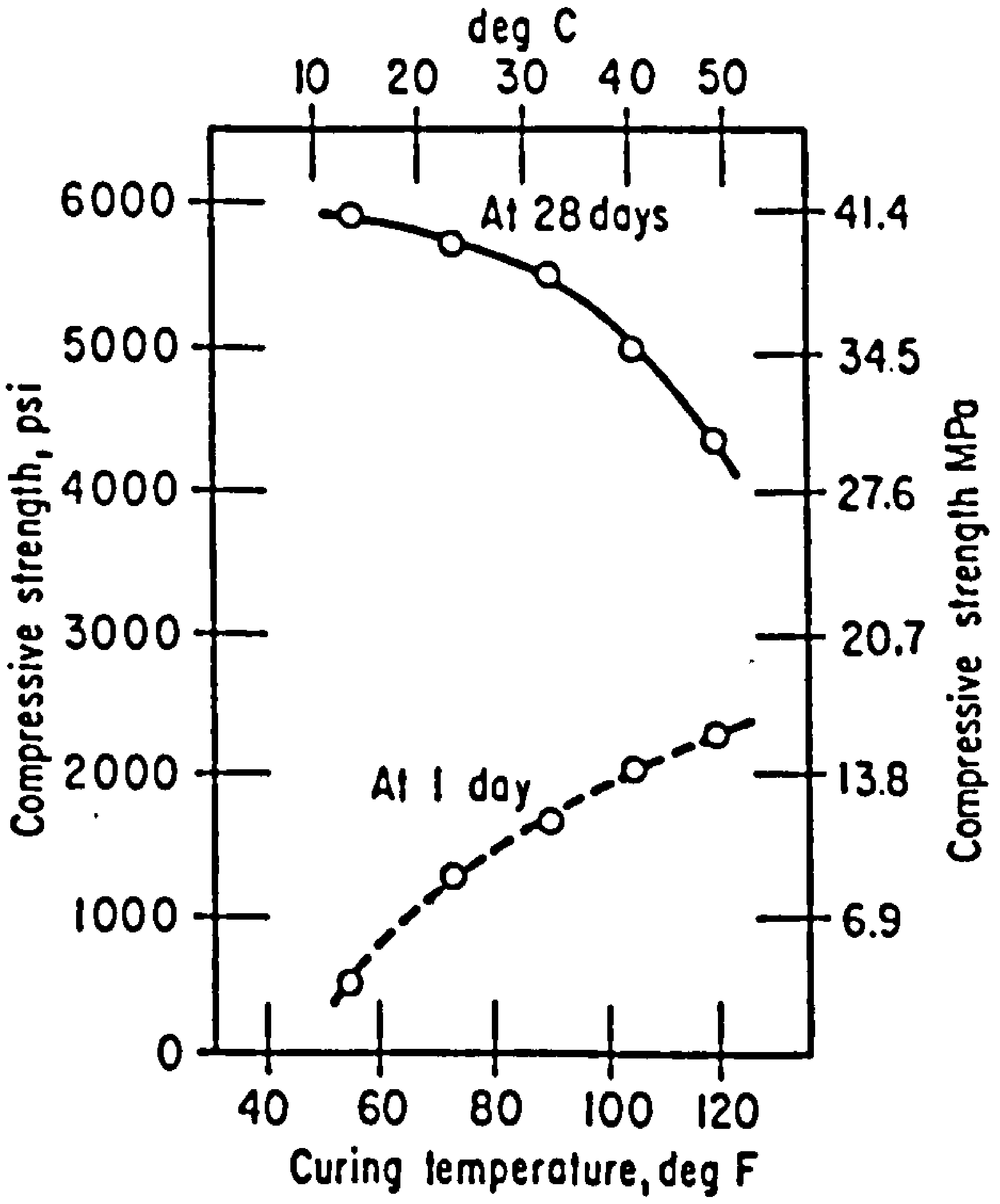


Fig. 2.4: One- day strength increases with increasing curing temperature but 28-day strength decreases with increasing curing temperature (26).

There is, however, some disagreement as to the effects of temperature on the compressive strength at later ages (i.e. 28 days and greater). The results reported by ACI (26) of work done by Verbeck and Helmuth, Fig. 2.4, show that the 28-day strength decreased as the curing temperature increased.

Shalon and Ravina (38) studied the effects of mix and curing temperatures on the 56 day compressive strength of concrete. Concretes with mix temperatures of between 30-40°C were water-cured for seven days on site then left uncovered for seven more days on site before transfer to the laboratory where it was left uncovered. The temperature and relative humidity of the laboratory were 20°C and 70%RH. In addition similar concretes were water cured for seven days in the laboratory and then kept uncovered in the laboratory until testing. They found that the strength of those concretes kept initially on site were 8-15% lower than those continuously kept in the laboratory. Ridley found, as reported by Shalon and Ravina (38), that concretes cast in Lagos, Nigeria (average temperature=30C,RH=70-87%) and cured under water at 23°C showed a reduction of about 15% in compressive strength at 28 days when compared to those cast in an environment of 20°C and 70%RH and cured under water at the same temperature.

Klieger (77), on the other hand, found that curing temperatures between -4°C and 49°C in a moist environment had practically no effect on the 28-day compressive strength of air-entrained concrete. He concluded that the concrete strength is not impaired until the temperature exceeds a certain value and this value varies from one type of cement to another. ASTM committee C-1 (78) reported that the effect of temperature on long term compressive strength is insignificant until the temperature of fresh concrete exceeds 38°C, above which the strength was seen to decrease. In addition to this, Price (112) reported results obtained by casting and maintaining the specimens for the first two hours at temperatures between 5°C and

46°C. The specimens were then sealed and maintained at 20°C. He found that the maximum 28-day compressive strength was achieved when the temperature was the highest. He also reported however that the long term strength (i.e. greater than 28 days) of concretes made and cured at higher temperatures was the lowest.

Abbasi and Alam (24), and Shalon and Ravina (38) investigated the effect of reducing the initial mix temperature on the 28-day compressive strength of concretes in hot environments. Abbasi and Alam (24) who performed their tests in a Saudi Arabian desert, concluded that the extra precautions taken to reduce the mix temperature were unnecessary. Shalon and Ravina (38) attempted to reduce the mix temperature by casting in the evening or at night; they concluded that there was no advantage to be gained by casting in the evening or at night, and in fact midday concreting yielded higher strength results at all ages up to 56 days.

The literature review indicates that there is an agreement among researchers that higher temperatures (over 30°C) will impair the long term (over 28 days) compressive strength of OPC mixes, when compared with those stored at lower temperatures. There is however some disagreement on the effects of ambient temperatures on the 28-day strength. This disagreement can be attributed, among other factors, to the fact that the cement composition used by the various researchers could have been different hence resulting in a totally different strength development behaviour. It is also important to mention that, with the exception of sealed and water cured specimens, small samples were used and evaporation was allowed to take place from all sides, a technique which does not represent conditions of site casting.

OPC/pfa Mixes

The effect of temperature on the strength of OPC/pfa mixes has also been investigated. March et al (69) showed that, at 20°C, paste samples containing 30% pfa were weaker than those of plain OPC having the same water/cement ratio at all ages less than 90 days, but the strength was statistically similar thereafter until one year of age. The strength development in the OPC/pfa samples, at 20°C, was slower than that of the plain OPC specimens. However, as the curing temperature increased, the pfa samples became stronger. For example, compared to OPC, specimens containing pfa and cured at 80°C were stronger after two days of curing only and those cured at 50°C were stronger after seven days, see Figs. 2.5, 2.6, and 2.7. Nevertheless, March et al (69) concluded that the general trends in both the OPC and OPC/pfa pastes were similar, i.e. strength rises with age to a maximum value after which strength degradation is noticed. The time at which strength reduction begins depends on the curing temperature and whether or not pfa is included, see Figs. 2.5 and 2.6.

OPC/ggbs mixes

Wainwright (80), who has intensively studied the behaviour of slag cements, investigated the effects of the inclusion of slag on compressive strength. Because of the fact that slag cements are slower to react with water than ordinary Portland cement, he advised that problems may be encountered in achieving the same 28-day compressive strength as Portland cements and hence longer periods of curing may be required. He also studied the effect of curing temperature on strength development of concretes containing ggbs. The one-day strength of OPC concrete was seen to be higher than that of slag cement concretes for temperatures up to 30°C. However, the 28-day compressive strength of slag cement concretes was higher than that of plain OPC for curing temperatures exceeding 25°C. Furthermore, Wainwright investigated the effect of the lack of curing on the strength of concretes with and without ggbs. He showed that the difference between uncured and wet cured specimens was bigger when slag was included. Wainwright (80) reported work done by Fulton which showed that the difference between uncured and wet cured specimens was a function of sample size as well as age. Furthermore Mather showed, as reported by El-essa (70), that OPC/ggbs mortars at 20°C

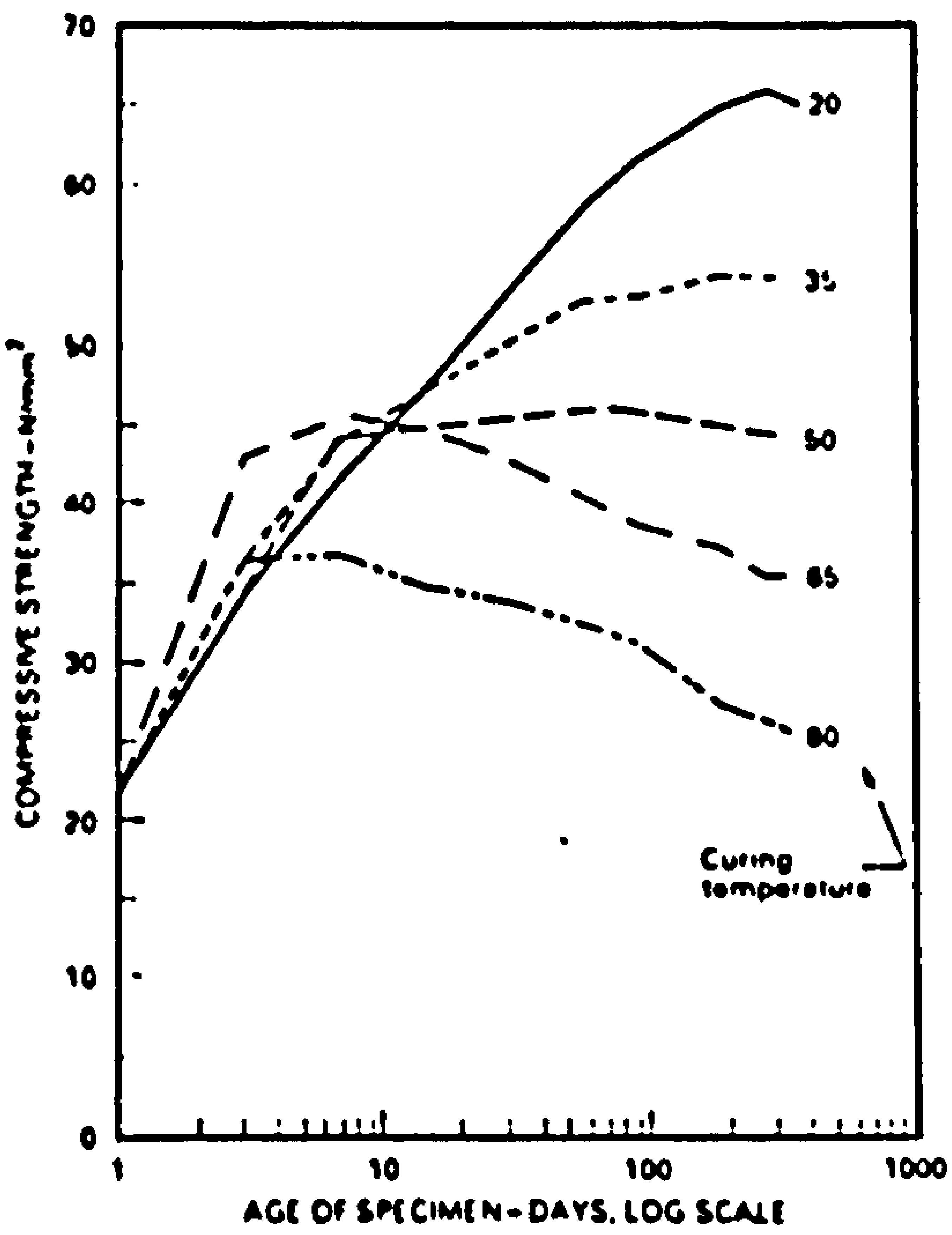


Fig. 2.5: Strength development in ordinary Portland cement pastes with time and curing temperature (69).

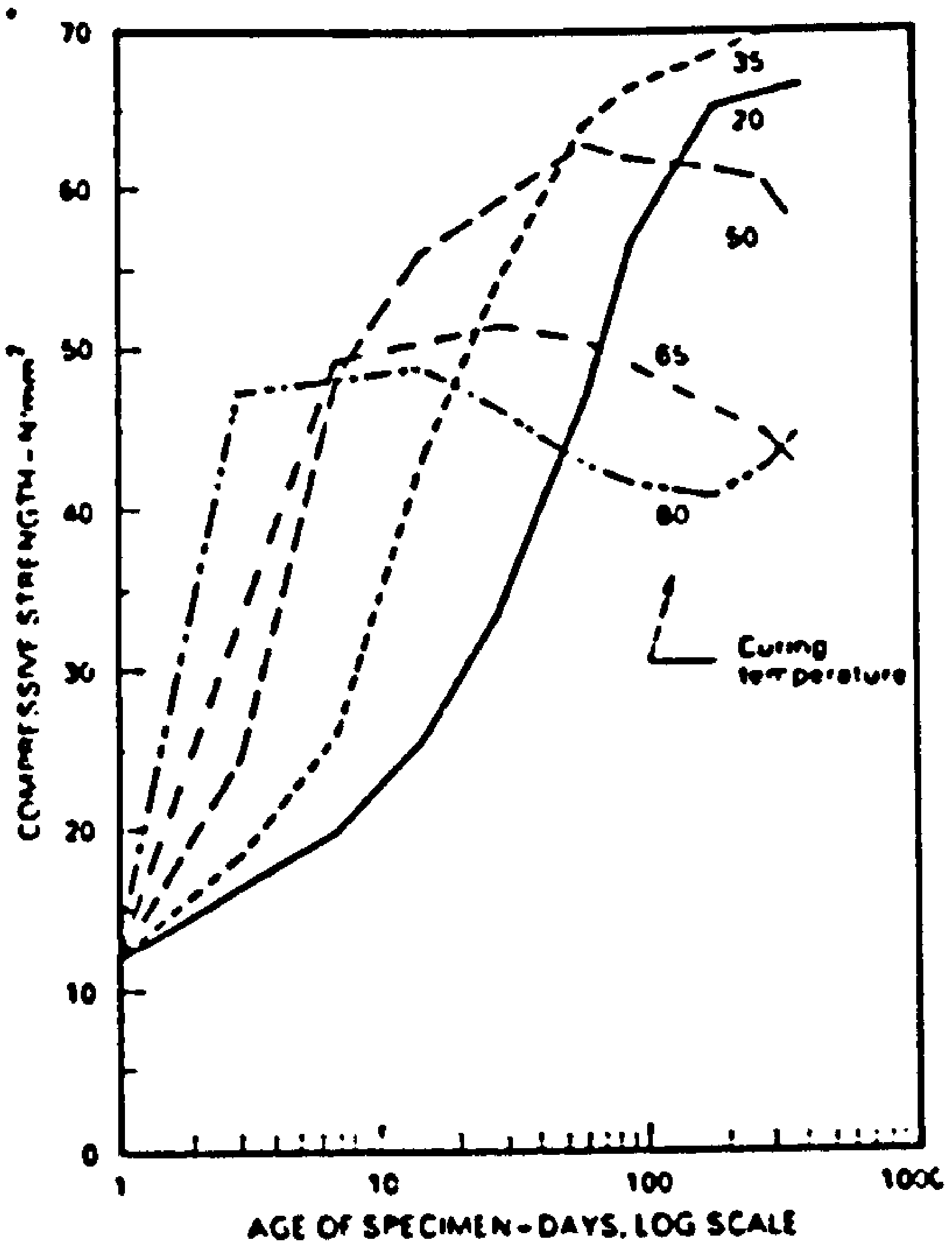


Fig. 2.6: Strength development in fly ash/cement pastes with time and curing temperatures (69).

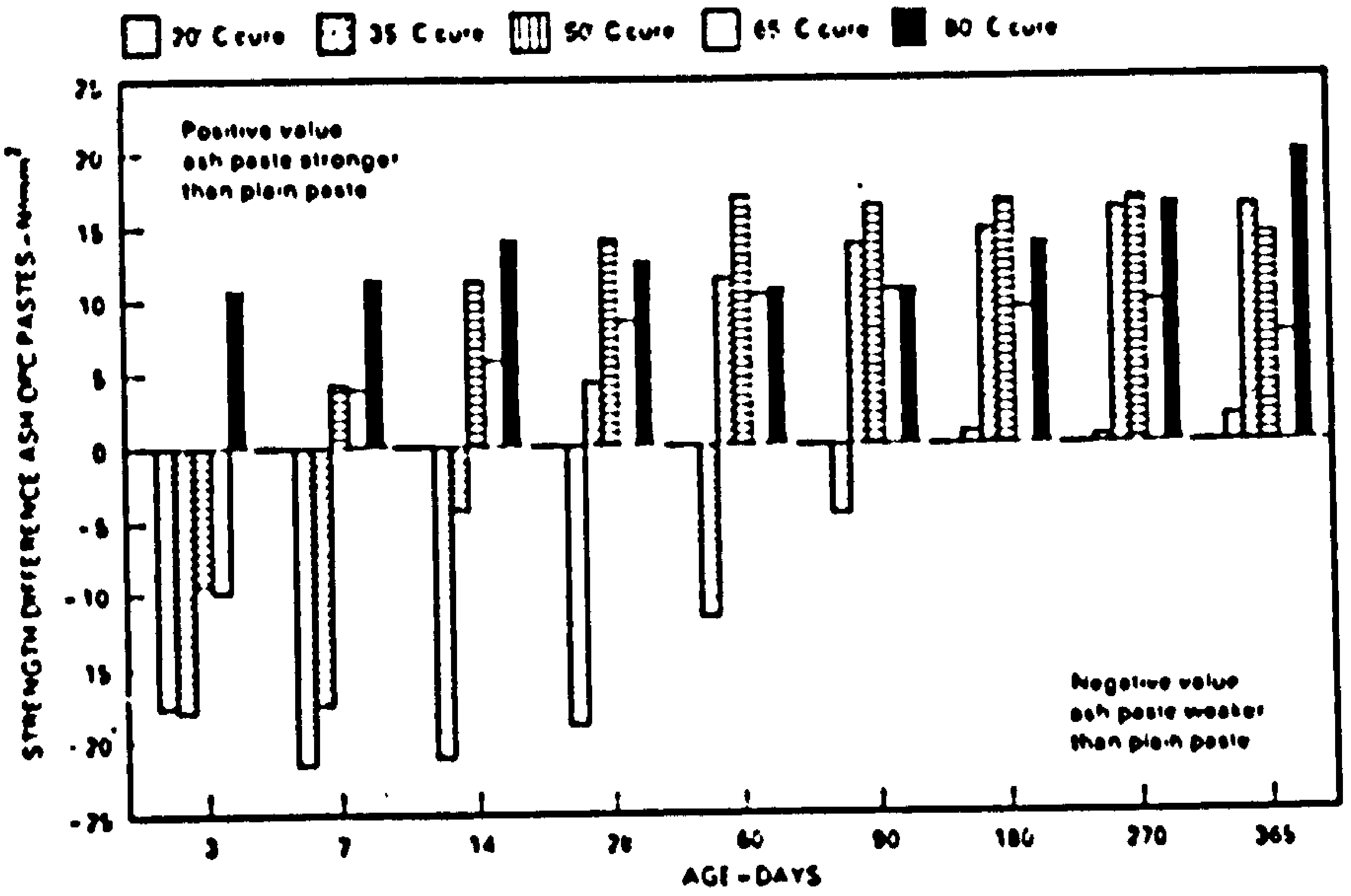


Fig. 2.7: Strength difference between pfa and plain OPC pastes with time and curing temperature (69).
]

developed strength more slowly than OPC mortars up to three days after which the strength development for the slag mixes increased sharply. At higher temperatures, the slag mortars were stronger at all ages (1, 7, 28 days) when compared to the OPC mixes. It would appear therefore that the effect of curing temperature on the strength development of OPC/pfa and OPC/slag cement mixes are similar.

The influence of ambient temperatures on the compressive strength of OPC/ pfa and OPC/slag cement mixes have mainly been investigated in a saturated environments such as water tanks. The resulting behaviour from these studies could be very different from those in an actual hot dry environment where the relative humidities can be very low, below 50%. Furthermore and unlike OPC mixes, the author was not able to find in the literature a work that investigated the strength characterestics of such mixes in hot dry environments similar to those seen in the Middle Eastern countries.

The Influence of Relative Humidity

With regard to relative humidity, there is a complete agreement among researchers that a lack of moisture will result in a lower strength. Fig. 2.8 shows the effect of relative humidity on the 28-day compressive strengths of OPC mixes.

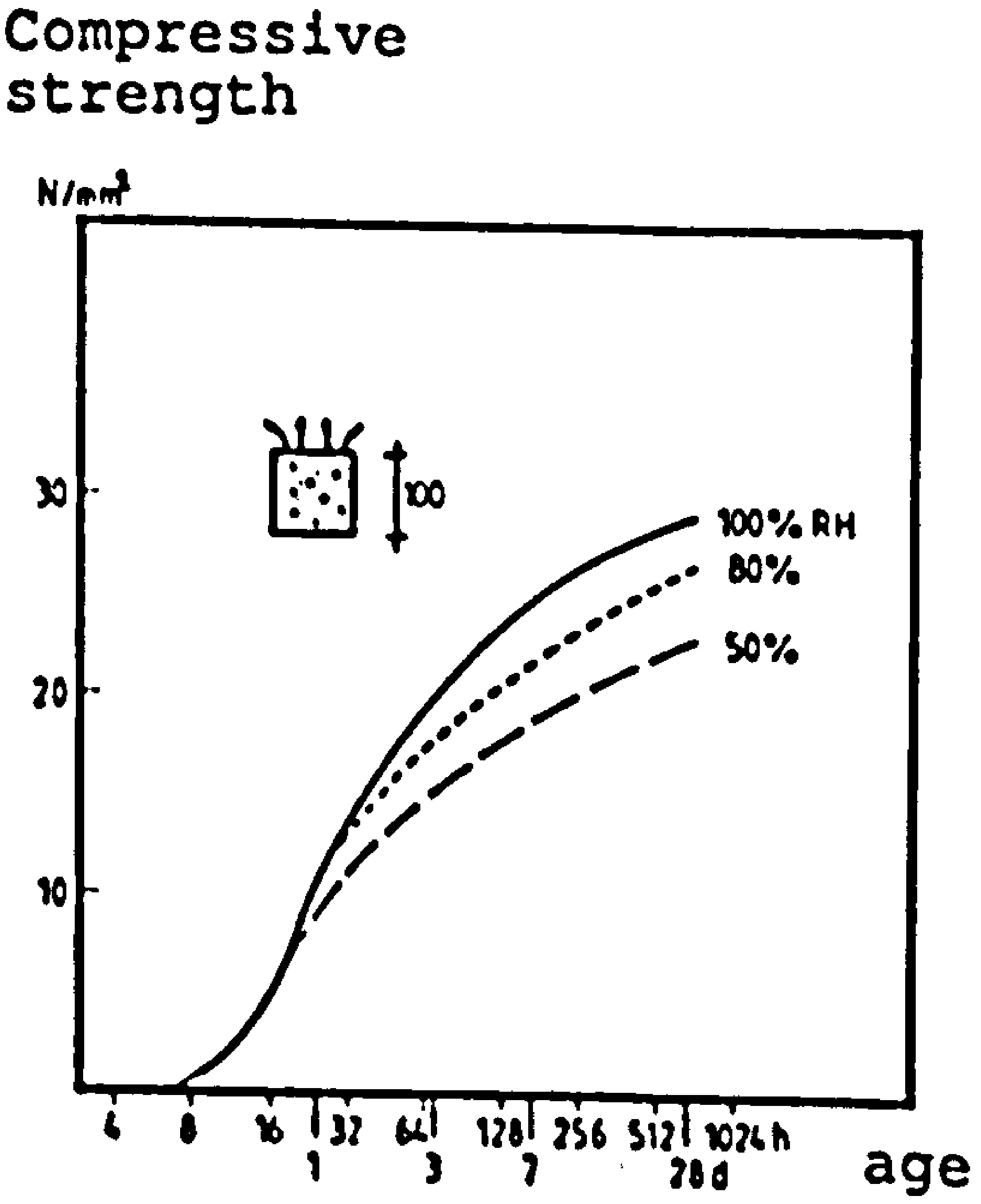


Fig. 2.8 : Compressive strength gain in concrete stored in different relative humidity (39).

The difference in strength between samples stored in a 100% and 50%RH environments increases with time. It is relevant to mention here that sample size can play an important role in the development of compressive strength in specimens exposed to dry environments. The work reported by Wainwright (80) showed that smaller samples, 102mm cubes as opposed to 230mm cubes, exaggerate the effects of drying when it is allowed to take place from all of the six sides.

2.2.2 - Porosity and Pore Structure

The structure of the hardened cement paste is thought to consist of two types of pores, namely capillary and gel pores. Capillary pores are classified as having a diameter of the order of 1.3 μm whereas gel pores are much smaller: between 0.0015 to 0.0020 μm in diameter (17). The quantity and sizes of these pores in the cement matrix are influenced by many factors such as: degree of hydration, water/cement ratio, type of cementitious material used, age and rate of hydration. Moreover, the first seven days are considered to be the most critical period with regard to the formation and structure of the pore system within the cement paste (17). As far as this review is concerned, the pore structure will be discussed in terms of the following:

1- Total porosity; the total pore volume per unit volume or weight.

2- Pore size distribution; pore volume and pore surface area as a function of pore size.

Capillary Pores

Capillary pore volume is defined by Neville (17) as the gross pore volume which has not been filled by hydration products. Continuous hydration results in a gradual reduction in capillary porosity, in addition to which pores may also become blocked by hydration products resulting in a reduction in the length of the pores. This is considered to be due to the fact that hydration products occupy more than twice the original volume of the cement paste (17).

Water/cement ratio is a very important factor affecting capillary porosity (17). At a water/cement ratio equal to 0.38, there is, theoretically speaking, sufficient water for complete hydration to take place in which case there would be no capillaries, see Fig. 2.9 (110). However, at water/cement ratios above 0.38, capillaries will be present even in the case of complete hydration. Some of these capillaries will contain excess water from the mix while others may acquire it from outside. Fig. 2.9 shows that increasing the water/cement ratio leads to an increase in the capillary porosity and that porosity also depends on the degree of hydration. However, the influence of water/cement ratio is much greater than that of age as shown in Fig. 2.10. The porosity was doubled when the water/cement ratio was increased from 0.47 to 1.00, but the effect of time was less significant. Similar results on the total porosity and pore size distribution have also be shown by Parker and Roy (21)

The rate of hydration has, according to Neville (17), no effect on the capillary porosity per se, but the type of cement used influences the degree of hydration at any certain time.

Gel pores

The gel pores are smaller than the capillary pores and classified in the region of 0.0015-0.0020 μm in diameter (17). The gel porosity is known to occupy about 28% of the total gel volume and as hydration continues, the gel porosity is increased while capillary porosity is reduced.

2.2.3 - Methods of Determining Porosity and Pore Size Distribution:

There are many methods available that will determine porosity and pore size distribution of pastes, mortar and concrete. Some of these methods determine

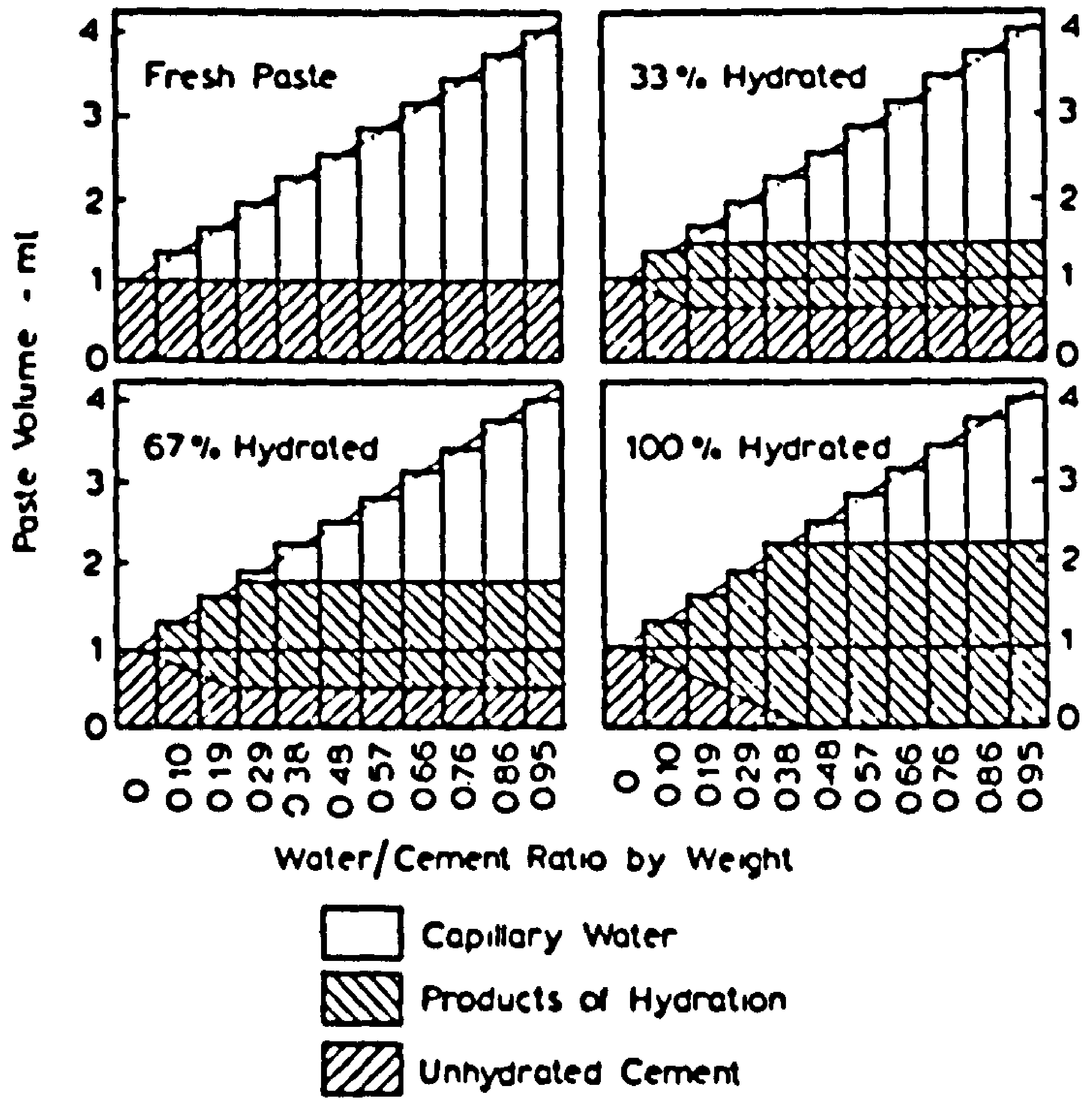


Fig. 2.9: Composition of cement paste at different stages of hydration. The percentage indicated applies only to pastes with enough water-filled space to accommodate the product at the degree of hydration indicated (110).

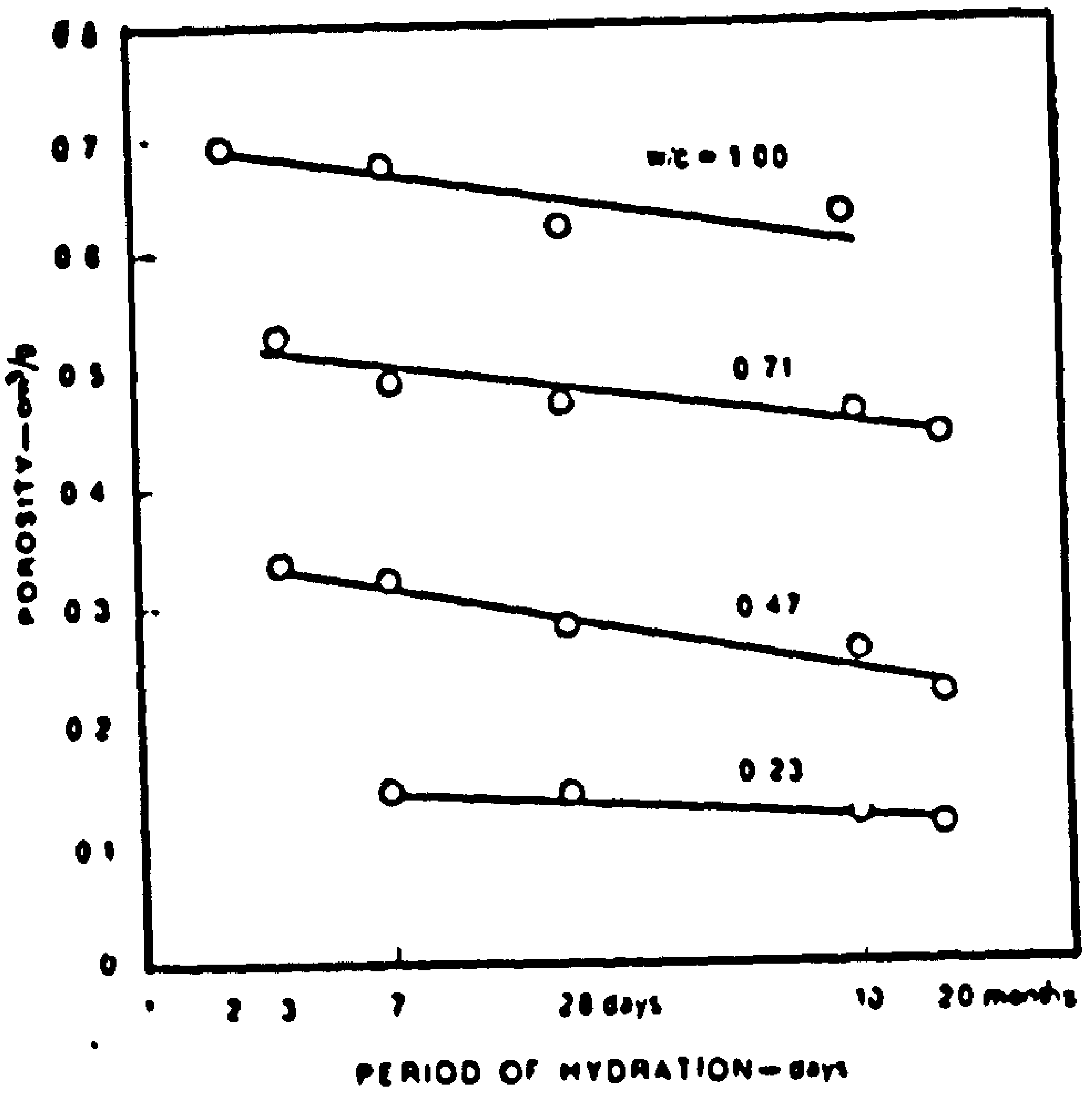


Fig. 2.10: Changes in porosity with hydration for various water/cement ratios (20).

total porosity while others determine capillary porosity only. As far as this review is concerned, the methods which will be used in this programme of research are the only ones reviewed. Further details of each test method will be given in Chapter 3.

1 - Helium pycnometry

This method uses a helium pycnometer which measures the specific gravity (S.G.) of the sample under test. The pycnometer works by sucking the air out of the sample and then calculates the volume by measuring the amount of helium absorbed. Porosity can be evaluated by the equation developed by Cabrera (73) which takes into account the dry density (D_d) of the sample:

$$\text{Porosity(\% of volume)} = 1-\left(\frac{D_d}{S.G.}\right)x\ 100\%$$

2 - Total water saturation method:

The method measures the volume of water absorbed after full saturation of the sample has taken place. Porosity is then calculated as follows:

$$\text{Porosity (\%)} = \left(\frac{\text{volume of water}}{\text{volume of sample}}\right)x100$$

3 - Pore size distribution method:

The machine that will be used in this programme of work is called a mercury intrusion porosimeter (MIP), the method estimates the distribution of pore sizes by intruding mercury into a sample at different pressures. At each pressure the corresponding pore sizes are determined using the following equation:

$$D = \left(\frac{-4S\cos\beta}{P}\right)$$

where;

D = diameter of pore

P = pressure applied

S = surface tension

β = wetting angle

This method is very useful since it gives both the capillary porosity as well as pore size distribution.

2.2.4 - Porosity and Pore Structure of Ordinary Portland Cement(OPC) Mixes:

Goto and Roy (46) published some information on the effect of curing temperature on the pore structure of OPC pastes. They used two method in investigating the pore structure, namely evaporated water and mercury intrusion porosimetry. They found that the porosity measured by MIP was always less than that measured by the evaporated water method. This observation is to be expected since water was able to fill most of the pores whereas mercury did not enter those pores smaller in diameter than about 0.0020 μm. The significant observation was that the capillary porosity, measured by MIP, was increased from 36% to 56% of the total porosity as the curing temperature was increased from 27 to 60°C.

The effects of curing temperature on the pore size distribution, measured by MIP, have also been studied by Goto and Roy (46), and Roy and Parker (21). They (21) concluded that higher curing temperatures result in an increase in the number of larger pores, and this effect was maximized when the curing temperature was increased from 60 to 90°C.

An explanation of this was given by Bakker (41) who said that at lower curing temperatures, the hydration products of OPC are better dispersed, resulting in a more complete blocking of the capillary pores than at higher temperatures. In addition to the increase in the capillary porosity due to the higher temperature, the pores also became larger in diameter (46).

The influence of curing duration on the pore structure of cement pastes was studied by Lach and Rosova (14). They produced sem-micrographs of hydrated cement pastes after 7, 14, 28, and 56 days of curing. The density of hydration products was clearly seen to be greatest after 56 days of curing and the longer the period of curing, the denser the products become. However, curing the samples in a water tank could result in some leaching of the calcium hydroxide, $Ca(OH)_2$, out of the cement matrix as shown by the electron micrographs in reference 9, which could result in a more porous and a more permeable sample.

2.2.5 - Porosity and Pore Structure of OPC/pfa Mixes:

The use of pfa as a partial replacement for cement affects the properties of both the fresh and hardened concrete. According to Cabrera (58), for concretes of equal compressive strength , the addition of pfa alters the pore structure by two mechanisms:

1 - The reduced water/cement ratio achieved in order to maintain a constant workability.

2 - The slow filling of voids by the pfa-lime reaction products.

Ramazanianpour (18) found that the pore size distribution in the mortar of an OPC concrete, designed to have a compressive strength of 40N/mm^2 at 28 days with a slump of 50mm, changed with time. The total porosity decreased with time, but more importantly, the number of pores larger than 0.010 μm diameter decreased sharply with age. Meanwhile, the use of pfa to replace 30% by weight of the OPC at a constant slump resulted in a decrease in water/cement ratio of 0.09 (67). Consequently a reduction in porosity was seen at an age as early as 3 days. However, the most significant effect was that the volume of pores over 0.010 μm in diameter was practically nil, whereas with OPC, there was significant number of pores above this diameter ,see Figs. 2.11, 2.12, 2.13. One important point to note is that the above results are from tests carried out in a controlled laboratory environment at 20°C and 100%RH.

March (71) measured the total porosity of OPC/pfa pastes by MIP and the helium pycnometry. He found that higher curing temperatures resulted in lower porosities at an early age as measured by both methods even though the long term result was not significantly different.

2.2.6 - Porosity and Pore Structure of OPC/ggbs Mixes:

Fig. 2.14 shows the effect of ggbs content on the pore volume of concretes for water/cement ratios ranging from 0.50 to 0.65 (40). This shows that in the long term, pore volume for those pores ranging from 30 to 7500 μm decreased sharply with increasing slag content.

Pigeon and Regourd (65) reported the results of mercury intrusion porosimetry measurements on 1:3 cement:sand mortar specimens made with OPC and Portland blastfurnace cements (PBFC) containing 28% and 60% slag all at 0.5 water/cement ratio after 28 days of curing. Although they found that the total porosities were similar, there was a significant difference in the pore size distribution. Pores became much smaller as the percentage of slag increased and at 66% slag, they found that most of the pores were less than 0.020 μm in diameter. Smolczyk (64) has earlier reported similar results. He also found that capillary pores over 0.030 μm in diameter are greater in number in OPC pastes than in OPC/slag pastes and that capillary porosity was reduced by about 20% when 76%

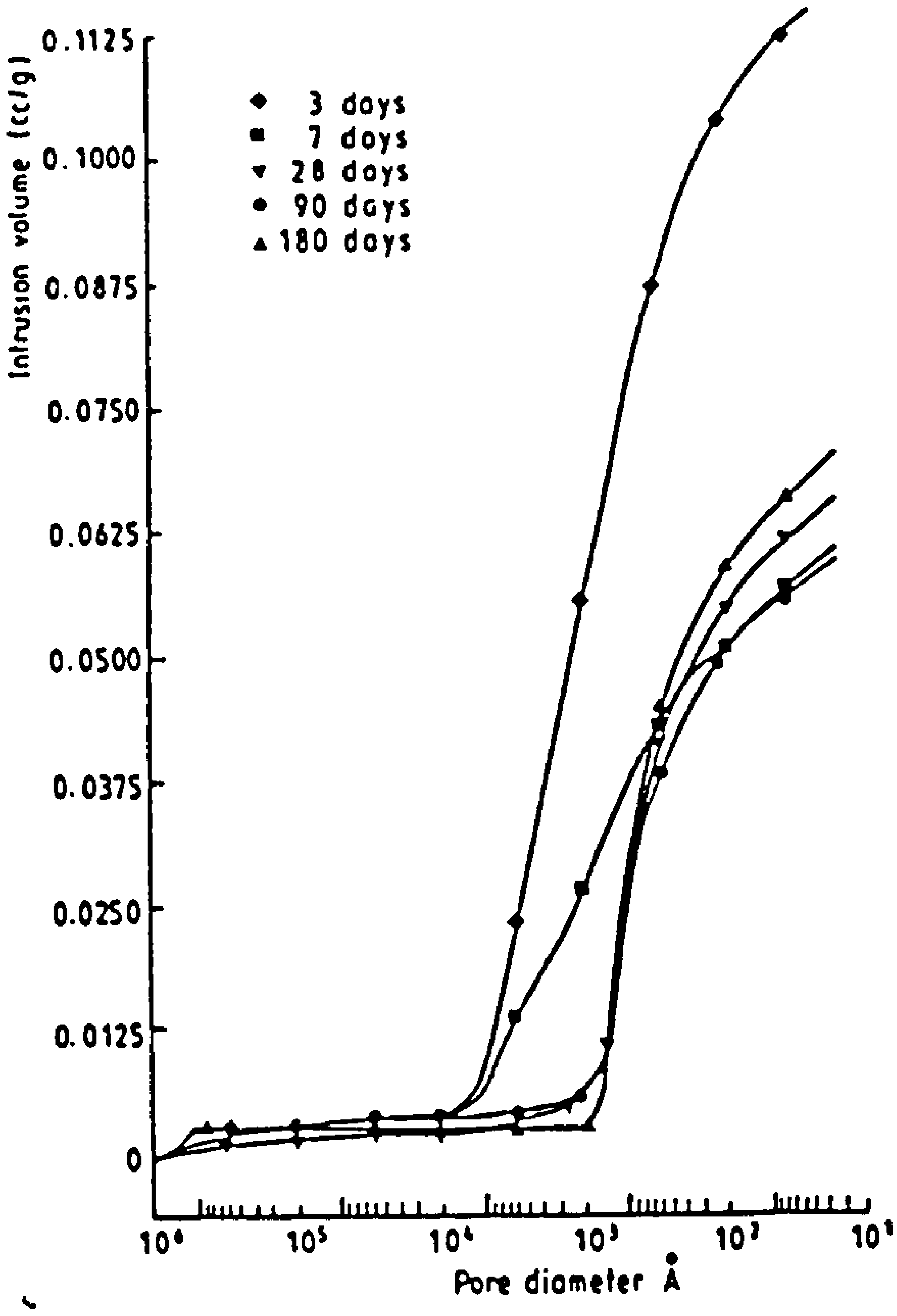


Fig. 2.11: Pore size distribution of OPC- concrete at different ages (58).

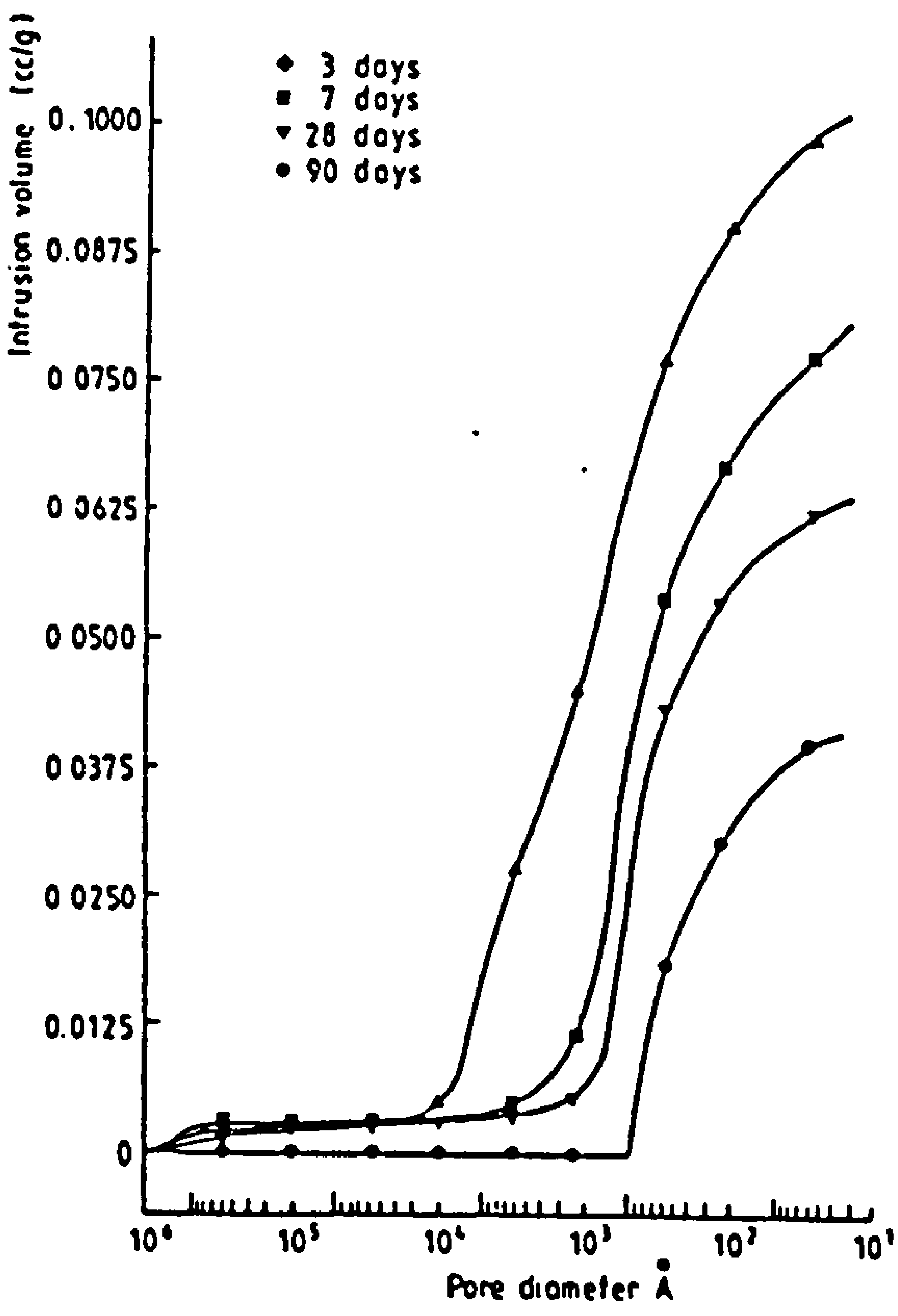


Fig. 2.12: Pore size distribution of pfa- concrete at different ages (58).

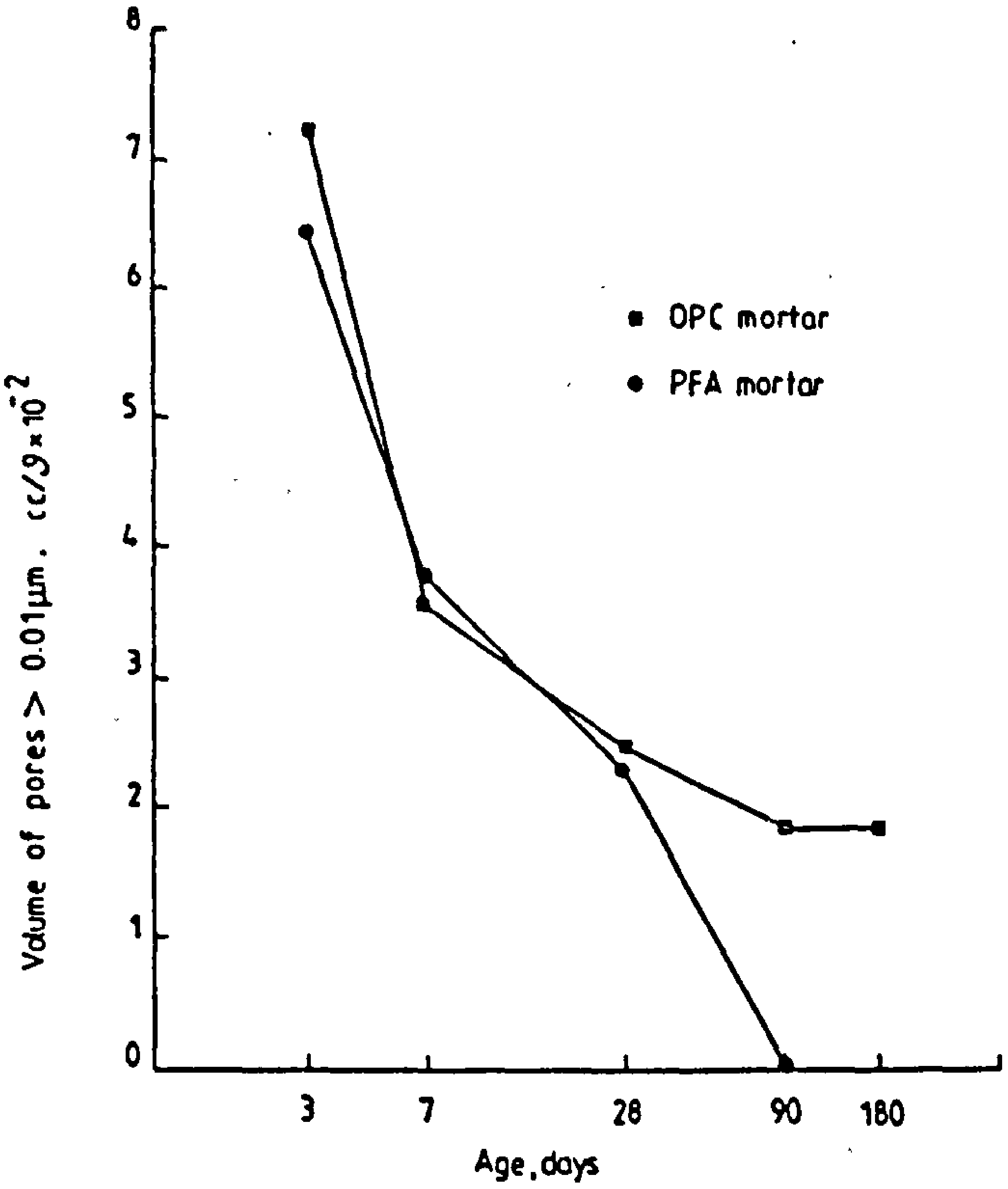


Fig. 2.13: Relation between volume of large pores and the age of OPC and pfa concretes (58).

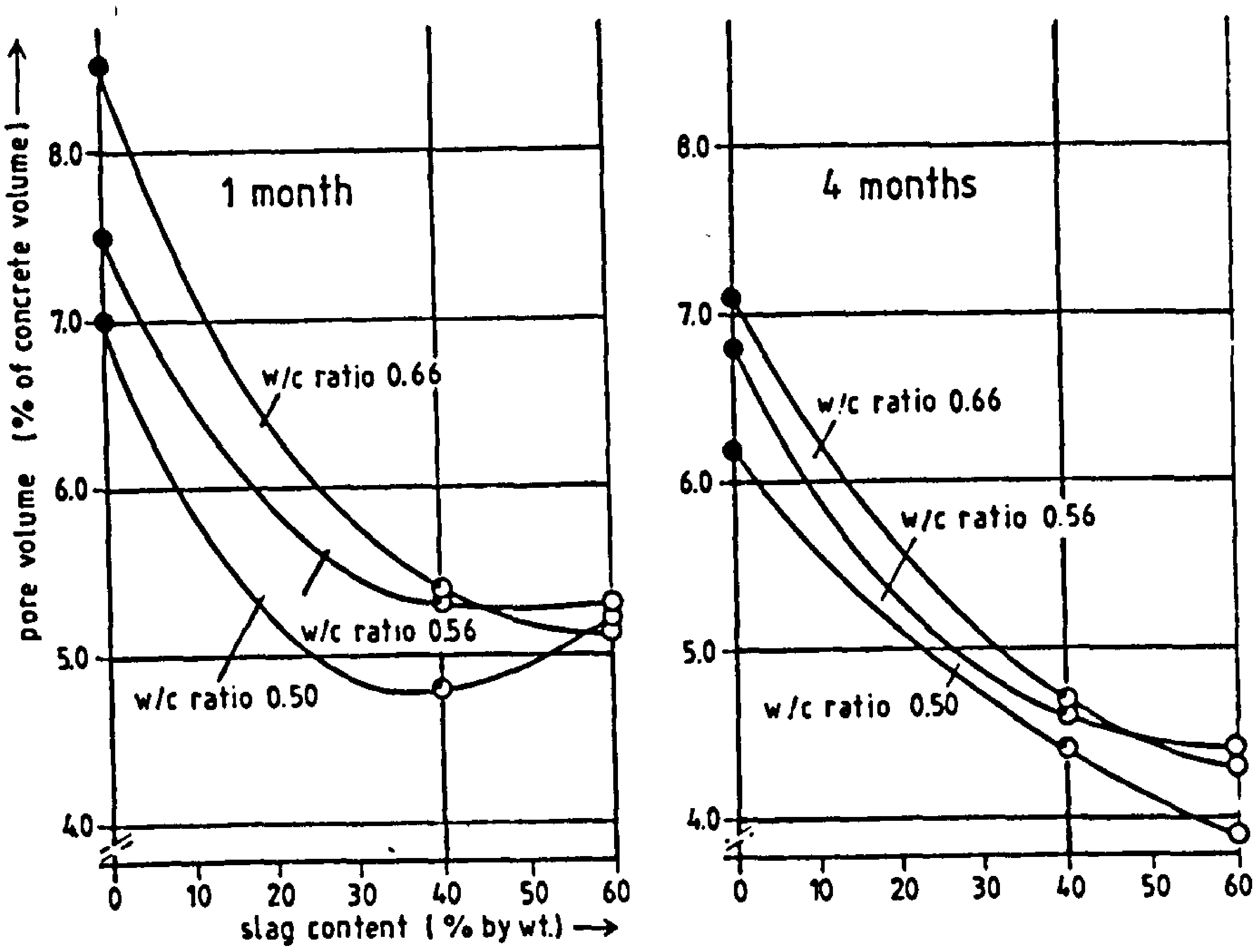


Fig. 2.14: Relation between pore volume of concentrate and slag content of the cement used, for different water/cement ratios and for different lengths of hydration time (pore ranging from 30 to 7500 μm) (40).

of cement was replaced by slag.

Roy and Parker showed (21) the effect on the pore size distribution of replacing 60% of OPC by ggbs. Although the total porosities were similar, the use of 100% OPC resulted in a critical pore diameter (i.e. the pore diameter at which the differential pore volume is maximum) of about 0.0125 μm whereas that of slag cement was significantly lower at about 0.0035 μm, see Figs. 2.15 and 2.16.

Similar results were obtained by Gjorv and Vennesland (62) who showed that in 80:20 slag:OPC pastes, 79% of the total porosity was made of up 0.020 μm diameter pores where this number was only 29% in 100% OPC pastes.

It has been suggested by Bakker (41) that the presence of slag results in additional precipitations between adjacent slag and clinker particles, see Fig. 2.17. This conclusion was based on the results of permeability tests where he found that the permeability of Portland blastfurnace cement (PBFC) is much lower than that of OPC pastes. This advantage was also maintained in specimens cured at elevated temperatures.

Another explanation as to the superiority of the pore structure of blended cements was given by Feldman (12). He concluded from his study that the nature of the pore structure appears to be related to the calcium hydroxide, $Ca(OH)_2$, content. $Ca(OH)_2$ produces, he said, an inhomogenous body with poor bonding between the major components. Therefore, blended cements are superior in terms of durability due to the lower permeability and $Ca(OH)_2$ content.

The effects of ggbs on the pore structure of cement pastes at normal temperatures is reviewed above and shown to be beneficial in this respect. According to Bakker, this beneficial effect is maintained at higher temperatures.

Parker and Roy (21) found a finer pore structure in 60:40 ggbs:OPC pastes when compared to plain OPC pastes. Curing temperatures up to 60°C had practi-

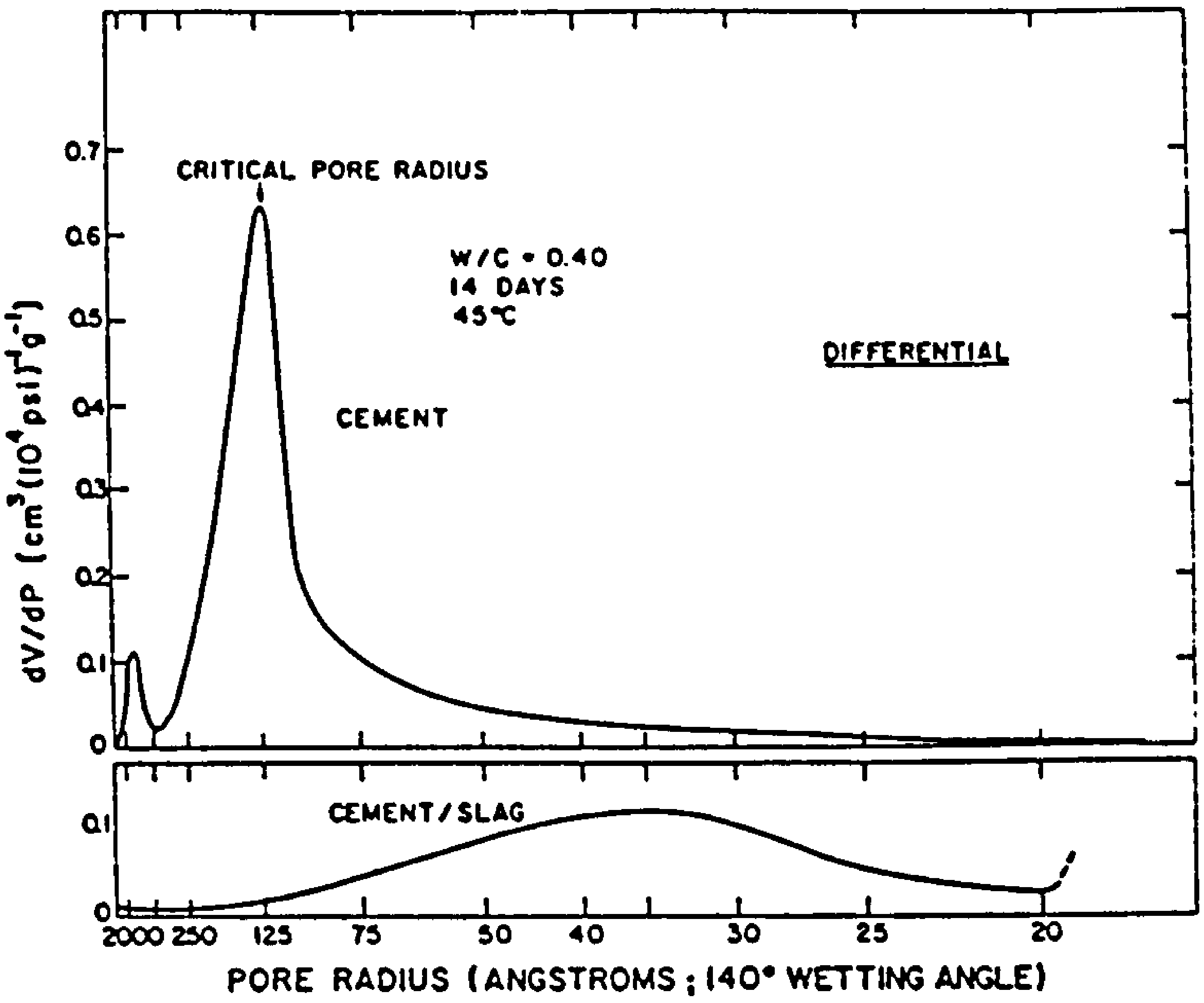


Fig. 2.15: dv/dp plots of comparable Portland cement and slag cement pastes (60:40) (21).

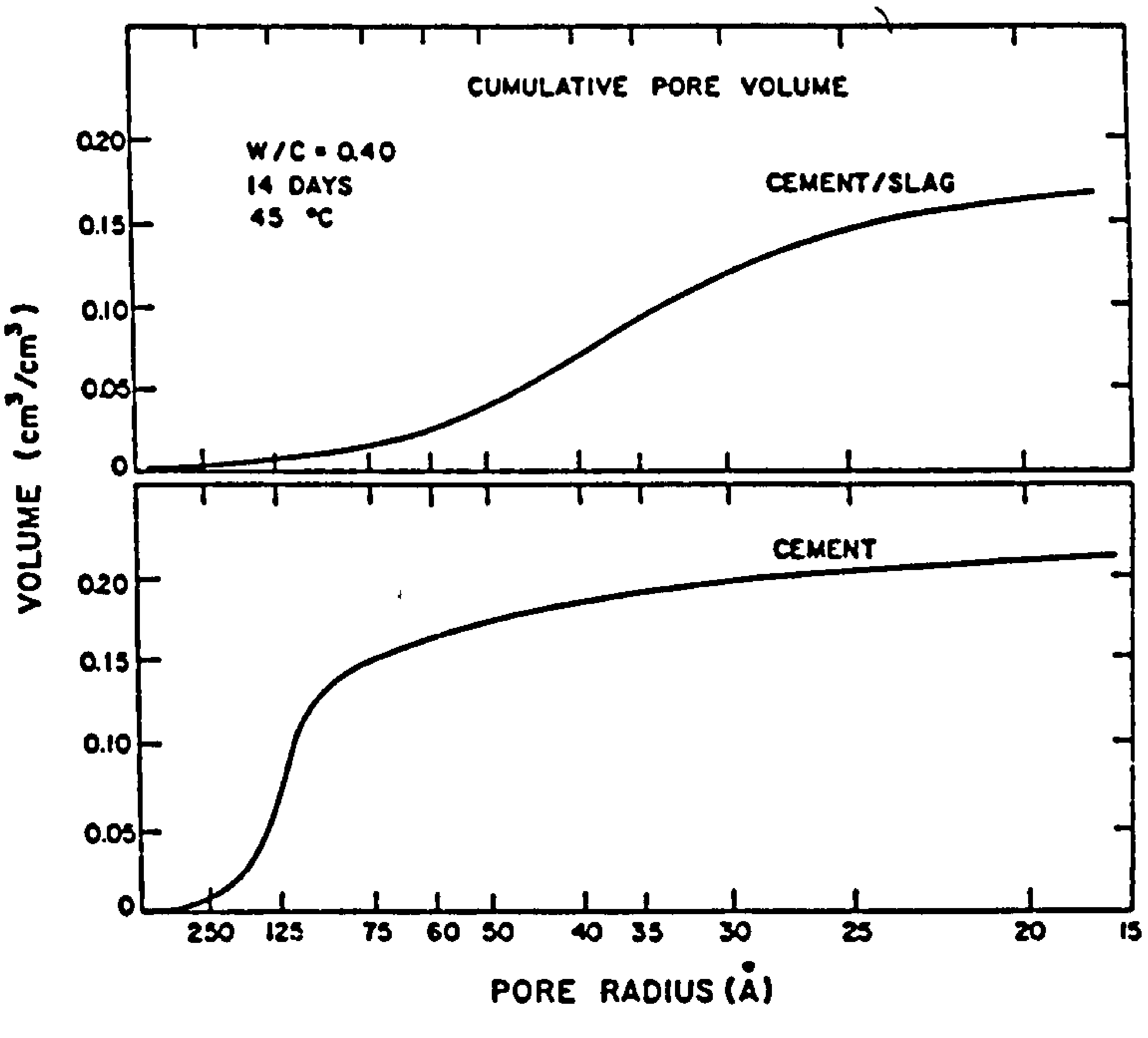
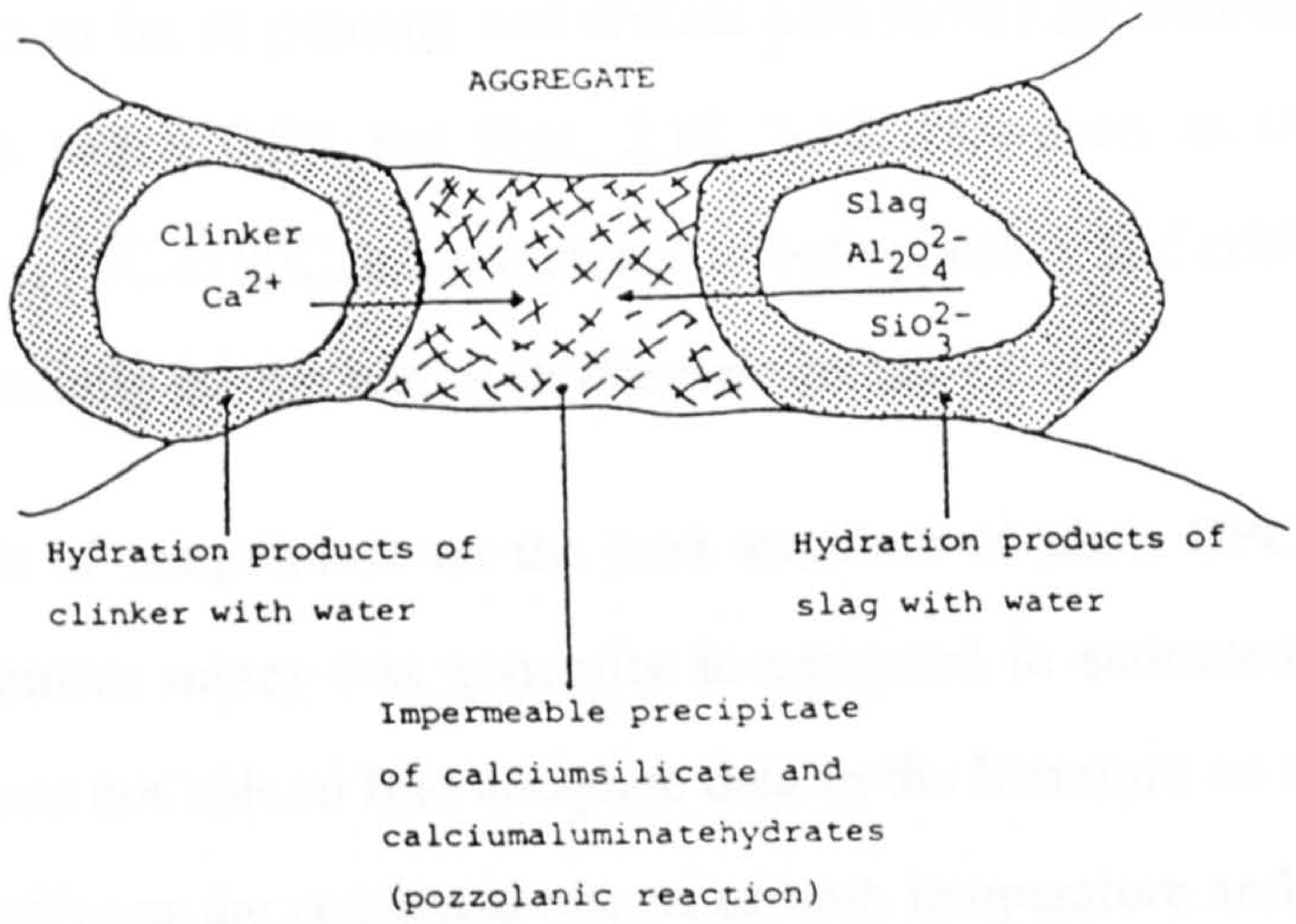
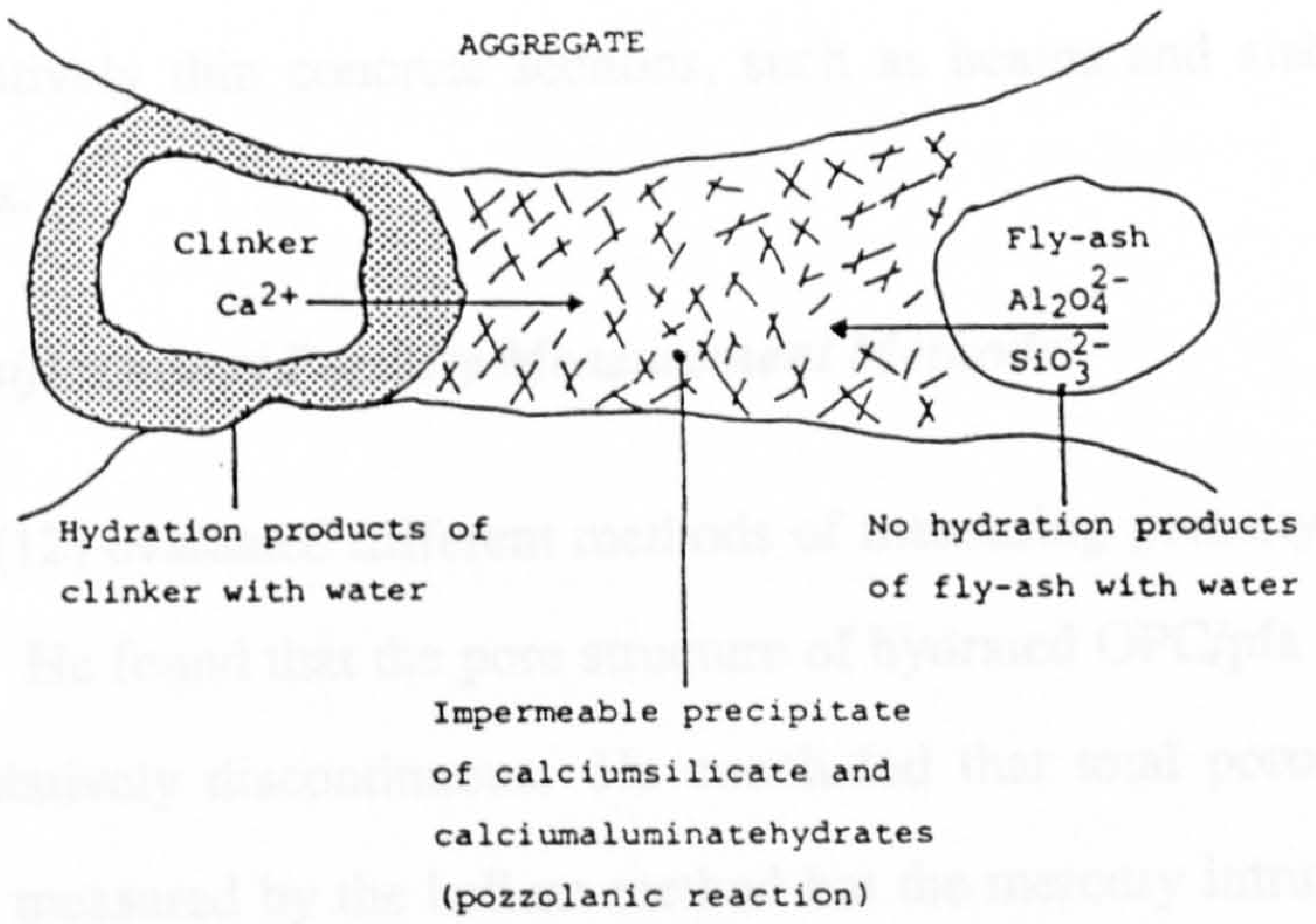


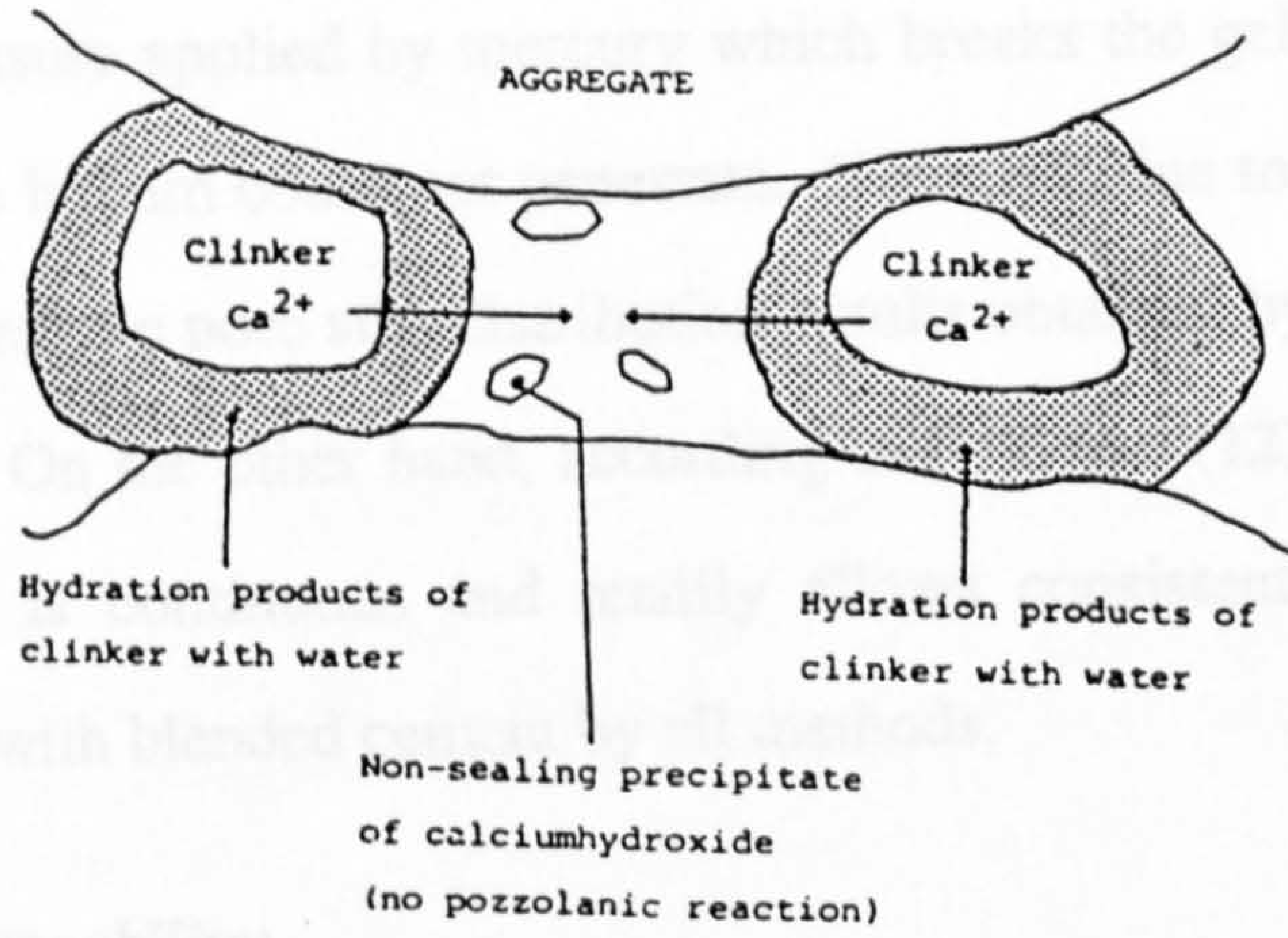
Fig. 2.16: Cummulative pore volume versus pore radius of Portland cement and slag cement (60:40) pastes (21)



c -Hydration of blastfurnace cement



b -Hydration of portland fly-ash cement



a -Hydration of portland cement

Fig. 2.17: Diagrams of the hydration of plain OPC, OPC/pfa and OPC/ggbs cements (41).

cally no effect as far as porosity and critical pore radius are concerned for water/cement ratios below 0.50, see Figs. 2.18, 2.19. However, as the temperature increased from 60°C to 90°C, a big increase in both porosity and critical pore radius was seen especially for the high water/cement ratios.

The effects of temperature on the pore structure of plain OPC, OPC/pfa and OPC/ggbs cement mixes was generally investigated in saturated environments. The author was not able to find adequate data in the literature on the influence of relative humidity or the combined effects of both temperature and humidity. The data reviewed and reported can, nonetheless, be relevant to interior parts of large castings, in which ggbs are normally used, but not to that of the surface or the cover of relatively thin concrete sections, such as beams and slabs, in hot dry environments.

2.2.7 - Significance of Porosity Measurement Methods:

Feldman (12) evaluated different methods of measuring porosity and pore size distribution. He found that the pore structure of hydrated OPC/pfa and OPC/ggbs blends is relatively discontinuous. He concluded that total porosity cannot be consistently measured by the helium method but the mercury intrusion porosimetry (MIP) gives better results. This improved consistency is thought to be due to the high pressure applied by mercury which breaks the gel structure and reaches places where helium could not penetrate. However, due to the damage caused at high pressures, the pore size distribution results obtained by this method could be misleading. On the other hand, according to Feldman (12), the pore structure of OPC pastes is continuous and readily allows consistent and more repeatable results than with blended cement by all methods.

2.2.8 - Permeability:

The durability of concrete is influenced mainly by its ability to resist penetration by liquids, aggressive salts and gases and depends largely upon its

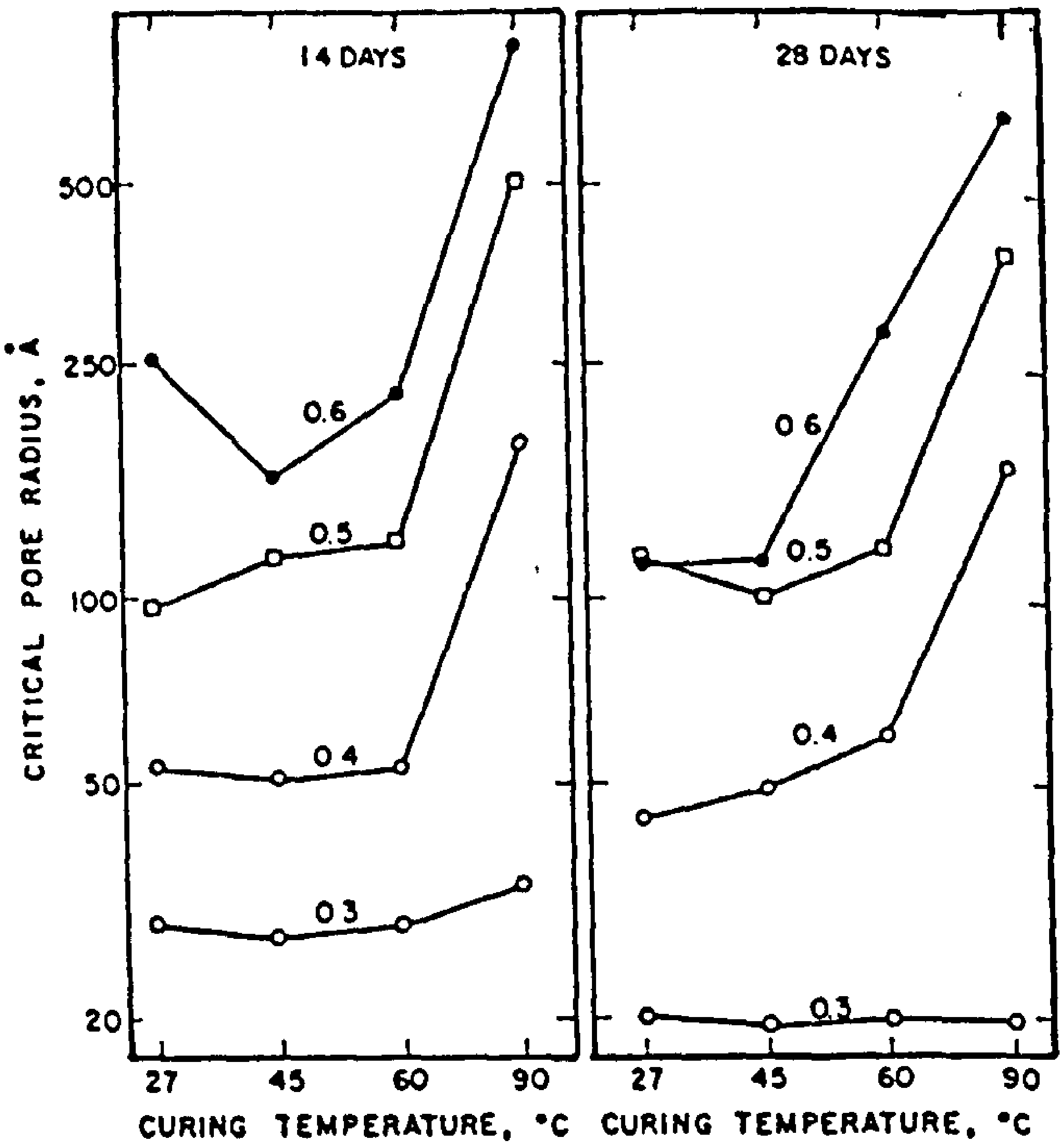


Fig. 2.18: Variation of critical pore radius with temperature (60:40 slag:OPC) (water/cement ratio are marked) (20).

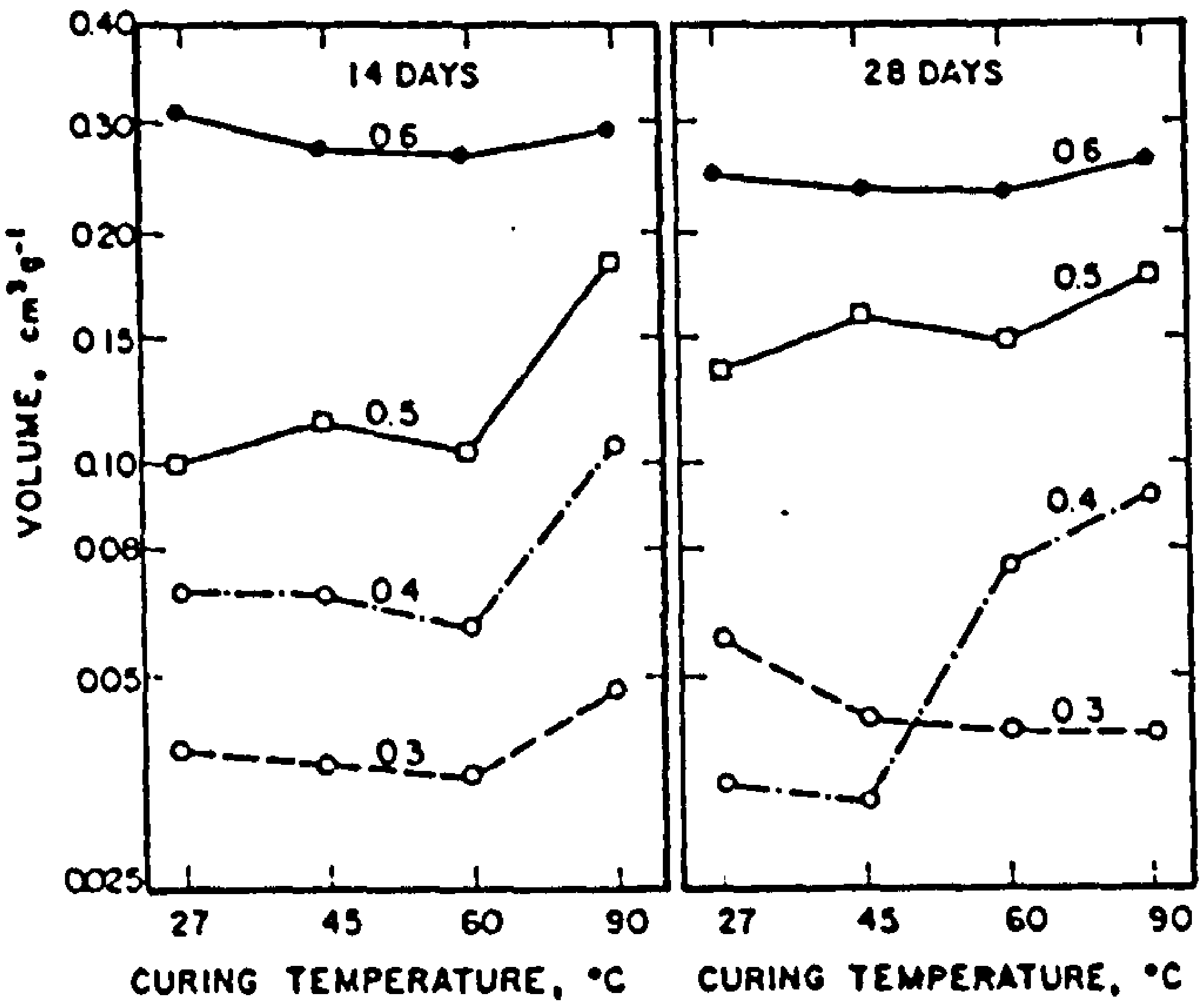


Fig. 2.19: Variation of pore volume with curing temperature (60:40 slag:OPC) (water/cement ratios are marked) (20).

permeability. In the case of reinforced concrete, the ingress of moisture, gases or aggressive salts could result in corrosion of the reinforcing steel and spalling of the concrete cover.

The permeability of concrete is not a simple function of its porosity, but it depends on size distribution and continuity of the pore structure (17). This can be seen when comparing cement paste to cement gel, although the porosity of cement paste may not be much different from that of the gel (depending on the water/cement ratio), its permeability is about 20-100 times greater due to the presence of capillaries (17).

2.2.9 - Measuring Permeability:

a - Methods:

Permeability to either liquids or gases can be measured by many methods. Some of these methods such as the Initial Surface Absorption Test (68) were designed to evaluate the relative permeability of the surface only. Others, such as the cell developed by Cement and Concrete Association (61) and Cabrera and Lynsdale (114) measure the steady-state flow of a liquid under pressure.

There are many methods that measure the permeability directly or give some indication of it. The methods referred to in the discussion are those used in the experimental programme.

1 - The Test for Water Absorption :

This is a British Standard test (68) and it measures the amount of water absorbed after 30 minutes submersion in water. The procedure of this test is described in detail in Chapter 3.

2 - Air Permeability by Figg's Method:

This method works by sucking air out of concrete or mortar and measuring the time taken for every 1kPa drop in pressure (43). The pressure drop and the time are expressed linearly and the slope of the relation (kPa/sec) is related to permeability; the smaller the slope the greater is the time and the less the permeability. Further details of this test are given in Chapter 3.

3 - Initial Surface Absorption Test (ISAT):

The ISAT test gives an indication of the permeability of the surface tested. It is a British Standard test (68) and measures the rate of water absorbed by the surface of the sample under a specific head of water. Further details are shown in Chapter 3.

4 - Oxygen Permeability:

Oxygen under pressure is applied at one end of the sample and collected at the other end after it reachs a steady-state condition. The flow rate of oxygen, the cross sectional area and the length of the sample are used to calculate the permeability coefficient. Details and equations are given in Chapter 3.

5 - Osmotic Effects of Salt Solutions:

This relative permeability apparatus consists of a hollow cylinder, made of the material to be tested, filled with a salt solution such as potassium hydroxide, KOH, see reference 41. The cylinder is closed by a rubber stopper holding a glass tube. The unit is then immersed in a water tank and the rise or drop in water height is monitored. It is important to note that the water movement in the tube is also influenced by the type and concentration of the salt solution.

b - The Effect of Testing Procedure :

Drying the specimens at high temperatures, over 100°C, before testing could affect the results due to the possible formation of ruptures between capillaries (55), these cracks will create new passages for air and water to penetrate. However, trying to reach an equilibrium moisture content at low temperature, such as 20°C, and constant relative humidity may be impractical due to:

1 - The length of time it may take to reach equilibrium, making young concrete very difficult to test.

2 - The additional changes that could occur during this time especially if concrete is brought from drier environments which could make results difficult to interpret.

2.2.10 - Factors Affecting Permeability:

2.2.10.1 - Degree of Hydration:

Due to the fact that the volume occupied by hydration products is about twice that of the unhydrated cement, the permeability decreases sharply as hydration continues. In a mature paste, permeability is controlled by the discontinuity of capillaries due to hydration, see Table 2.1 (17).

2.2.10.2 - Water/Cement Ratio:

According to Powers (55), the permeability of cement paste is greatly influenced by the water/cement ratio, and it is increased significantly at water/cement ratios above 0.6 (55), see Fig. 2.20. The permeability of cement pastes was found to increase by about 100 times as the water/cement ratio increased from 0.3 to 0.7 (55). Kasai et al (48) found that the permeability of a cement paste with a 0.5 water/cement ratio was approximately one fifth that of a similar paste with a water/cement of 0.65. A similar trend was also found by Goto and Roy (46).

The effect of water/cement ratio on the permeability was explained by Powers in terms of capillary porosity, see Fig. 2.21. He showed that at water/cement ratio of 0.38, the volume of capillaries was negligible yet the capillary porosity

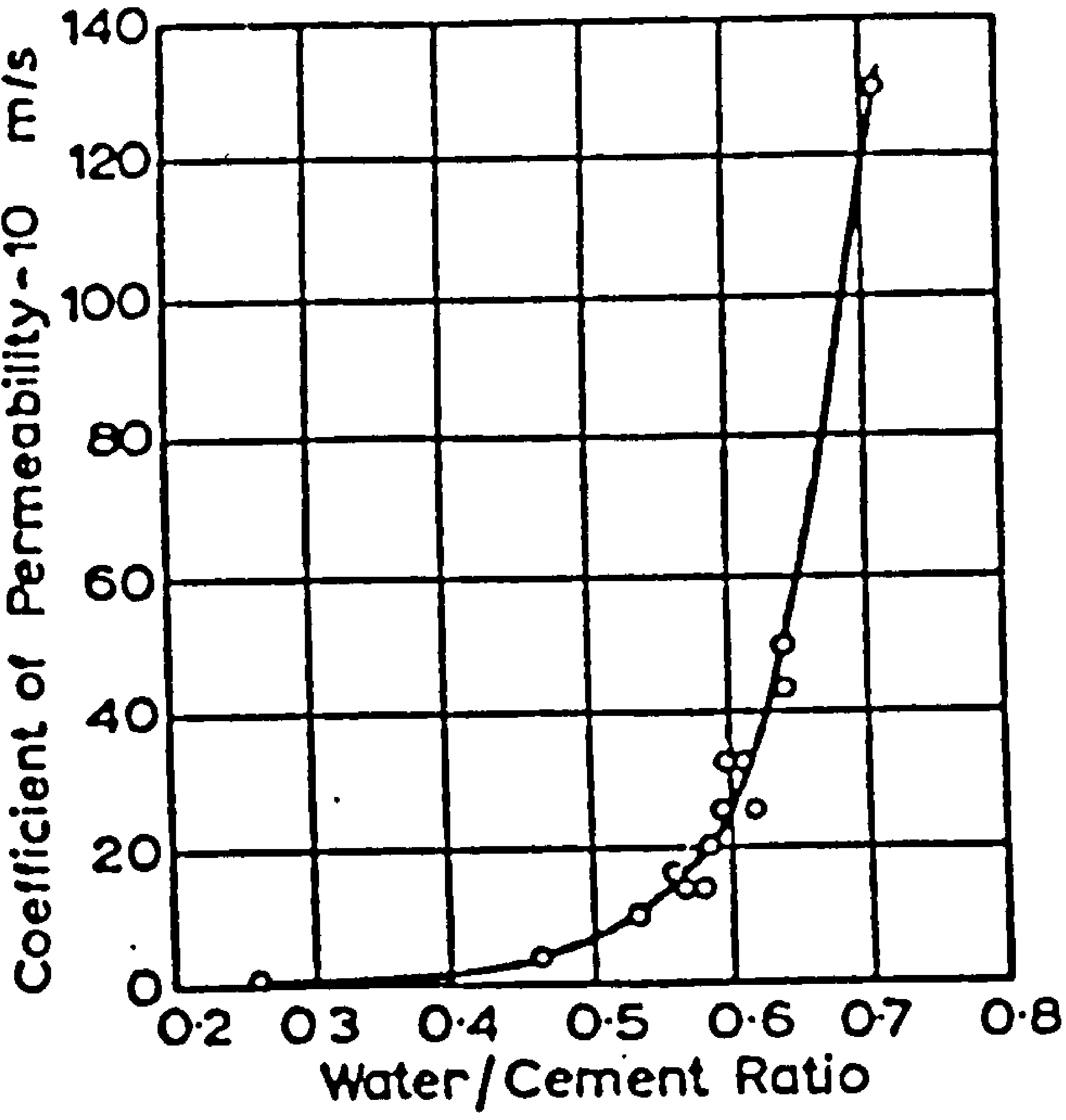


Fig. 2.20: Relation between permeability and water/cement ratio for mature cement pastes (93% of cement hydrated) (17).

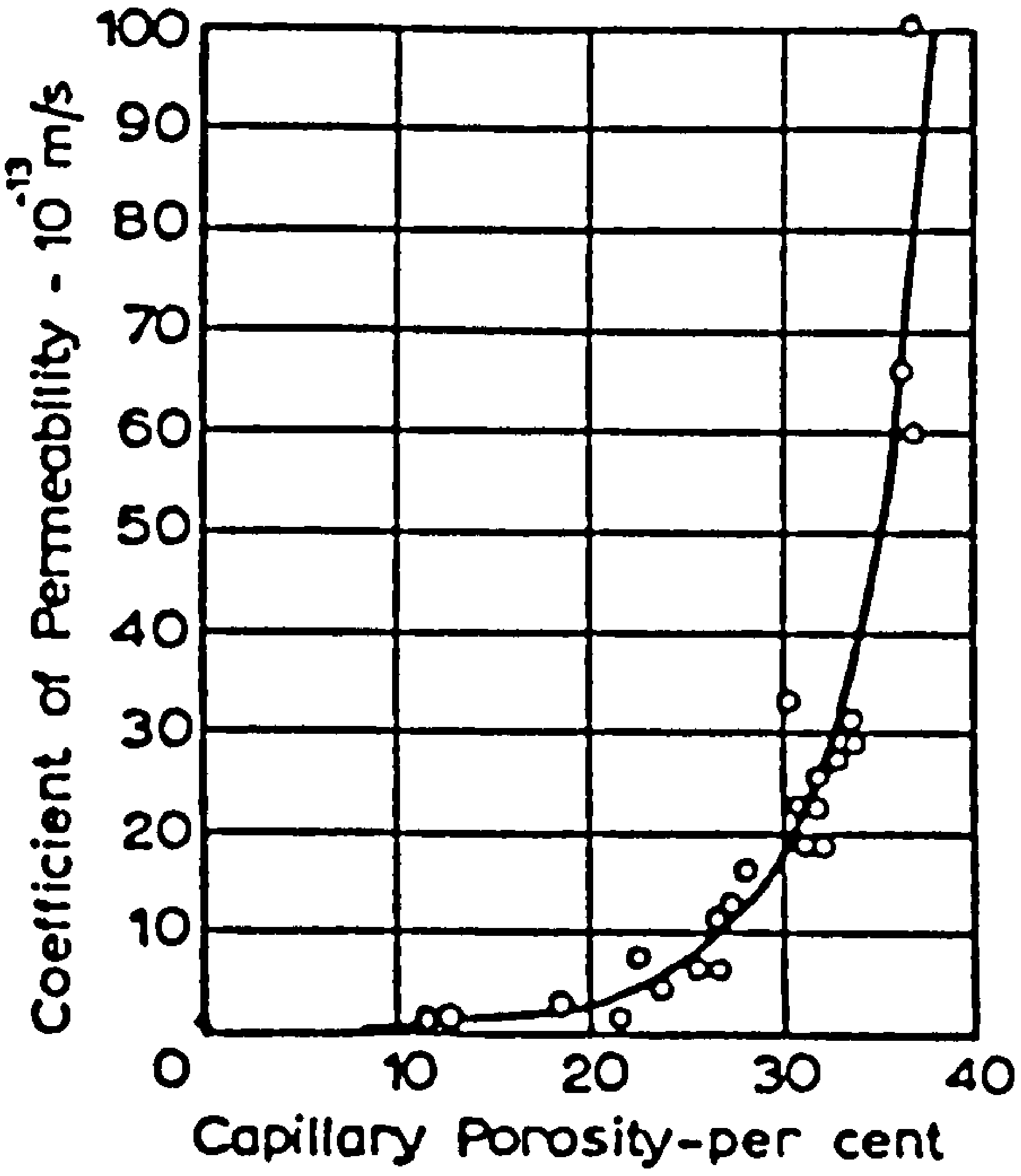


Fig. 2.21: Relation between permeability and capillary porosity of cement paste (17).

was about one third that of the total porosity at water/cement ratio of 0.8.

2.2.10.3 - Aggregates:

The permeability of aggregates has an influence on the permeability of concrete (17). The presence of low permeability aggregates reduces the area over which flow can take place which can lead to a reduction in the permeability.

The permeability may be influenced by maximum size of aggregate used. Pihlajavaara and Paroll (54) compared the permeability results of two different mixes having the same compressive strength and water/cement ratio. They found that concretes made with 32 mm maximum size aggregate were more permeable than those made with 8 mm aggregates, although the cement content was much greater in the case of 8 mm maximum size aggregate. It was expected by the writer that at the same water/cement ratio and curing condition, the mix having the greater cement paste to aggregate ratio would be more permeable. Pihlajavaara and Paroll did not however offer any explanation for such unexpected behaviour.

2.2.10.4 - Curing:

Parrot (66) investigated the length of curing time needed to reach a specific permeability value for different water/cement ratios. He showed that for a water/cement of 0.73, it was almost impossible to reach that value. However, when water/cement ratio was reduced to 0.59, it took only 18 days of curing, see Table 2.2.

Ho and Lewis showed the importance of early curing on permeability (109). The effects were greater for lower grade concretes and as the strength increased it became less sensitive to curing duration, see Fig. 1.3 in Chapter 1 (44).

Table 2.1 : Reduction in permeability of cement paste (water/cement ratio=0.7) with the progress of hydration(17).

Age (days)	Coefficient of permeability (m/sec)
fresh	2×10^{-6}
5	4×10^{-10}
6	1×10^{-10}
8	4×10^{-11}
13	5×10^{-12}
24	1×10^{-12}
ultimate	6×10^{-13} (calculated)

Table 2.2 : Free water/cement ratios to obtain a given 28-day strength and corresponding moist cure times to yield a permeability of 25×10^{-14} (m/s) (66).

	1950 OPC		1980 OPC	
28-day strength	w/c	cure time	w/c	cure time
25 N/mm	0.62	80 days	0.71	900 days
35 N/mm	0.51	16 days	0.59	18 days
45 N/mm	0.48	5.7 days	0.50	4.5 days
55 N/mm	0.38	3.2 days	0.43	2.0 days

2.2.10.5 - Properties of Cements :

The permeability of concrete may also depend upon the coarseness of the cement particles. Coarser ground cements produce a matrix with a higher porosity and permeability at the same water/cement ratio (55). However, for pastes with equal porosity, results show that the ultimate permeability, i.e. 100% hydration, is not necessarily different (55).

The chemical composition of cement affects the permeability at early ages because it influences the rate of hydration. However, the ultimate permeability and porosity are unaffected (55).

The effects of a combination of OPC and pfa on the permeability of concrete has not been studied thoroughly and there is a dearth of published information on it especially when dealing with hot dry environments. However, according to the limited data available, there exists a diversity of opinion as to the effects on permeability.

Bakker (41) showed that the permeability of an OPC/pfa pastes was greater than that of plain OPC paste at normal temperatures and at a constant water/cement ratio. He did not however mention the age of testing which makes a difference when comparing pozzolans with OPC because pozzolans are inherently slower to react. According to Hughes (43), the permeability at 7 days was greater for OPC/pfa pastes than for plain OPC pastes having the same water/cement ratio, but at 4 and 12 weeks, the permeabilities were similar.

On the other hand, March (60) reported that OPC/pfa pastes are superior to plain OPC pastes of a constant water/cement ratio as far as permeability is concerned. He showed that after one week of curing, OPC paste samples exhibited similar permeabilities to OPC/pfa in the range of 10^{-11} to 10^{-12} m/sec. As curing was extended, the permeability of OPC/pfa pastes was reduced to between 10^{-14} and 10^{-15} m/sec whilst that of the OPC pastes remained almost constant (59). This trend was confirmed to some extent by Nagataki and Ujike (51), they showed that after 28 days of curing, the permeability of OPC/pfa and OPC specimens (made to a similar 28-day strength) were similar but the OPC/pfa specimens were less permeable after 90 days of curing.

Kasai et al (48) investigated the effects of curing periods on the permeability of OPC/pfa samples, as expected their results showed that lower permeabilities were obtained in those specimens that were cured longer.

The permeability of slag cement mixes has been shown to be very dependent on the curing conditions. Kasai et al (48) studied the effects of curing periods, before placing the samples at 20°C+70%RH. They found that, for curing periods of up to seven days, the OPC/slag specimens were more permeable than the plain OPC samples. However, the difference between the two mixes was seen to decrease as curing periods increased.

The results reported by Kasai et al (48) were somewhat confusing; they showed that, contrary to expectations, samples exhibited higher permeability with increasing age. The reason behind this behaviour could be attributed to the moisture content of the samples. It is understood that Kasai et al did not condition their samples to a constant moisture content. For example, the moisture content of specimens tested at seven days was greater than that of specimens tested at three months of age and this could be the reason behind this unusual trend. They, nonetheless, did not give the reason for choosing this procedure of sample conditioning before testing.

Bakker (41) on the other hand, showed that for seven-day cured samples which were tested at the end of the curing period, specimens containing ggbs were less permeable than the plain OPC mixes.

2.2.10.6 - Temperature:

The level of permeability is thought to be influenced not only by the amount of gel formed but also by the locality where the gel is precipitated within the capillaries (41).

Temperature affects both the amount of gel formed and its locality and therefore, it influences the permeability. At a temperature of 20°C, the hydration products of an OPC pastes are well dispersed resulting in a more effective closure of the capillaries and a lower permeability (41), see Fig. 2.22.

Fig. 2.22 : Influence of locality of precipitation of the same amount of gel on the sealing effects in a pore (41).

The effect of temperature on the permeability of OPC pastes was studied by Goto and Roy (46), see Fig. 2.23.

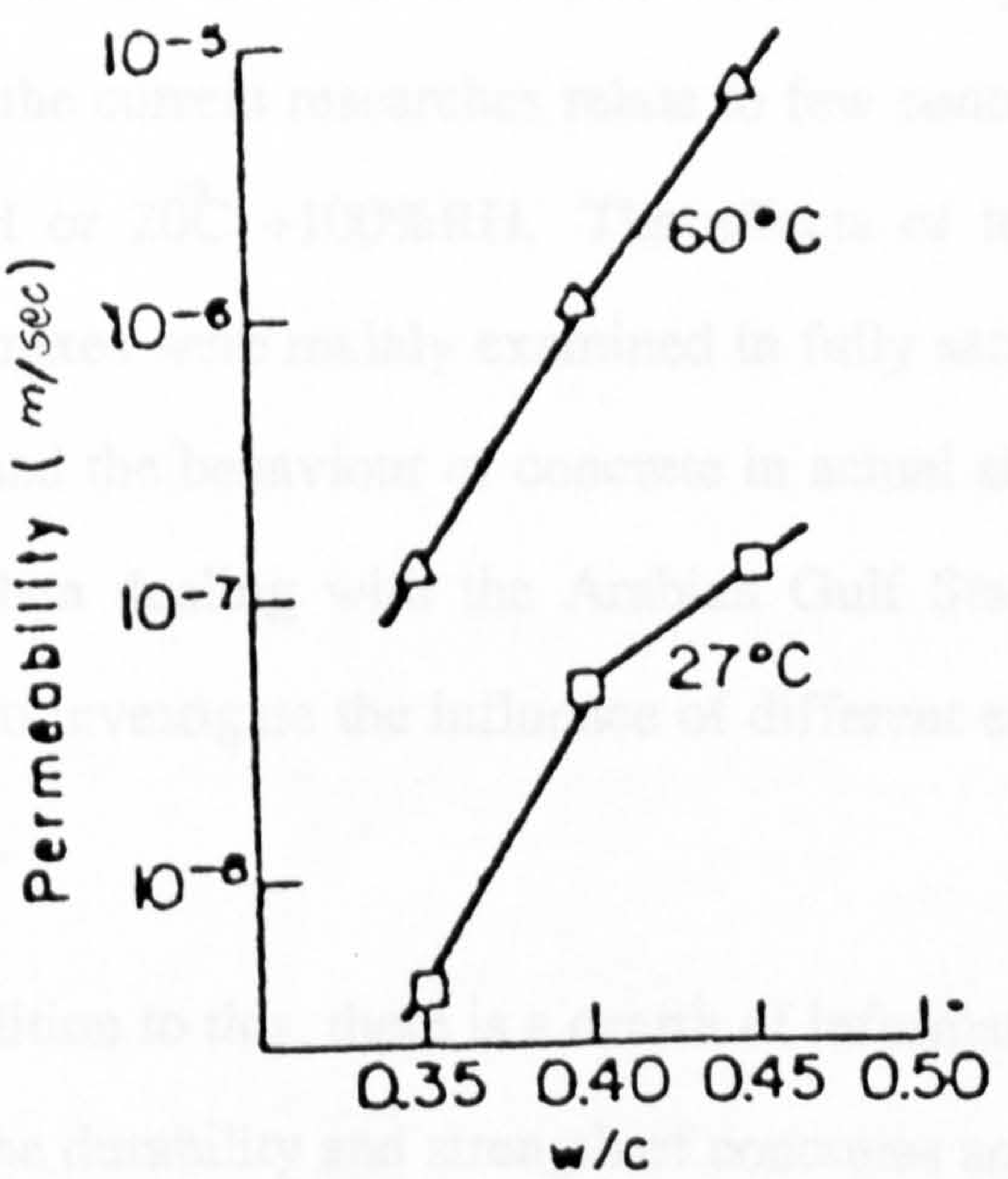


Fig. 2.23: Relationship between permeability and water/cement ratio (46).

They, i.e. Goto and Roy (46), have shown that the permeability at 60°C was greater than that at 27°C even though porosity was smaller. This observation was valid for all water/cement ratios used, from 0.35 to 0.45, see Fig. 2.23.
This trend was thought to be due to the larger diameter pores resulting from the high temperatures. However blended cements, i.e. pfa and slag, behave in a reverse manner to this, higher temperatures resulting in lower permeabilities measured using a technique based on osmotic effects of salt solutions (see page 38), see Figs.. 2.24, 2.25. The results of Bakker showed that at 20°C the pfa mix was the most permeable of the three studied, but when cured at 80°C for only the first 18 hours, it became superior to the OPC mix. The reason for the superiority of blended cements over the plain OPC was explained in section 2.2.3 on pore structure.

2.3 - Discussion and Significance of Research:

Most of the reports on the problem of concrete deterioration in the Gulf area deal with observation of cracks, salt attacks and steel corrosion. The problems of bad workmanship and inadequate materials are always included (30, 33, 34, and 36). The behaviour of concrete or mortar in environments simulating those of Middle East site conditions has not been thoroughly investigated by researchers. Most of the current researches relate to few controlled environments such as 20°C +70%RH or 20°C +100%RH. The effects of temperature on the properties of cement mixes were mainly examined in fully saturated environments whereas the quality and the behaviour of concrete in actual sites could be very different especially when dealing with the Arabian Gulf States. Hence, a research study is needed to investigate the influence of different environments on the properties of concrete.

In addition to this, there is a dearth of information on the effects of curing periods on the durability and strength of concretes and mortars in the environments of the Middle East. The availability of water is essential for the continuation of the hydration process. The hydration is known to cease if relative humidity within

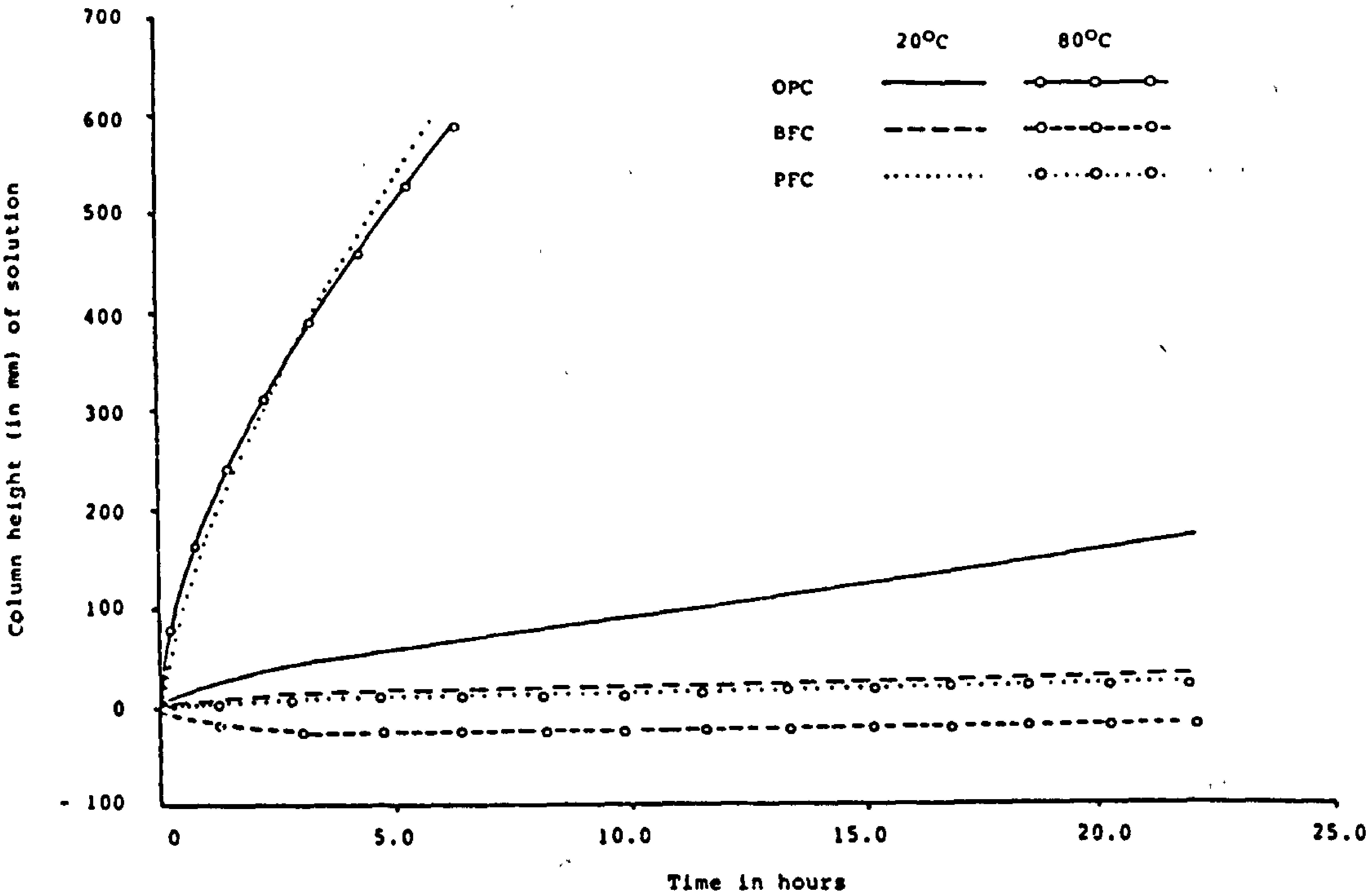


Fig. 2.24: The effect of curing temperature on the permeability of mortar of different cement types (water/cement ratio = 0.50; aggregate/cement ratio = 2.00) (41).

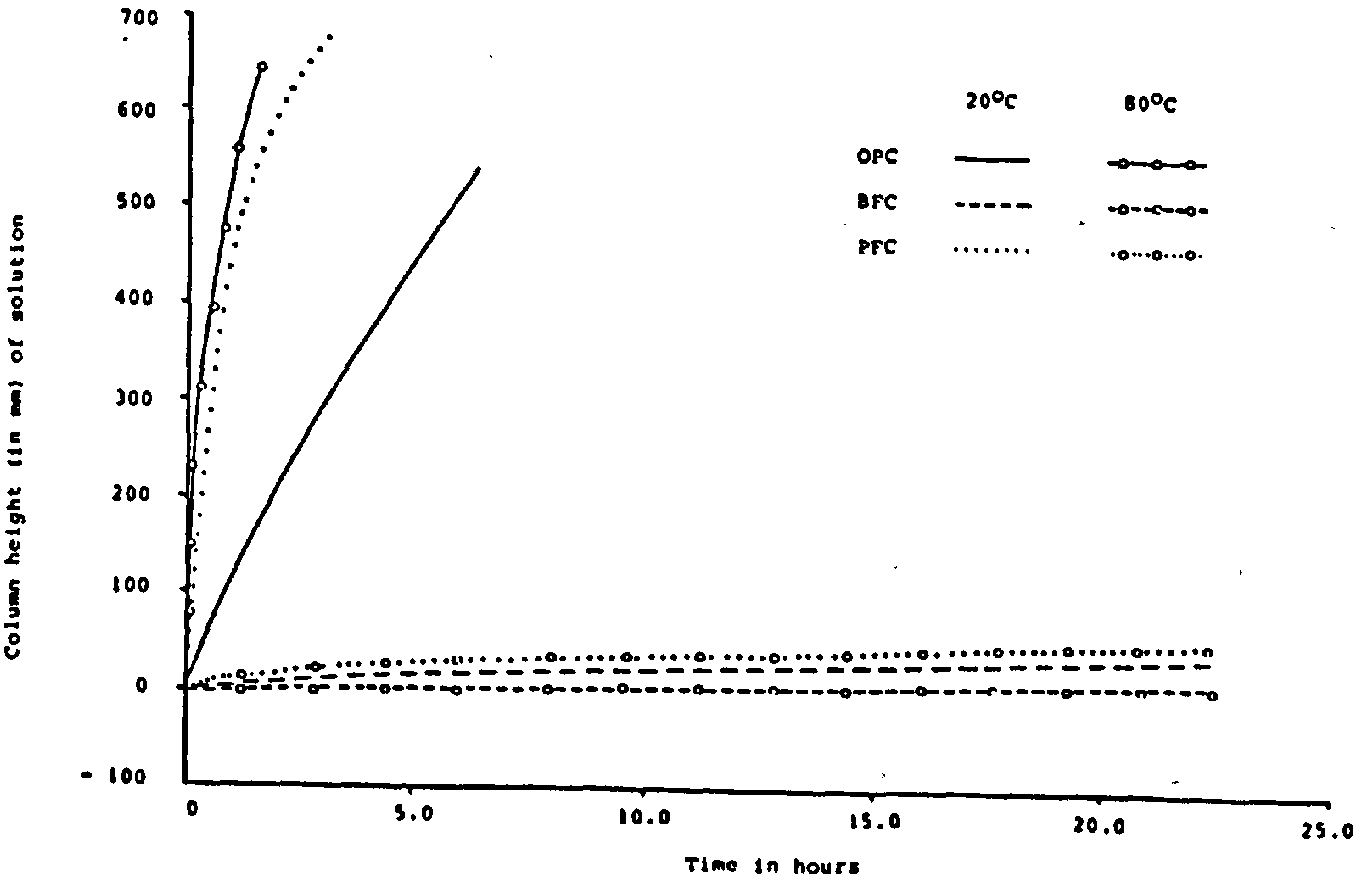


Fig. 2.25: The effect of curing temperature on the permeability of mortar of different cement types (water/cement ratio = 0.65; aggregate/cement ratio = 2.80) (41).

the pore of the concrete drops to below 80% (44). On the other hand, as is the case with most chemical reactions, the hydration process is accelerated by high temperatures. Therefore, the curing period needed to reach a certain durability parameter value may be shorter at, for example, 45°C than at 20°C.

The use of cement replacement materials such as pfa or slag in dry hot environments needs intensive investigation. It is true that mixes containing pfa or slag become inherently less permeable and exhibit a finer pore structure than equivalent Portland cement, as was explained earlier, see section 2.2.2. However, this is only true when samples are adequately cured. In most environments, concrete is likely to be saturated during the curing period only (if curing is properly carried out) after which it will continue to lose water until it reaches an equilibrium state with the ambient conditions. Hence, the quality of the concrete pore structure attained at the end of the curing period is likely to improve little with time particularly in dry hot environments.

In hot countries, where the average daily temperature is often over 35C during several months of the year, the inclusion of pfa or ggbs may show advantageous results compared to pure cement even though the relative humidity may be very low. It is seen from the literature review that both strength development and pore structure of cements containing pfa or ggbs are superior to those of equivalent Portland cements when adequately cured and subjected to high temperatures. Information is lacking however on how curing time and temperature are related in dry environments and how this relationship is affected by the use of pfa or ggbs.

The investigation into the effect of curing periods and either pfa or slag in different environments on some durability properties of concrete or mortar has to be linked to the pore structure. Hence, the influence of the above parameters on the pore size distribution is very important and would need to be evaluated.

The test for compressive strength of concrete is widely used as a quality control test. It is a good test for engineers to verify the mix proportion and to assess the ability of the structure to carry the design load. It is also useful for engineers during the construction periods to know when to dismantle the falsework and the formwork. Nevertheless, more information is required to be able to establish whether or not this test can be used as a measure of durability and gives an indication of the efficiency of the curing program. If this test can not be used to evaluate the efficiency of the curing programme, then it is necessary to try and establish what tests, if any, can be included in the quality control programme and how they should be implemented.

The planned programme of testing, which is designed to study the combined effects of curing environments, similar to those of the Gulf States, and initial curing periods on plain OPC and the combinations of OPC and either pfa and ggbs, is therefore divided into three parts as follows:

1 - Initial Investigation:

This acts as a pilot study for the two primary parts of the research.

2 - Primary Mortar Investigation:

It was important to understand how the pore structures of OPC, OPC/pfa and OPC/ggbs cement mixes are altered by the different curing periods in hot dry environments in order to explain their durability performance in sit . Steady-state permeability and water absorption tests were also performed and linked to the pore structure.

3 - Primary Concrete Investigation:

The influence of curing periods in hot dry environments on the strength and some durability-related properties were investigated on practical concrete mixes with typical cement content designed to a given workability.

CHAPTER THREE

MATERIALS, TESTING EQUIPMENT, CURING ENVIRONMENTS

3.1 - Materials:

3.1.1 - Ordinary Portland Cement:

The Ordinary Portland cement used throughout the investigations was supplied by the Blue Circle cement company from their works in Derbyshire and its chemical composition is shown in Table 3.1.

3.1.2 - Pulverized-Fuel Ash (pfa):

The pfa used in this research was supplied by the Central Electricity Generating Board from Drax power station and its chemical composition is shown in Table 3.1.

3.1.3 - Ground Granulated Blastfurnace Slag (ggbs):

The ggbs was supplied by Frodingham Cement Company, Scunthorpe and its chemical composition is shown in Table 3.1.

3.1.4 - Aggregates:

The aggregates used throughout the research were quartzite in origin and their source location was the Tarmac quarry pit in north Nottinghamshire.

The coarse aggregate used was a blend of crushed and uncrushed quartzite gravel with maximum size of 10 mm which had 'smooth' to 'rough' surface texture with 'regular' to 'irregular' shape. The general properties of the gravel were found to be conforming with BS882:1983 (56), see Table 3.2.

Table 3.1: Composition of the cementitious materials used

constituent	percent by weight		
	OPC	pfa	ggbs
SiO_2 %	20.9	51.9	36.8
Al_2O_3 %	5.5	26.9	10.0
Fe_2O_3 %	2.7	11.3	1.2
CaO %	64.3	1.5	41.9
MgO %	2.5	1.6	7.2
Na_2O %	0.3	1.2	0.3
K_2O %	0.8	3.8	0.5
TiO_2 %	-	0.9	0.6
SO_3 %	2.8	0.6	0.1
Alkali-Soluble SiO_2 %	-	30.0	-
Alkali-Soluble Al_2O_3 %	-	6.2	-
loss on ignition %	0.7	2.6	2.3
Specific Surface m^2/g	0.38	0.22	0.40
Specific Gravity	3.10	2.36	2.89

Table 3.2:Aggregates gradation, % by mass of passing

size (mm)	fine aggregates		coarse aggregates		all-in aggregates sand:gravel=1:2	
	BS882 zone F	research	BS882	research	BS882	research
10.	--	--	85-100	92	95-100	95
5.0	--	--	0-50	13	30-65	42
2.36	80-100	89.6	0-10	2	20-50	31
1.18	70-100	85.0	--	--	15-40	28.0
.600	55-100	63.0	--	--	10-30	21.0
.300	5-70	27.0	--	--	5-15	5.7
.150	--	2.0	--	--	0-8	0.6
S.G.	2.63-2.68		2.65-2.72		---	

S.G.= specific gravity

The fine aggregate used was a quartzite sand the general properties of which were found to be conforming with Zone F in BS882:1983 (56), see Table 3.2.

The proportion of fine aggregates to gravel used in the concrete mixes was 1:2 by weight and the all-in aggregate gradation conforms with BS882:1983 (56), see Table 3.2 and Fig. 3.1.

3.2 - Batching:

Batching of cements, aggregates, and water was done by weighing. Mixing the concrete materials was performed by loading the coarse aggregate first followed by the cement, the sand and finally the water. The materials were mixed for two minutes in a Cumflow 5122 mixer of 0.1 m^3 capacity. Mortar mixes were achieved by loading the sand first followed by the cement and finally the water. The materials for the mortar mixes were mixed for two minutes in a small pan-type mixer before casting in the moulds. The cement mixtures were cast in moulds in two layers and vibrated using a vibrating table to remove entrapped air.

3.3 - Details of Test Performed:

3.3.1 - Compressive Strength:

The test for compressive strength was carried out in accordance with BS1881:part 116:1983 (68), using 100 mm cubes. The results recorded were the average of two samples.

3.3.2 - Dynamic Modulus of Elasticity:

The dynamic modulus of elasticity(E_d) test was carried out on 100X100X500 mm prisms. The apparatus measures the natural frequency of the sample (maximum deflection).The following equation was used to calculate the E_d :

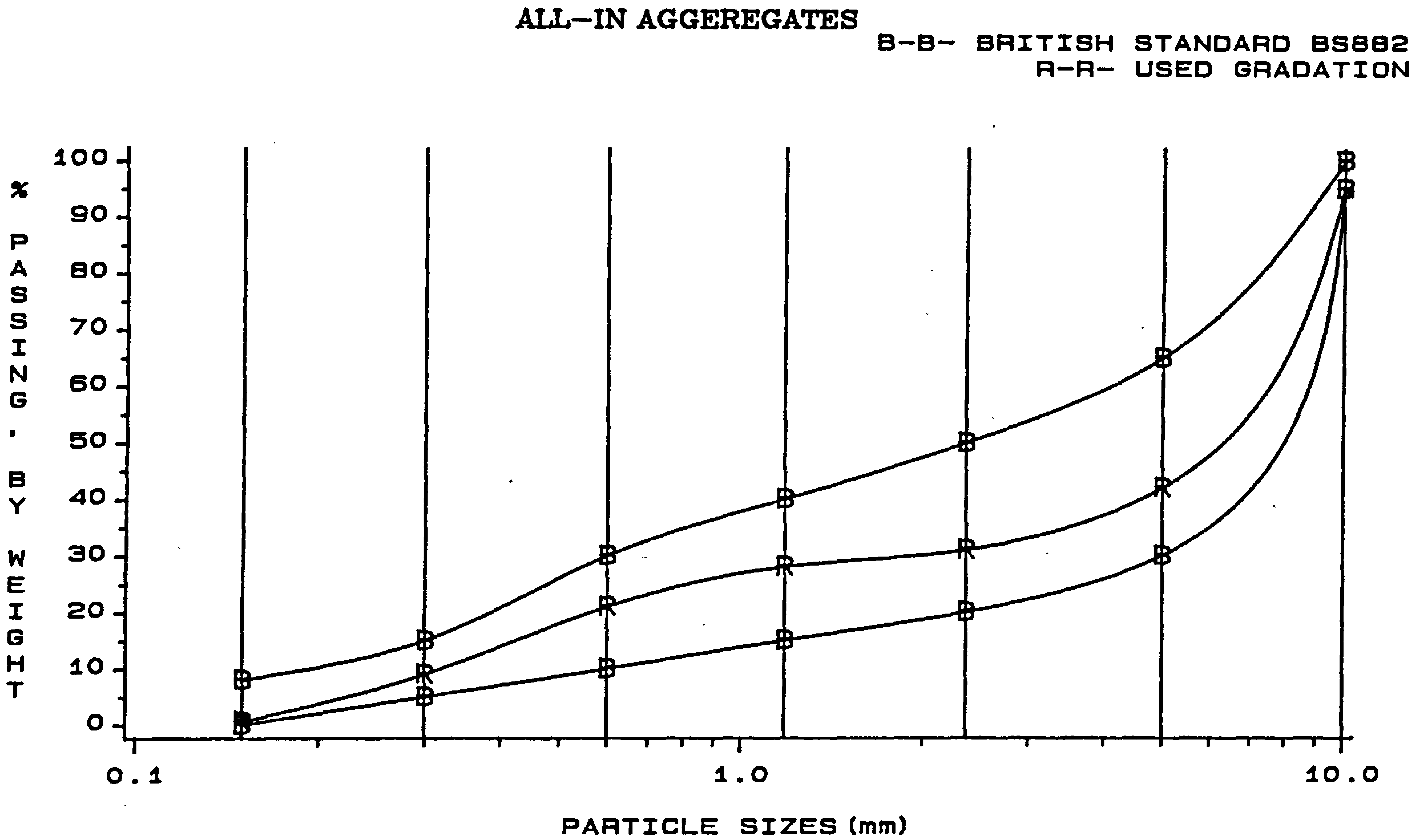


FIG. (3.1) ALL—IN AGGREGATE GRADATION, SAND: GRAVEL=1: 2

$$E_d = 4\omega N^2 L^2 \tag{3.1}$$

where,

E_d = the dynamic modulus of elasticity

ω = the density of the concrete

L = length of the prism

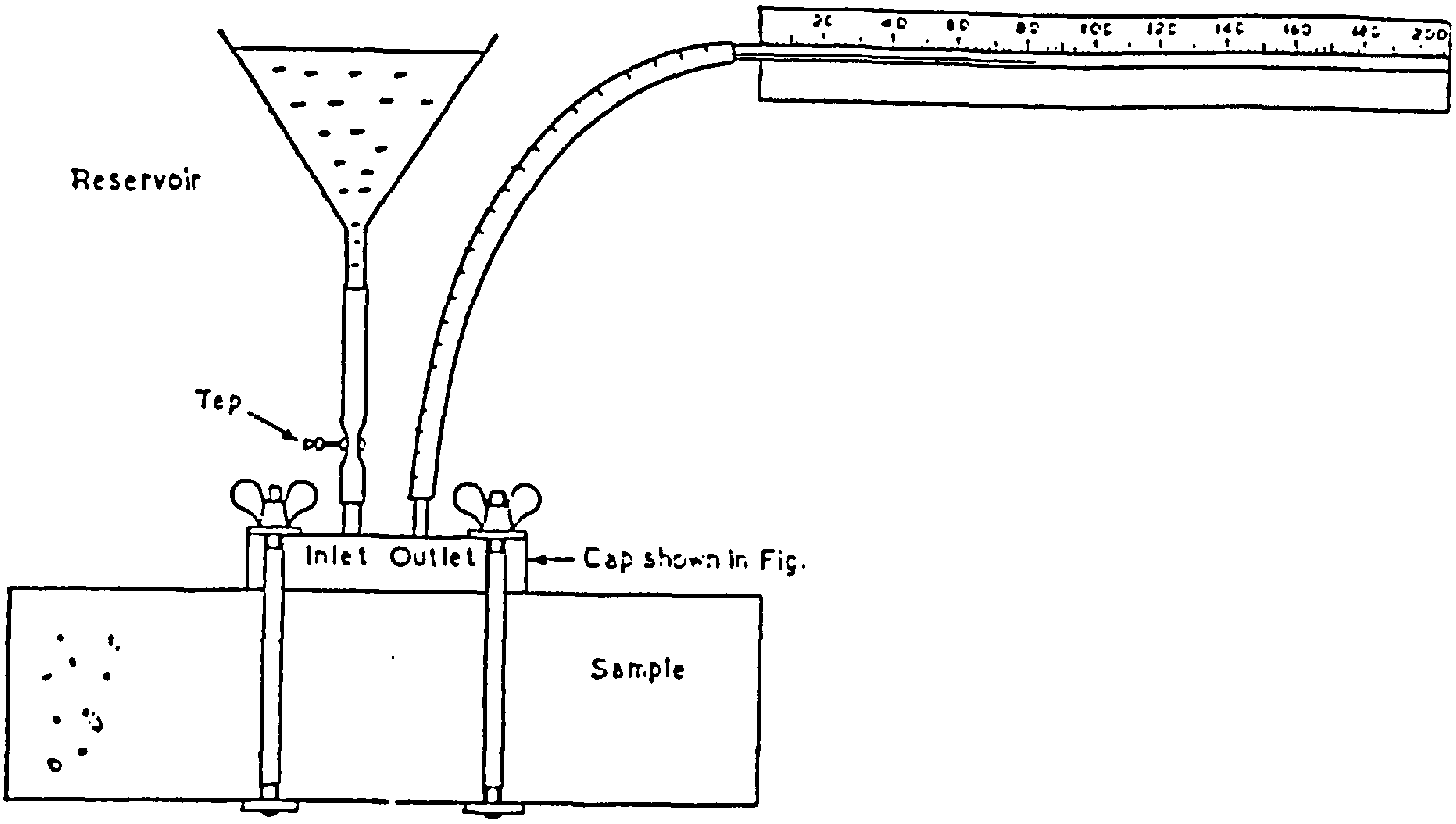
N = the natural frequency of the sample.

3.3.3 - The Test for Water Absorption:

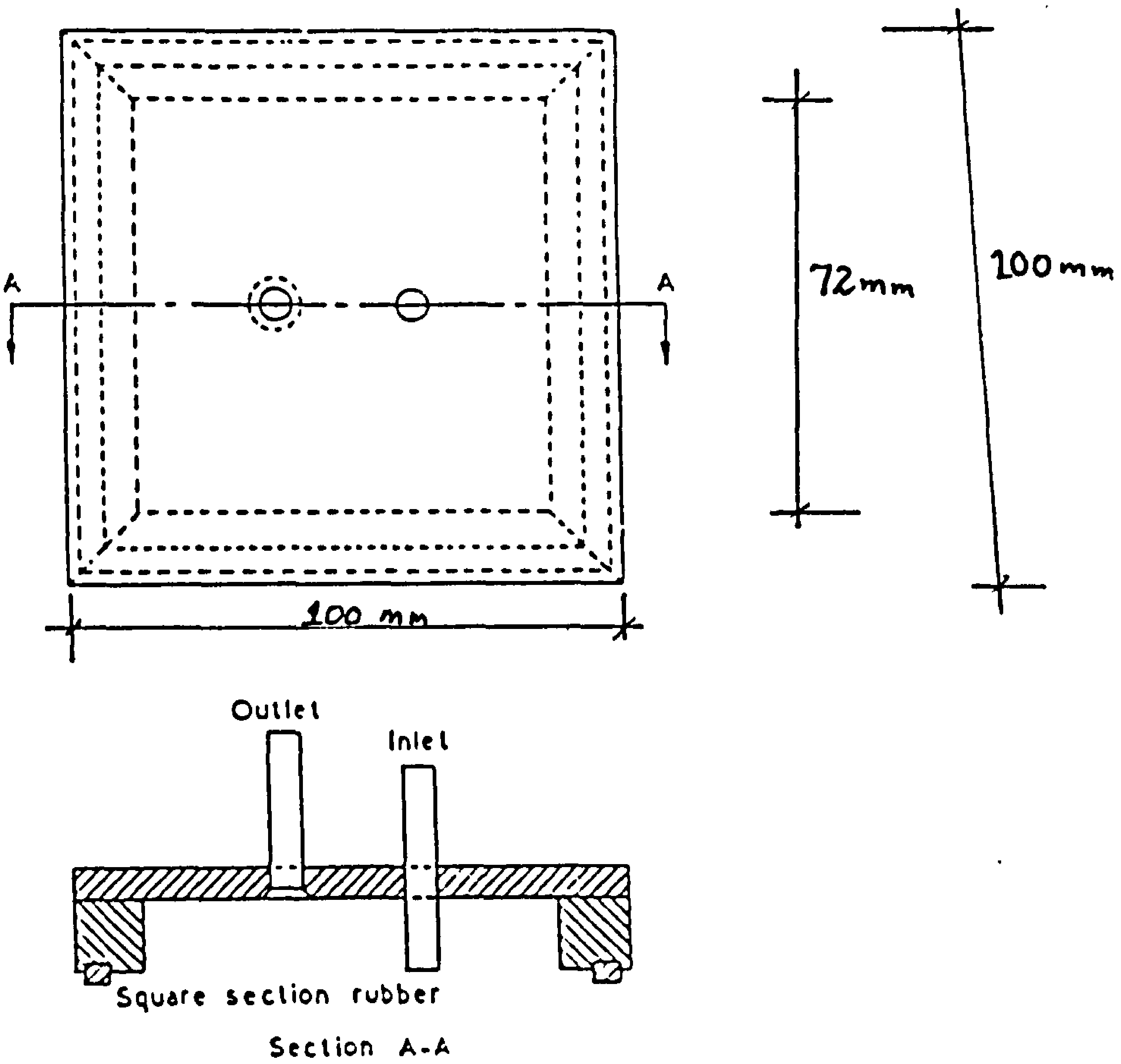
The test for water absorption was performed in accordance with BS:1881:part 5 (68). The mortar specimens used were 50 mm cubes and the concrete samples were either 100 mm cubes, (as used in the initial part of the investigations), or 150 mm diameter 100 mm thick discs (as in the primary part of the investigation). According to the test procedure, specimens at 24 days of age were put in a ventilated drying oven in which the temperature was controlled at 105°C for 72 hours ± 30 minutes. The samples were then removed from the oven and placed in an airtight vessel for 24 hours ± 30 minutes to enable them to reach room temperature. After that the specimens were weighed and totally submerged in water at a temperature approximately 20°C for 30 minutes ± 30 seconds. The water absorption was then calculated as the weight of water absorbed expressed as a percentage of the dry weight of the sample. The recorded results were the average of two samples.

3.3.4 - The Initial Surface Absorption Test (ISAT):

The initial surface absorption test (ISAT) measures the rate of flow of water into a sample per unit area. This test was also carried out in accordance with BS:1881:part 5 (68) and the apparatus is shown in Plate 3.1 and schematically in Fig. 3.2. The flow of water into the sample is measured at 10, 30, 60 and 120



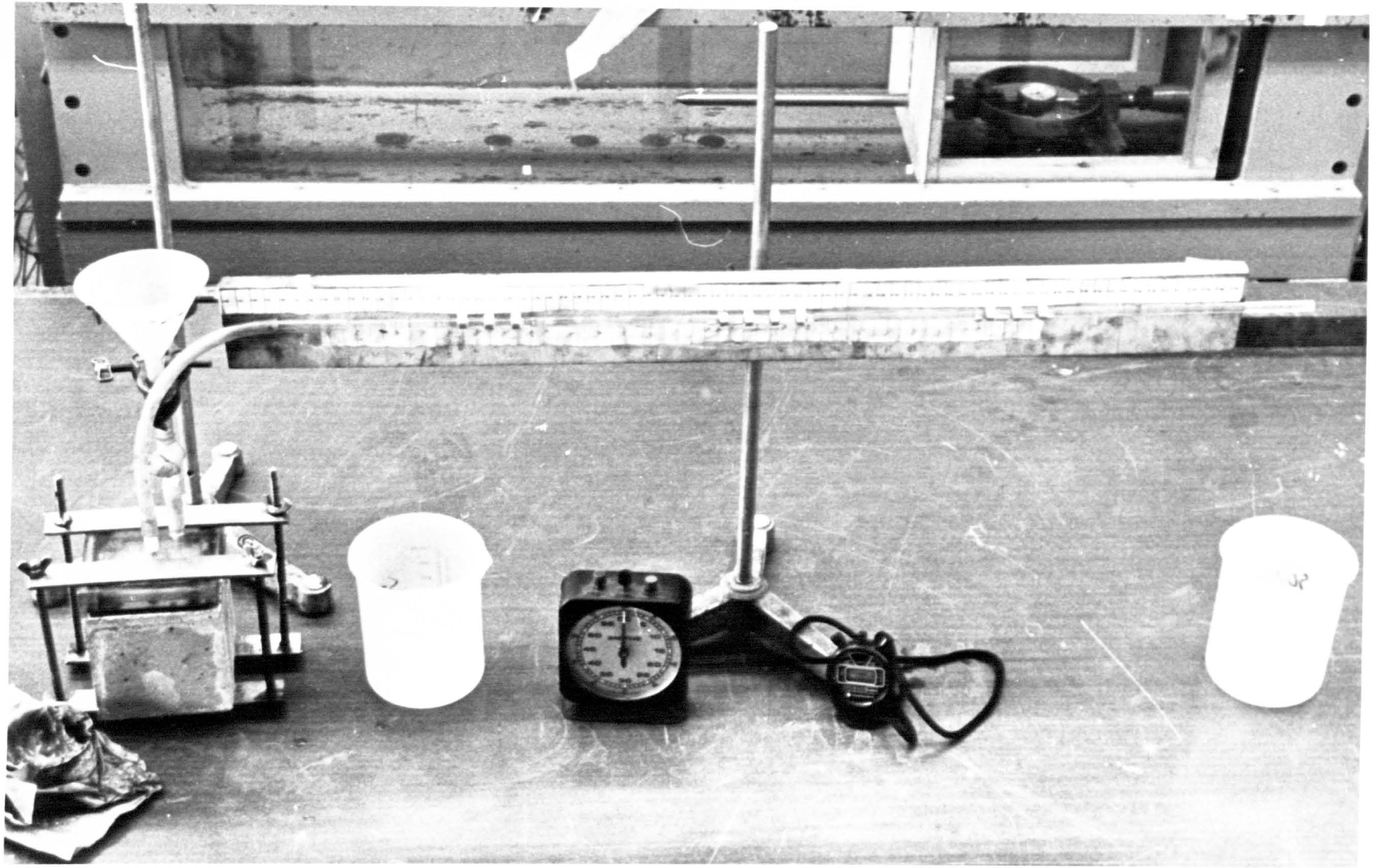
Complete assembly, excluding clamp, stands, etc.



Typical cap suitable for clamping onto horizontal surface

Fig. 3.2: Schematic diagram of the Initial Surface Absorption Test (ISAT) (68).

Plate 3.1: The initial surface absorption Test (ISAT).



minutes from the start of the test under a constant head of water of 200 mm ± 20 mm. The calibration scale depends on the area of contact of water with the specimen (A_1) calculated from the dimensions of the cap and the area of the capillary bore (A_2). It is recommended by the standard that A_1 should be no less than 5000 mm^2. The scale is then marked in units of 0.01 ml/m^2/sec and spaced $6 \times 10^{-4} \times \frac{A_1}{A_2}$ cm apart.

Apart from the initial investigations, where the ISAT was performed on a vertical face of 100 mm cubes, the test was conducted on the top-as-cast face of the 150 mm diameter 100 mm deep discs. The ten minute reading was the only one recorded and the results shown are the average of two specimens. The way samples were conditioned for this test was identical to that for the water absorption test and this procedure started at 24 days of age.

3.3.5 - Mercury Intrusion Porosimetry (MIP):

Since the introduction of high pressure mercury intrusion porosimetry by Ritter and Drake (72), it has become widely used in the cement industry as a method for evaluating the pore structure of hardened cements pastes and mortars. A schematic drawing of the MIP equipment used is shown in Fig. 3.3. Mercury, which is a none-wetting fluid, is intruded at high pressure into the sample.

The equation used for calculating pore diameter is derived from equating the work (W_1) needed to force a non-wetting liquid in a pore of a diameter (D) and length (L) with the work (W_2) needed to force a mercury of a volume (V) into the pore under external pressure (P) as follows:

$$W_1 = \pi D L S \cos\beta$$

where;

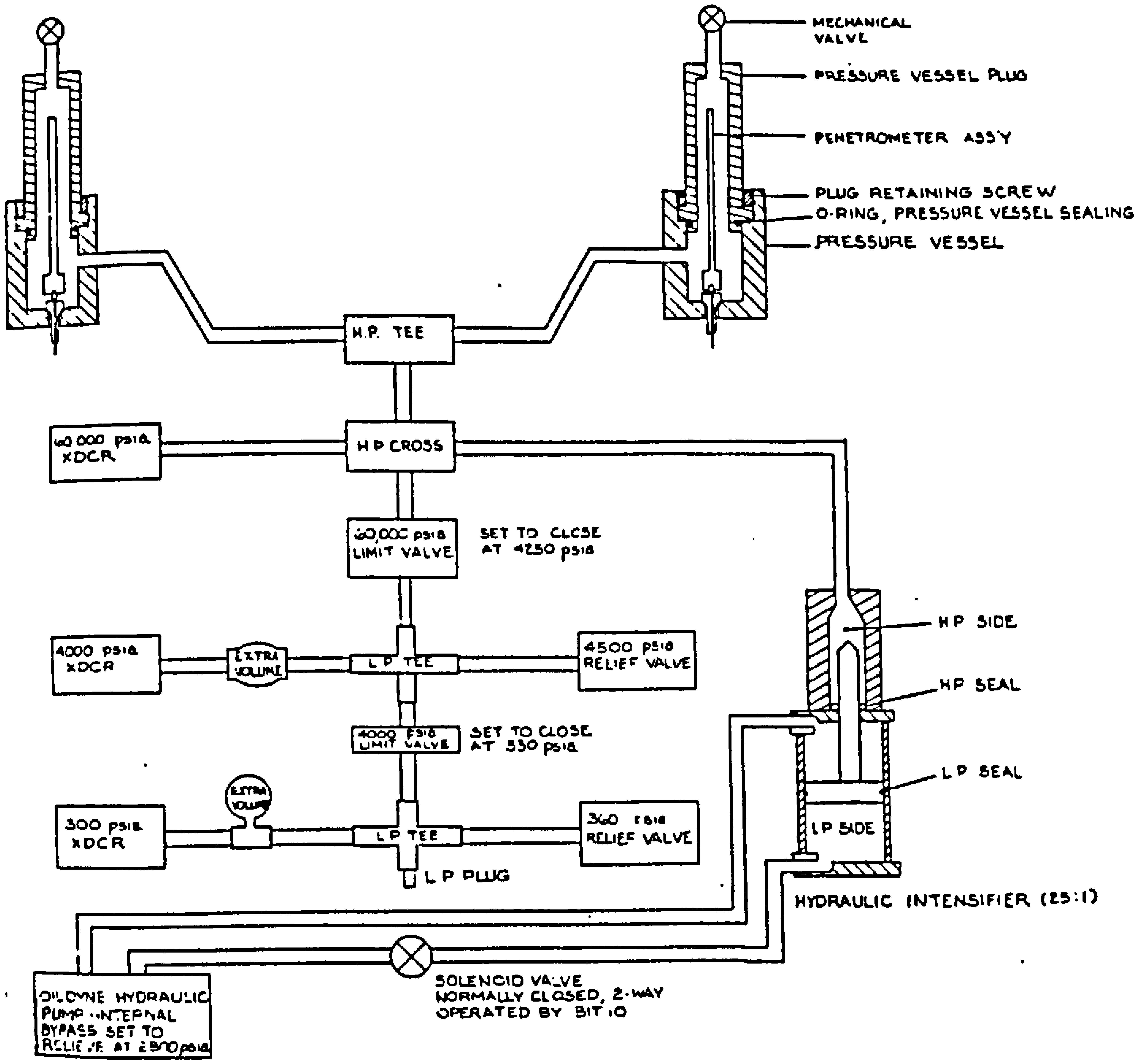


Fig. 3.3: Operation schematic for Autopore 9200 Mercury penetration porosimeter.

D = diameter of the pore

P = the applied pressure

S = surface tension

β = contact angle between the liquid and the wall of the pore, see Fig. 3.4.

and

$$W_2 = PV = \pi PL\frac{D^2}{4}$$

if $W_1 = W_2$ then

$$D = \frac{-4S\cos\beta}{P} \tag{3.2}$$

Types of Pores

Equation (3.2) assumes that all pores are cylinders of a uniform radius. This assumption is an important source of error, as pointed out by Ritter and Drake (72). They reported that the intrusion and extrusion curves do not coincide. This was attributed to the existence of ink-bottle pores whose entry diameter is smaller than that of the pore itself. In addition to this, there are pores which have an entry smaller than the minimum pore diameter which can be measured by the machine (0.003 μm in this research). These pores cannot be measured by mercury intrusion porosimetry.

Apparatus

The instrument used in this research was a Micrometirics Autopore 9200 Mercury Penetration porosimeter. It is capable of exerting a pressure of up to 414 MPa (60,000 psi). The range of pores measured by this instrument is between 36 to 0.003 μm in diameter with intrusion volume of 1.8 cm^3. A schematic drawing of this instrument is shown in Fig. 3.3.

Sample Preparation

The samples were small mortar discs of 25.4 mm in diameter by about 12-14 mm in height cut from cores cut from the 50 mm cubes as shown in Fig. 3.5 at an age of 24 days. After cutting, the discs were placed in an oven of 105°C ± 5°C for approximately 24 hours and left to cool to room temperature before the start of the test. The recorded results were the average of two samples.

Test procedure

This method works by first evacuating the gases from the pores and then forcing mercury into the sample by systematically increasing the pressure on mercury. Both the volume of mercury intruded and the pressure to achieve the intrusion are recorded for the calculation of the pore size distribution using equation (3.2).

The pore size distribution was obtained using pressures up to 60,000 psi (414 MPa). A wetting angle of 130 degrees was used in equation (3.2) to calculate the pore diameters. This value was used for all specimens as a compromise value most widely used by researchers in this field.

Type of Results

The MIP test produces many results that help to describe the pore structure of the cement paste. The direct parameters given by the machine are: total porosity, total pore surface area, median pore diameter by pore volume, median pore diameter by surface area and the average pore diameter. These five parameters are calculated from the pore size distribution by use of the pore volume and the pore surface area.

1 - Total porosity

Total porosity is a parameter which is independent of the shape and size of the

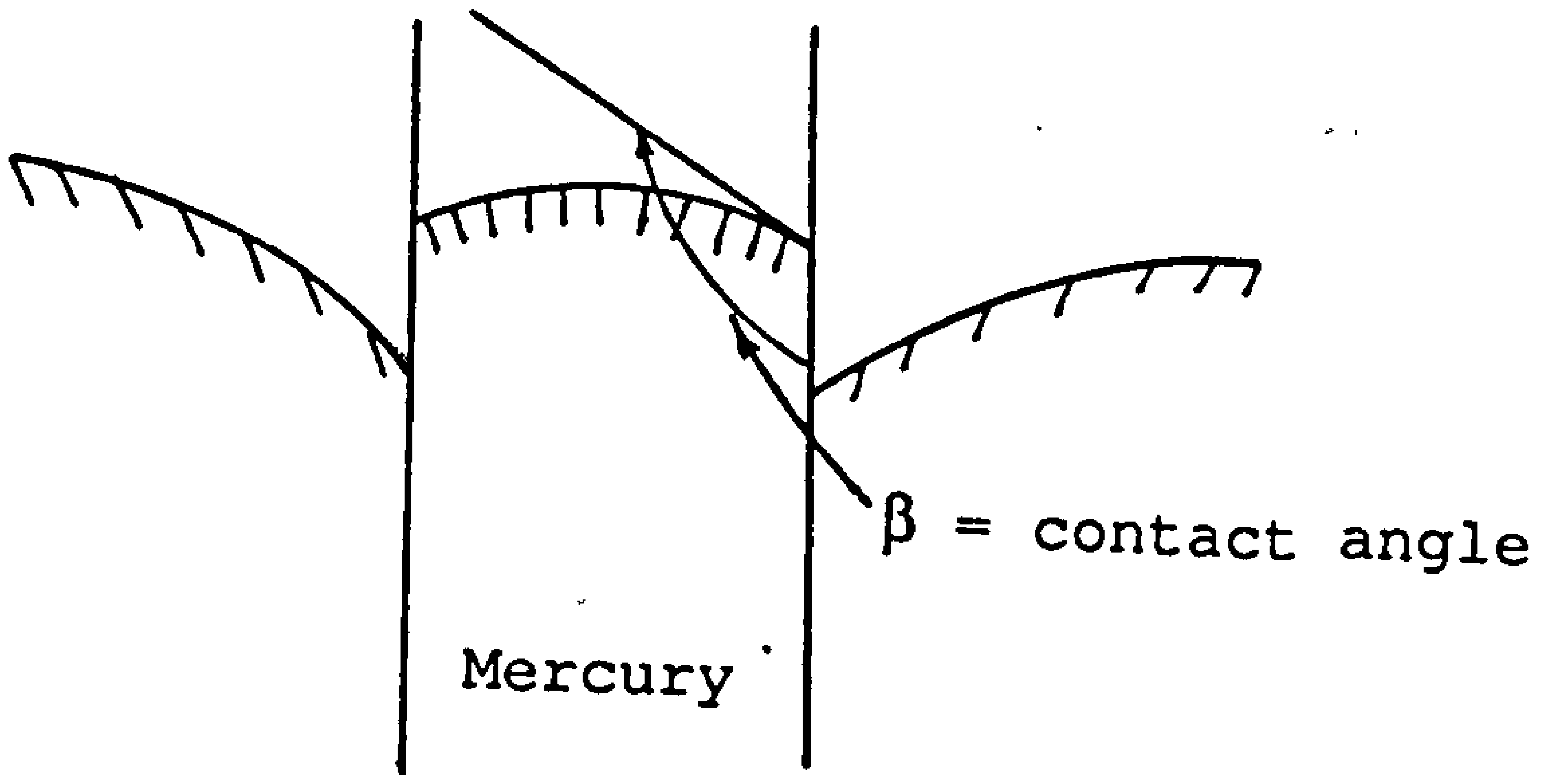


Fig. 3.4: Capillary depression of mercury, β > 90

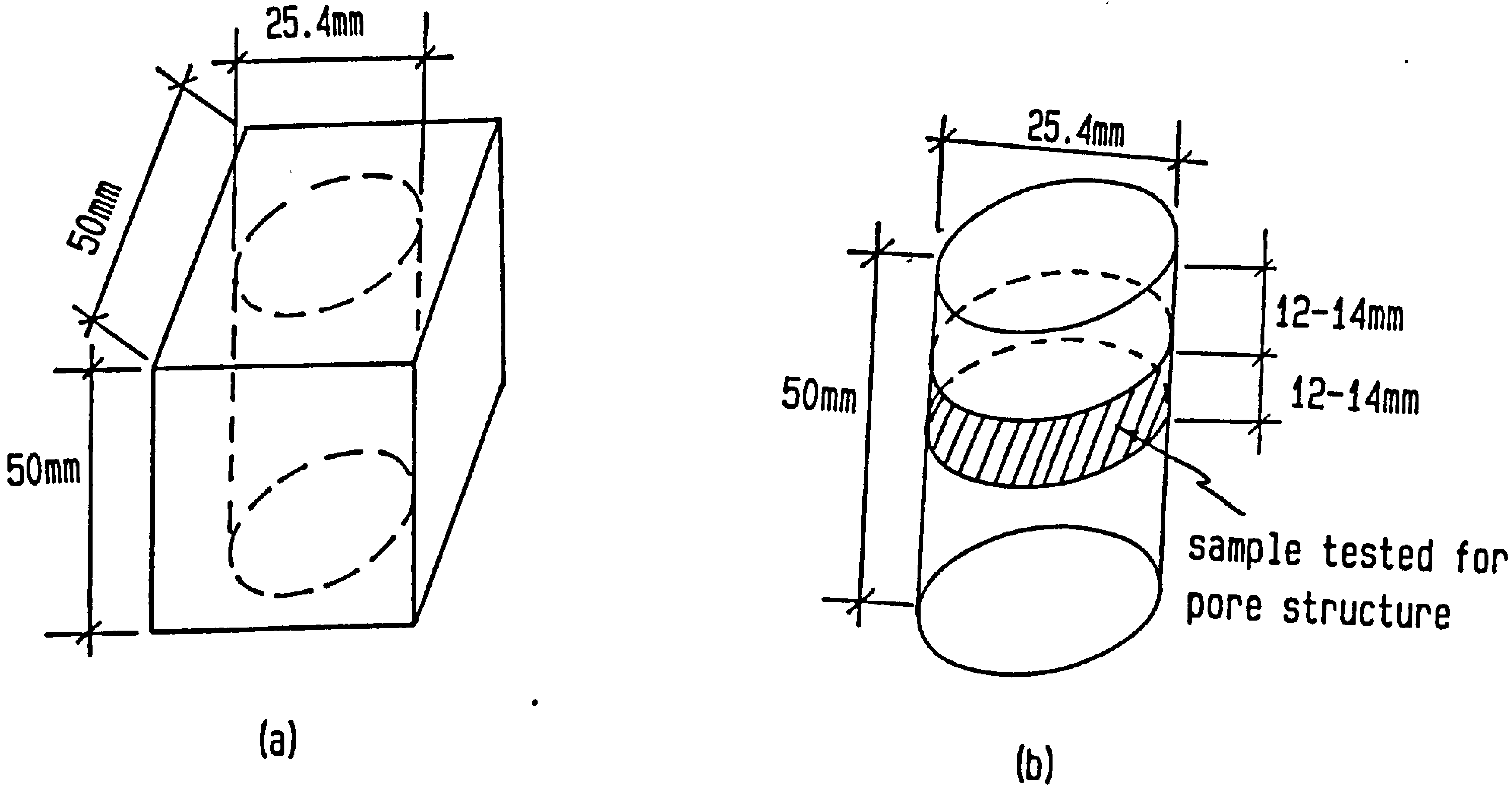


Fig. 3.5: Sample preparation for the evaluation of pore size distribution.

pores. It is the cumulative value of the volume of all the pores intruded by mercury in the cement matrix.

2 - Pore Surface Area (PSA)

The pore surface area is directly related to the number of pores in the matrix. Hence, at a constant porosity, the greater the pore surface area , the higher the number of smaller pores.

3 - Median Pore Diameter by Surface Area (MPD-A)

The median pore diameter by area relates to the number of small pores present in the cement matrix, the smaller the median pore diameter the greater the number of smaller pores, see Fig. 3.6 a. .

4 - Median Pore Diameter by Pore Volume (MPD-V)

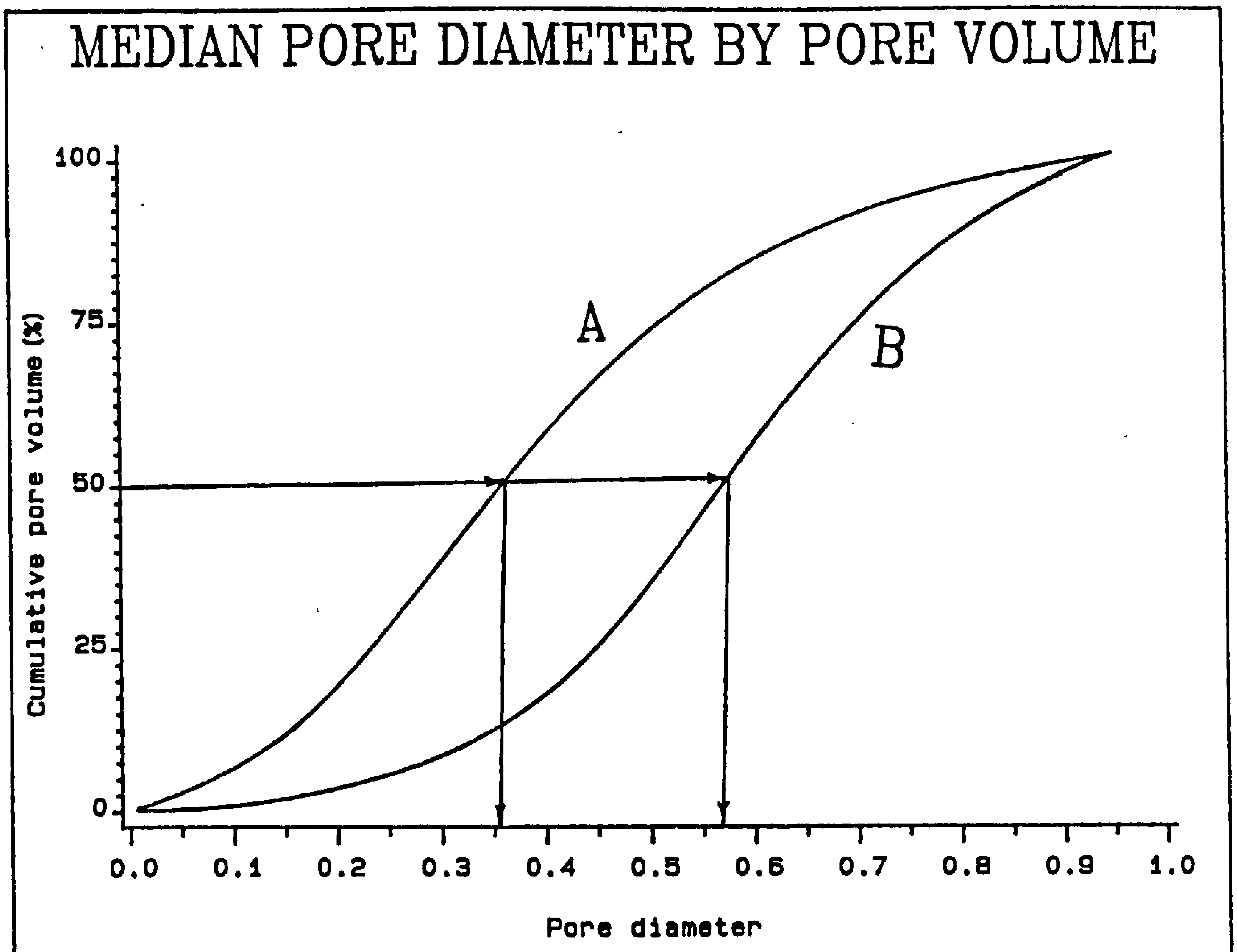
The median pore diameter by volume relates to the relative volume of smaller pores, the greater this value is the greater the volume of larger pores, see Figs. 3.6 b.

5 - Average Pore Diameter (APD)

The average pore diameter (APD) is a parameter that takes into account both the porosity and the pore surface area by use of the following equation:

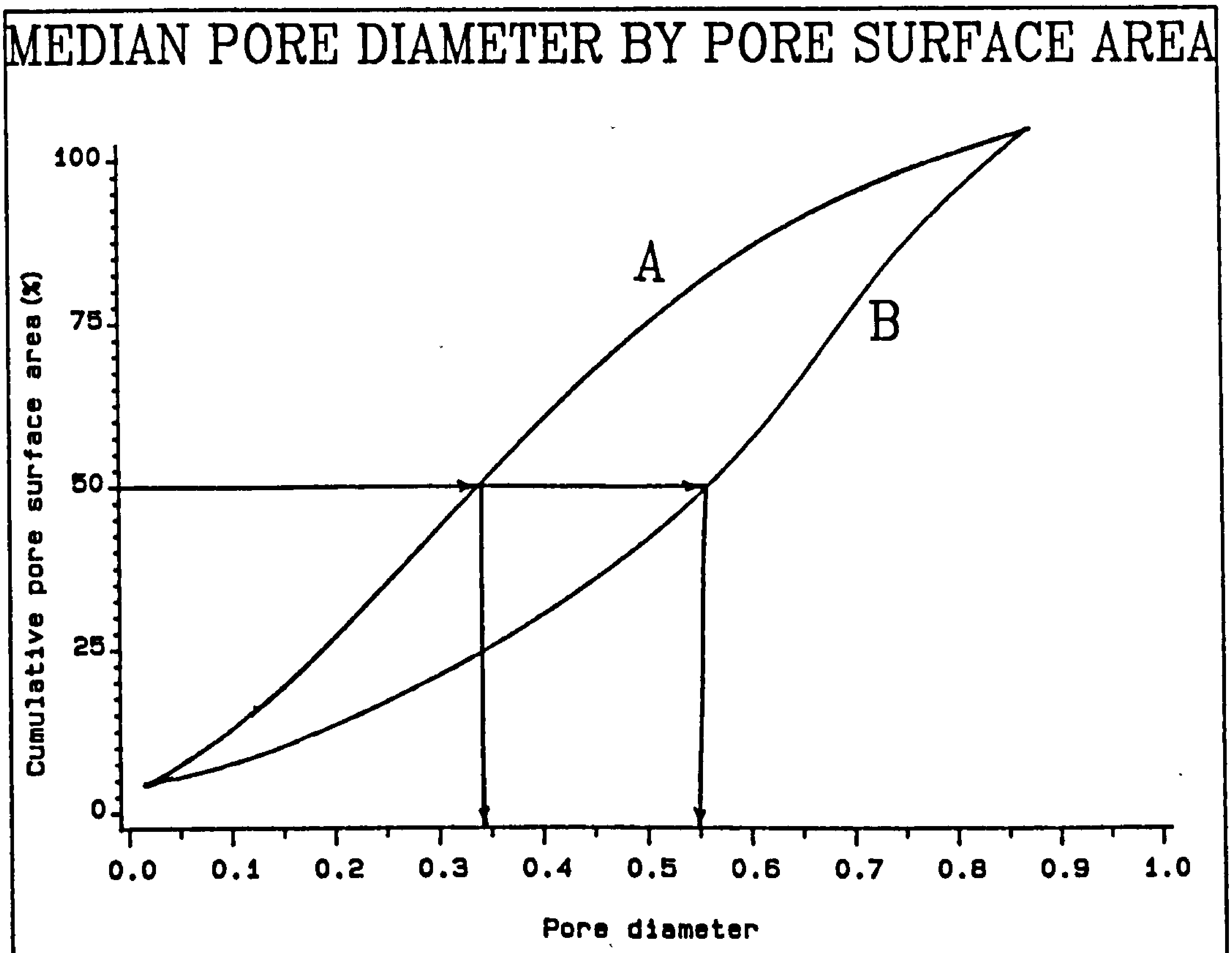
$$\text{APD} = \frac{4(\text{porosity})}{\text{pore surface area}}$$

Thus the higher the pore surface area and the lower the porosity, the smaller the APD is.



MEDIAN PORE DIAMETER BY PORE VOLUME

Fig. (3.6 a) Mixes A and B have the same pore volume, but mix A has greater volume of smaller pores



MEDIAN PORE DIAMETER BY PORE SURFACE AREA

Fig. (3.6 b) If mixes A and B have the same porosity; then mix A has greater number of smaller pores

3.3.6 - Total Porosity Tests:

Three different methodswere employed to measure the porosity of concrete and mortar specimens.

1 - The Mercury Porosimetry Method:

A description of this method has been given earlier in section 3.3.5. This method was only used in the mortar part (Chapter 5).

2 - The Helium Pycnometry Method:

Apparatus

The instrument used in this investigation is Micrometirics Auto Pycnometer 1320. It is cabable of measuring the solid volume of samples up to 9 cm^3 with an accuracy of ± 0.02 cm^3. The schematic drawing of this machine is shown in Fig. 3.7.

Test procedure

The total porosity of a concrete or mortar sample was calculated following the method proposed by Cabrera (73). It consists of measuring the density (D_w) of the sample and also the moisture content by drying in an oven at 105C. The dry density (D_d) is then calculated as follows:

$$D_d = \frac{D_w}{1+(\frac{\text{moisture content}}{100})} \tag{3.3}$$

The specific gravity (S.G.) is then measured using the helium pycnometer. The helium machine works by sucking the air out of the pores of the sample and assessing the net volume of the solids. The specific gravity is then measured by

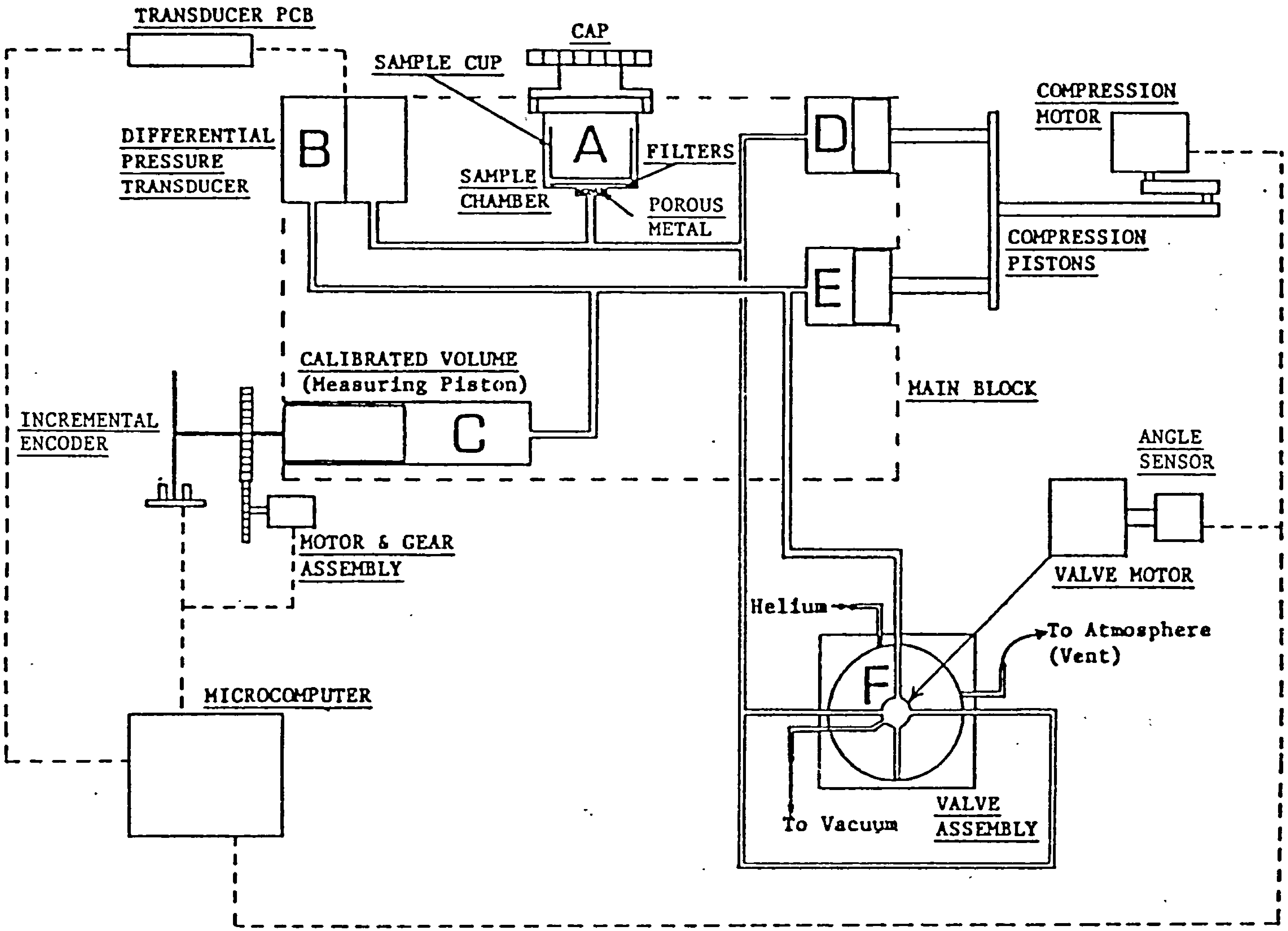


Fig. 3.7: Operation schematic for autopycnometer 1320.

the following equation:

$$S.G. = \frac{\text{weight of the sample}}{\text{volume of the sample}}$$

Sample Preparation

Mortar samples were either ground down to about 75 microns (as in the initial investigations) or prepared in the same way as the MIP samples, 25.4 mm diameter by about 15 mm deep discs as in Fig. 3.5. However, due to the presence of coarse aggregates in concrete mixes, it was suggested to grind down a relatively big sample, 300-500g, to about 75 microns and take powder samples out of it. The total porosity was then calculated as follows:

$$\text{Total porosity} = (1-(\frac{D_d}{S.G.}))x100 \tag{3.4}$$

3 - Total Water Saturation Method:

Small concrete samples of approximately 300-400 g were taken from the debris of crushed cubes. The samples were dried in an oven at 105°C for three days after which they were removed, weighed (W_1) and left to cool for 24 hours. They were then immersed in water until full saturation was reached after approximately 7 days. The samples were then weighed in air (W_2) and in water (W_3) and the porosity calculated using the following equation:

$$\text{Total porosity} = \frac{(W_2-W_1)}{(W_2-W_3)}x100 \tag{3.5}$$

3.3.7 - A Relative Air Permeability Test:

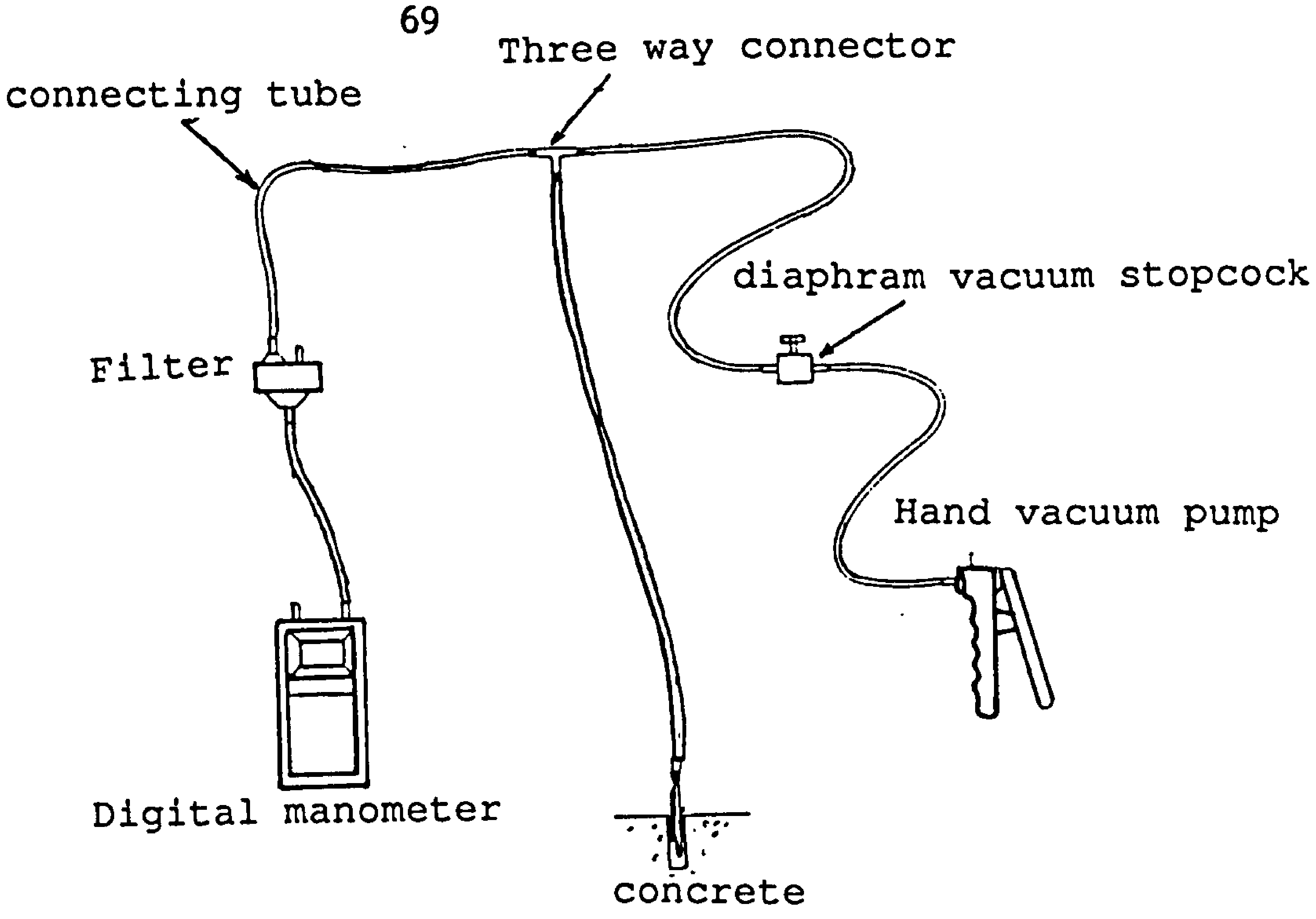
Apparatus and Test Procedure

The relative air permeability test used in this research was the one developed by Figg (43) and named after him. The test involves drilling a hole 10 mm in diameter 40 mm deep into the sample. A silicone rubber plug is inserted in the outer 20 mm of the hole leaving the remaining 20 mm as a cavity which has previously been cleared of all dust by means of compressed air. A hypodermic needle is then inserted through the rubber plug and the permeability assessed by attaching a digital manometer and a hand vacuum pump to the other end of the needle, see Fig. 3.8 a and Plate 3.2. A vacuum pressure of 55 kPa (55 kN/m^2) is created in the hole by means of the vacuum pump and the time needed for the pressure to drop 5 kPa ,i.e from 55 to 50, is measured. A typical relationship between pressure drop and time is shown in Fig. 3.9, the longer the time taken for the pressure to drop the less permeable the sample is. Results of this test will be recorded as the time taken for the pressure to drop by 1 kPa or simply the inverse of the slope of the line in Fig 3.9.

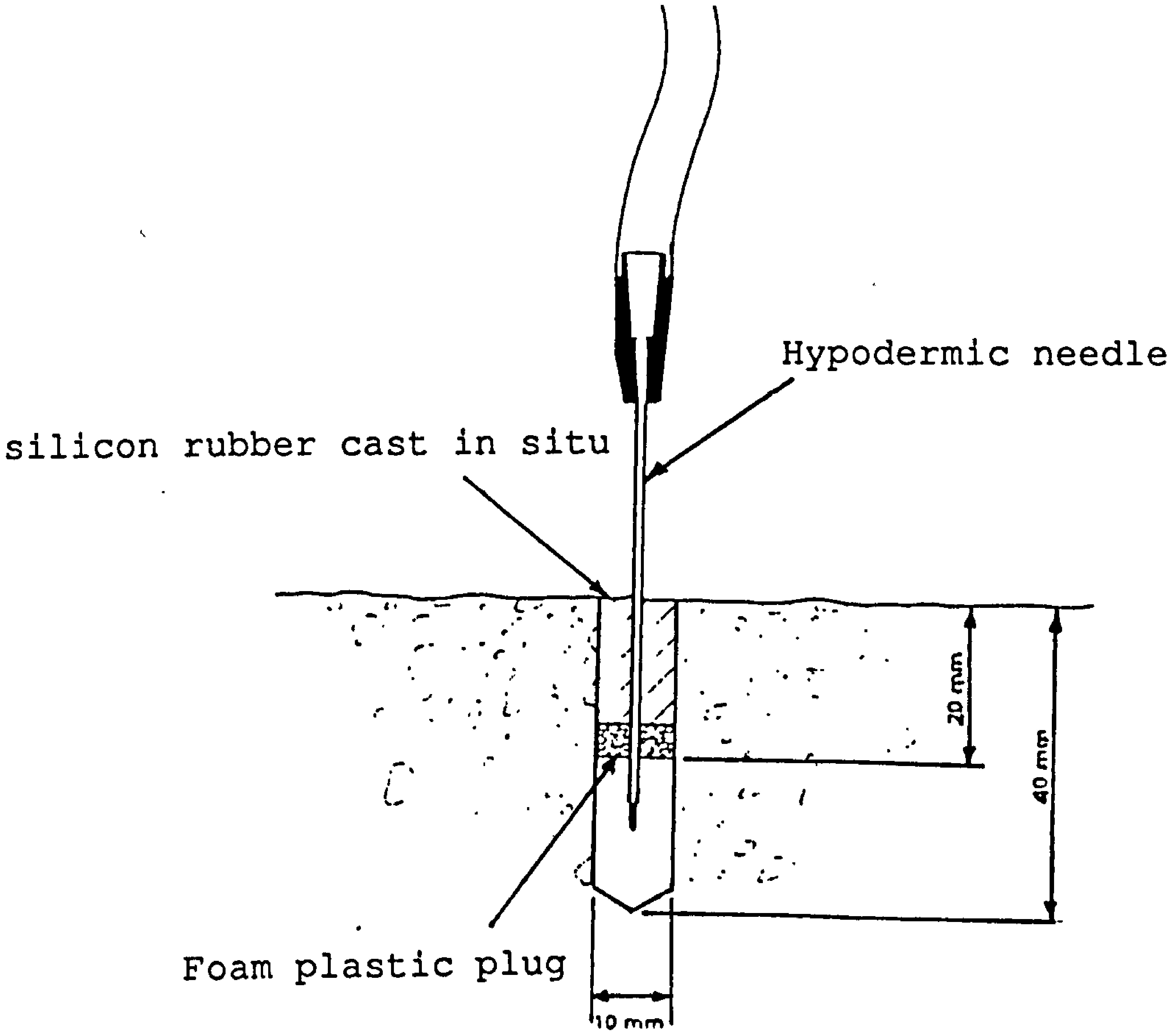
Sample Preparation

With the exception of the initial study where the samples were 100 mm cubes and holes drilled in a vertical face, the holes were made in the top-as-cast face of 150 mm diameter 100 mm deep discs. The procedure of sample- conditioning before testing is identical to that in water absorption tests and samples were removed from the relevant environment and put in the drying oven at 24 days of age.

This test was modified in the primary part of the investigation. The 40 mm deep holes were prefabricated using 10 mm diameter 40 mm deep bolts. The reason for this modification is to minimize the micro cracks that could be created



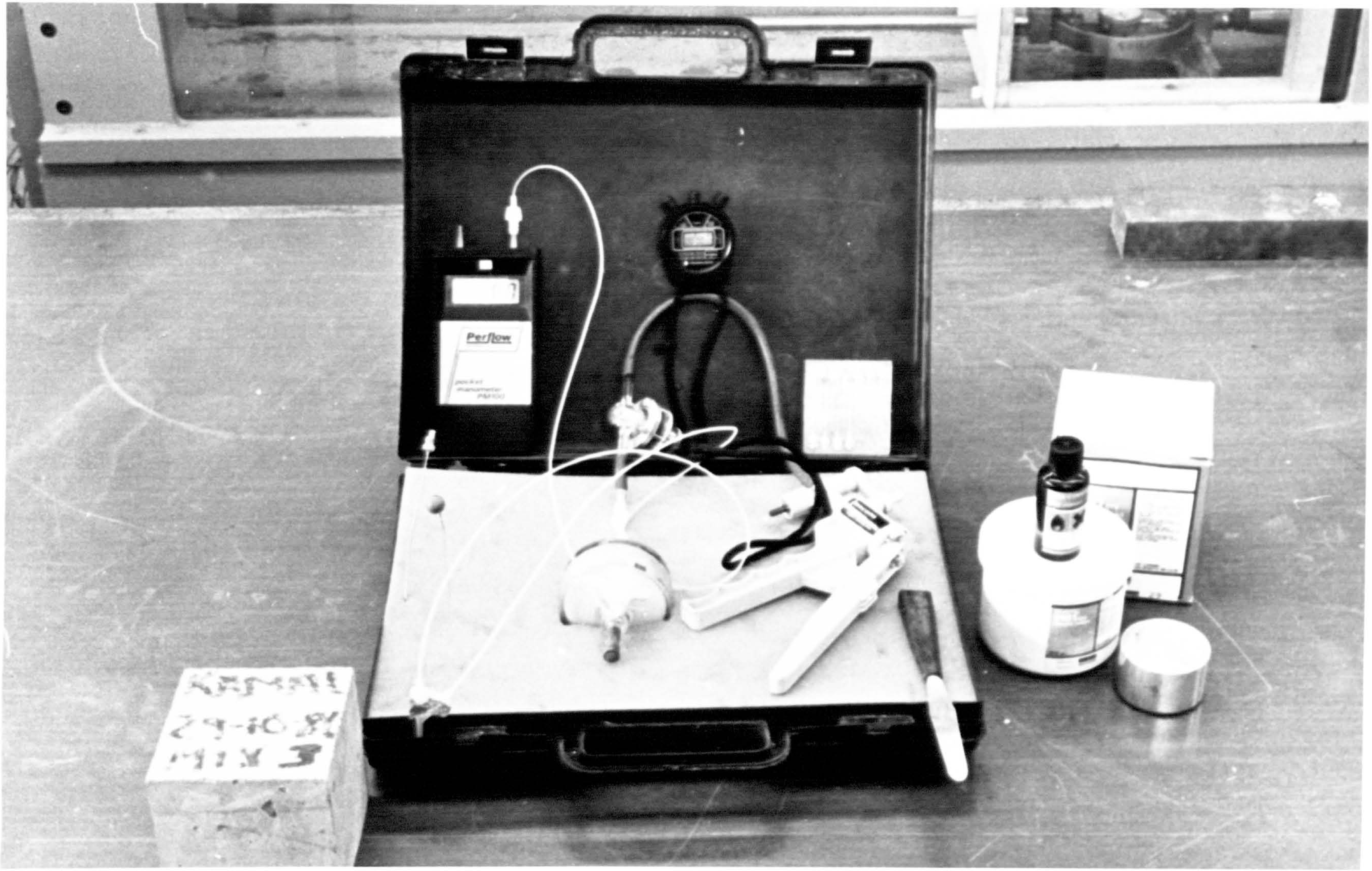
Arrangement of test



Method of making an airtight seal to concrete

Fig. 3.8: The modified Figg relative air permeability test (43)

Plate 3.2: The Figg relative air permeability apparatus


Perflow
pocket manometer PM100
KEMAH
29-10-91
MIX 3

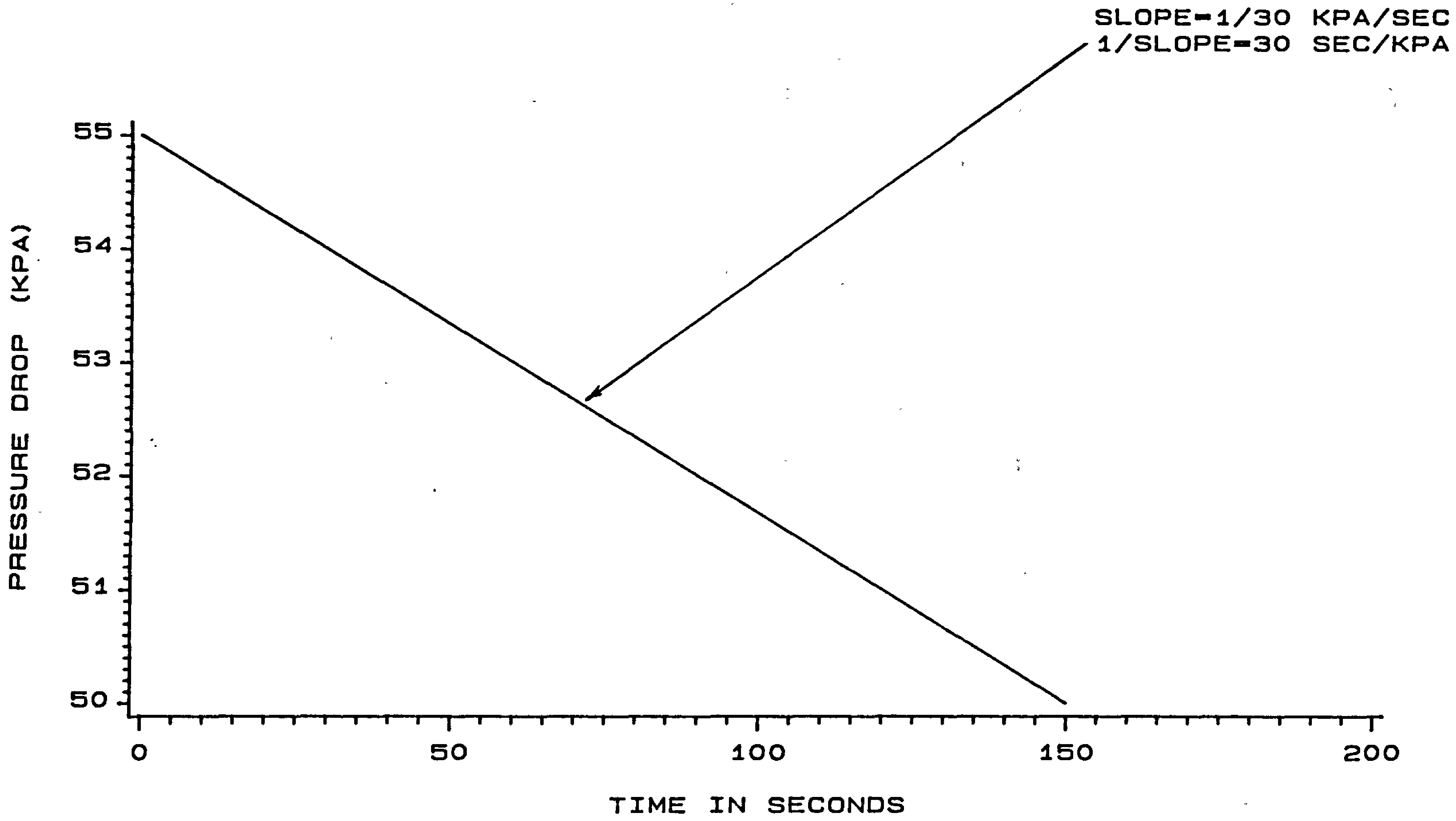


FIG. (3.9) The Figg relationship between pressure drop and time by drilling.

3.3.8 - Permeability to Oxygen:

Apparatus

The oxygen permeability test equipment used in this research was developed by Cabrera and Lynsdale (114) and is shown in Plate 3.3 and schematically in Fig. 3.10.

Test Procedure

Oxygen was applied by pressure at one end of the sample and collected at the other end after reaching a steady-state condition. The applied pressure was 1 bar above atmospheric and the flow rate was measured by one of the capillaries mounted on the board as shown in Plate 3.3. The coefficient of air permeability was than calculated by the equation derived from D'Arcy's equation by Nagataki and Ujike (51) as follows:

$$K = \frac{2LQ\omega P_2}{(P_1^2 - P_2^2)A} \tag{3.6}$$

where

K = coefficient of permeability (cm/sec)

L = length of the sample (cm)

Q = flow rate (cm^3/sec)

A = cross sectional area (cm^2)

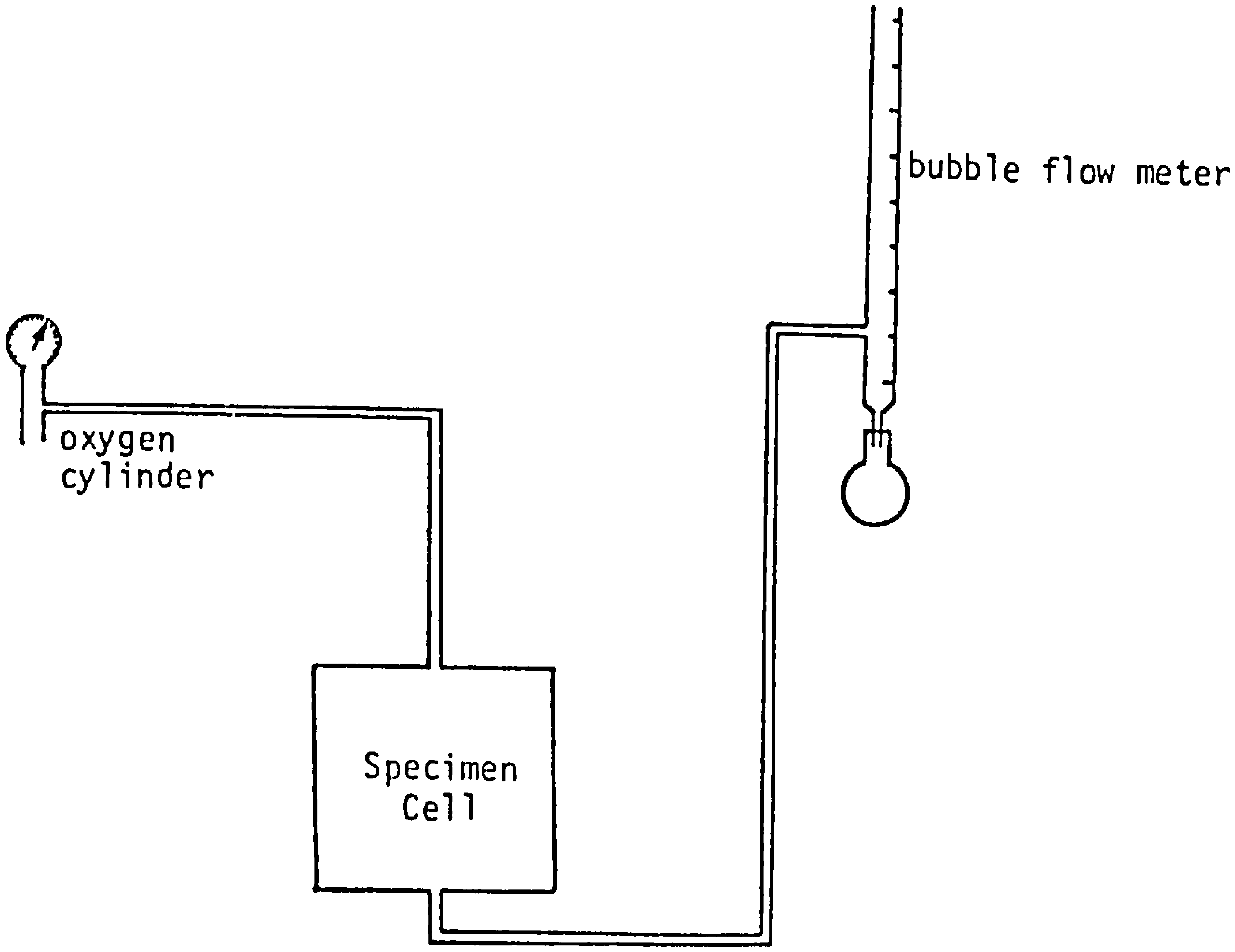
ω = unit weight of the oxygen (kg/cm^3)

P_1 = applied pressure (kg/cm^2)

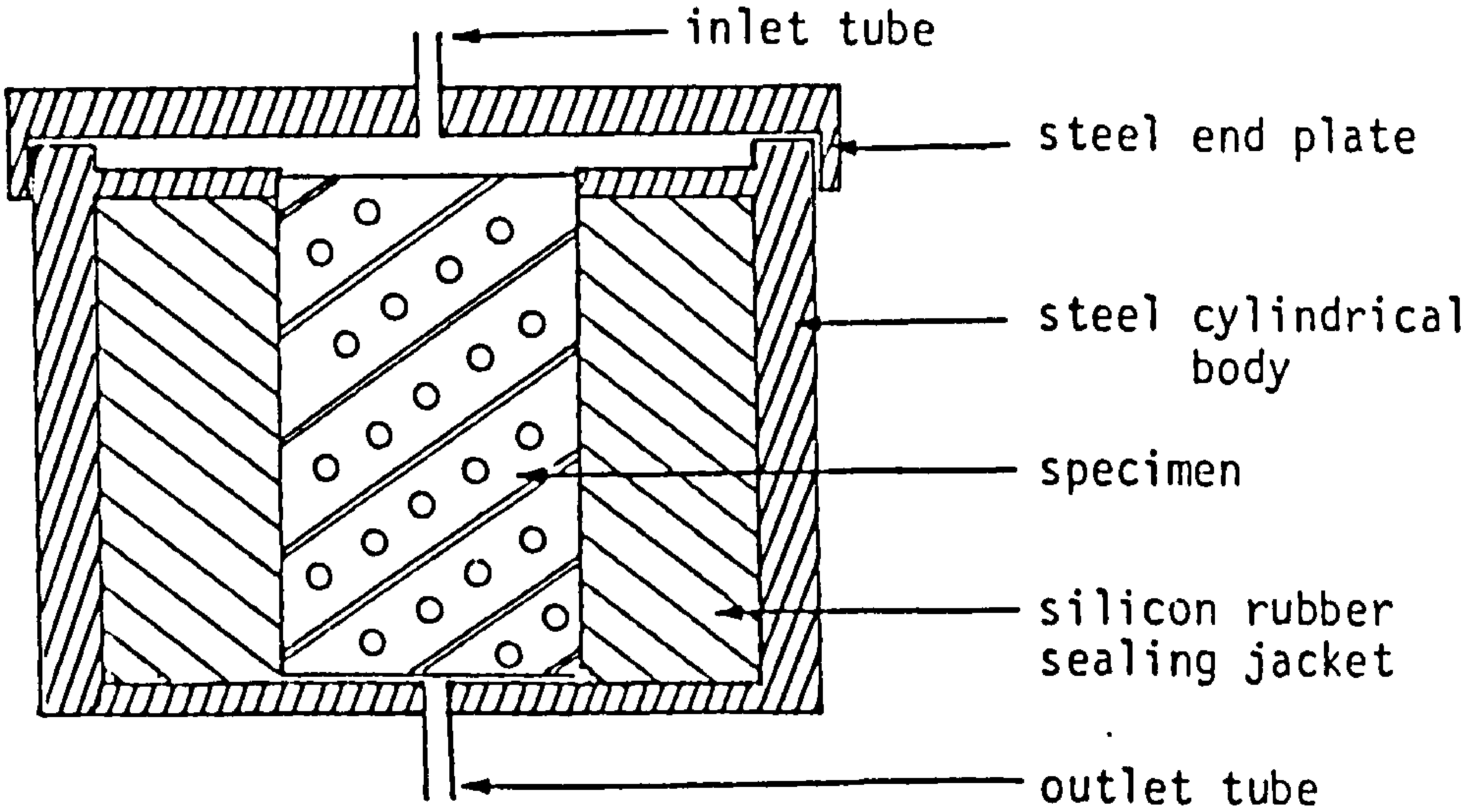
P_2 = pressure at the other end of the sample (kg/cm^2)

Plate 3.3: The oxygen permeability apparatus used for the measurement of the permeability of mortars.


TAPS



Arrangement of apparatus



Cross section of permeameter

Fig. 3.10: Schematic diagram of gas permeability apparatus.

It is important to note that Grube and Lawrance (75) have also derived a similar equation with the exception that the viscosity of the oxygen is used instead of the unit weight and therefore the units for K are cm^2 ; i.e. intrinsic permeability. Viscosity and unit weight of oxygen are both constants and do not vary with different samples if the ambient temperature is constant. Hence using one or the other does not affect the results if consistently used throughout the calculations.

Sample Preparation

This method was used for the mortar samples only and the samples used were 25.4 mm in diameter by 48-50 mm in height cored from the 50 mm cubes as in Fig. 3.5a. The sides of the specimens were themselves sealed with a non-corrosive silicon rubber to avoid any oxygen escaping from the sides of the samples.

The samples to be tested were removed from their respective curing environment at the age of 24 days, cored and placed in an oven at 105°C for 72 hours. They were then put in an air-tight vessel until they reached room temperature before the start of the test.

3.3.9 - Portable Air Permeability Test:

The Figg relative air permeability test is simple and theoretically very good. However, this test cannot be used successfully to estimate the permeability efficiently. Therefore, it would be very useful if the Figg and oxygen permeability apparatuses are combined to produce a test easy to perform and can estimate the permeability correctly. In the following paragraphs, an attempt will be made to develop such an idea.

Apparatus:

The apparatus of the portable air permeability test is shown schematically in

Fig. 3.11. It consist of a hand vacuum pump, manometer, valve and a cell in which samples are placed.

Test Procedure :

The test is performed by connecting the different components of the apparatus in the same way as in Fig. 3.11. A vacuum pressure of about 80 kPa(.8 bar) below atmospheric is created by means of the vacuum pump and the valve is then closed. The vacuum pressure is then monitored by the manometer until it reaches 50.5 kPa. The time in seconds for the pressure to drop from 50.5 to 49.5 is recorded using a stop watch. The length and the cross-sectional area of the sample are also recorded for future calculations. The author will attempt to relate the oxygen permeability values and the results of this test statistically and mathematically in Chapter 5.

Specimens:

The portable air permeability test was carried out on the same samples tested for oxygen permeability. Descriptions of the sample preparation, curing, and conditioning are given in section 3.3.8.

3.4 - Curing Environments:

1 - 50°C ± 2°C + 15%RH ± 5%:

This curing environment was accomplished using a small oven where temperature was easily controlled but the relative humidity was not. However, the relative humidity was monitored throughout and found to be between 10 and 20%.

2 - 45°C ± 2°C + 30%RH ± 5%

A walk-in environmental chamber was built in the Civil Engineering Department of the University of Leeds, see Plate 3.4. The specification of this

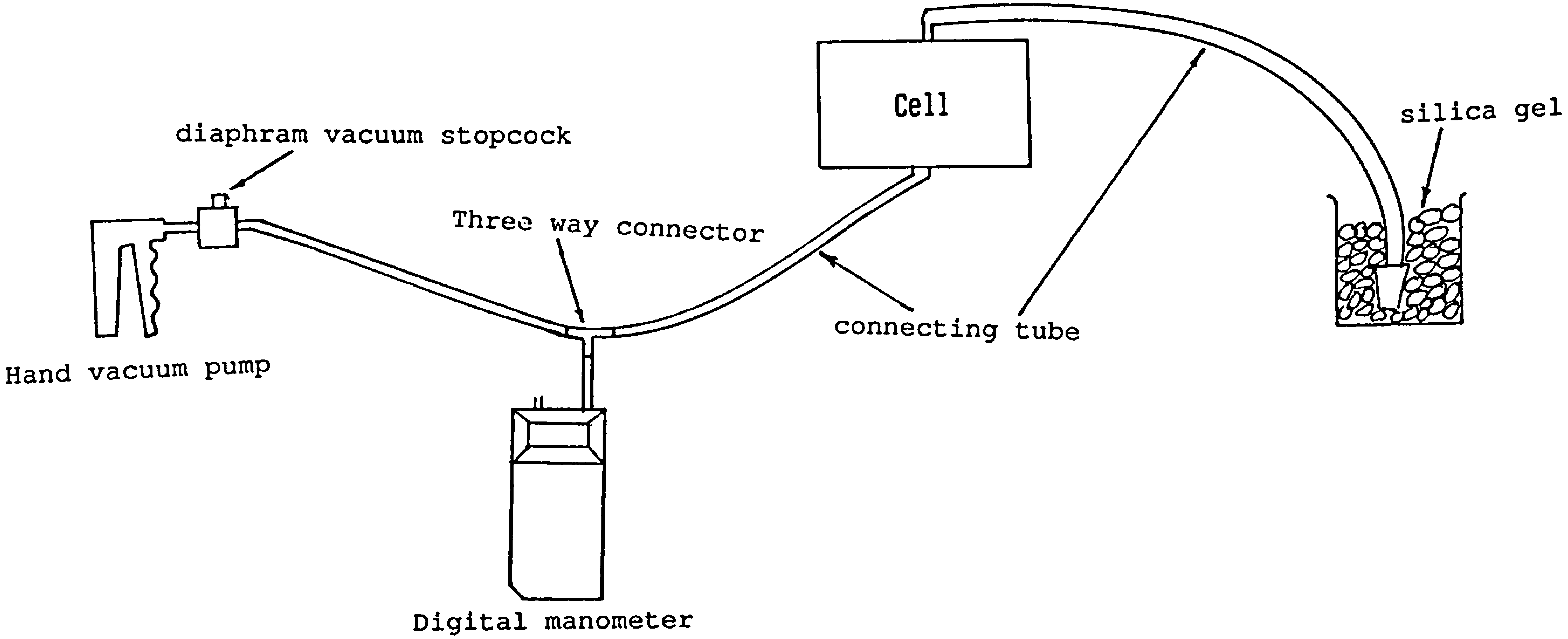
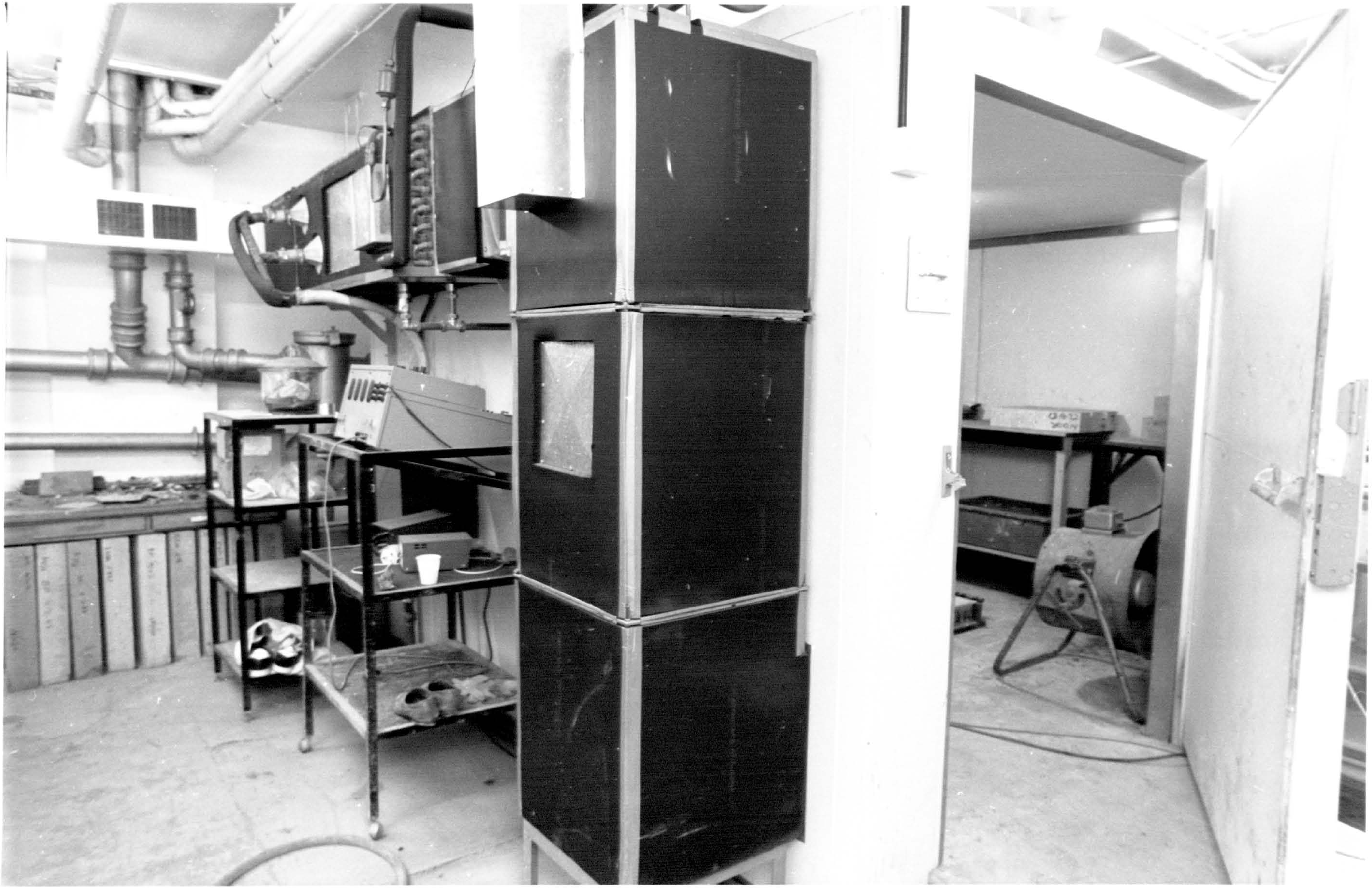


Fig. 3.11: Schematic drawing of the portable air permeability test.

Plate 3.4: The walk-in environmental chamber built in the Civil Engineering Department of the University of Leeds.



room are as follows:

Length x Width x Height = 3 x 3 x 2 metres
Temperature range = 10 to 60°C ± 2°C
Relative Humidity = 25 to 95% ± 5%

3 - 35°C ± 2°C + 70%RH ± 5%:

This environment was achieved using the same walk-in chamber described above in number 2.

4 - 40°C ± 2°C + 60%RH ± 5%:

A small Gallenkamp environmental chamber was used in which temperature was easily controlled but the relative humidity was not. A small water tray was continuously used to achieve 60%RH.

5 - 20°C ± 2°C + 70%RH ± 5%:

The Civil Engineering Department of the University of Leeds has a room where the temperature and the relative humidity were continuously controlled to be 20°C and 70%RH, respectively. This room was used to simulate this environment.

6 - 20°C ± 2°C + 100%RH

This environment was achieved in the so-called fog room. It is the standard moist curing condition where water is sprayed in the specimen to make it saturated.

CHAPTER FOUR

INITIAL INVESTIGATION OF THE EFFECTS OF CURING/ENVIRONMENTS ON MORTAR AND CONCRETE MIXES CONTAINING PFA AND GGBS

4.1 - Introduction:

The work described in this chapter was designed to act as a pilot study, the main purpose of which was to give guidelines for the principal testing programmes which are dealt with in Chapters 5 and 6. The effects of water/cement ratio, cement content, curing/environmental and different levels of OPC replacement, by either pfa or slag, on some durability properties are dealt with in the mortar programme. Moreover, four different concrete mixes, made to a constant workability, were studied under four different curing and environmental conditions. Their performance was assessed by means of two mechanical tests in addition to the four durability tests used in the mortar programme. In addition to the effects of curing and environmental conditions, the concrete mixes are also designed to study the effects of cement content, pfa and slag. The effects of all the different variables on the properties of the concrete mixes were evaluated at six months as well as 28 days of age to explore the effect of age.

4.2 - Analysis of Mortar:

4.2.1 - Mix Proportions:

The mix proportions used throughout this test programme are shown in Table 4.1. Mixing was carried out as described previously in Chapter 3 and with each mix cast, the following specimens were cast:

1 - (16) 50 mm cubes, 8 for the water absorption test and 8 for the measurement of the total porosity.

2 - (8) 100 mm cubes for the Figg and initial surface absorption tests. Two vertical faces of each cube were examined, one by ISAT and the other one by the Figg test.

4.2.2 - Curing/Environmental Conditions:

Specimens were cast in the laboratory, the temperature of which was not controlled, but was maintained at approximately 18°C throughout the duration of the test program. Immediately after casting, specimens were covered with polythene sheeting and kept in the casting room. Specimens were demoulded at an age of one day after which they were subjected to one of four different curing/environmental conditions as listed in Table 4.2. Details of these environmental conditions are shown in Chapter 3. With the exception of condition 3, all specimens were left completely uncovered in their particular curing environment.

4.2.3 - Tests Carried Out:

The following tests were carried out at an age of 28 days on the specimens cast:

1 - The test for water absorption;

2 - The relative air permeability test, Figg method;

3 - The surface water absorption test and

4 - The total porosity using the helium method.

These tests were performed following the procedures described previously in Chapter 3.

4.2.4 - Results:

The actual 28 day results for each test are expressed in graphical form in Figs.

Table 4.1: Mix proportions of the mortar mixes

mix	OPC	PFA	GGBS	SAND	WATER
1	1	0	0	2.3	0.45
2	1	0	0	2.7	0.45
3	1	0	0	2.7	0.50
4	0.8	0.2	0	2.7	0.50
5	0.6	0.4	0	2.7	0.50
6	0.5	0	0.5	2.7	0.50
7	0.7	0	0.3	2.7	0.50

Table 4.2: Curing and environmental conditions

number	Description
1	50°C ±2°C + 15%RH ±5 %
2	40°C ±2°C + 60%RH ± 5%
3	Wrapped in polythene for two more days at 20°C and then placed in oven at 50°C + 15%RH
4	20°C ±2°C + 100%RH

4.1, 4.2, 4.3 and 4.4.

4.2.4.1 - Water absorption:

Fig. 4.1 shows the results for water absorption. A statistical analysis carried out on the differences between readings from nominally identical specimens has indicated a degree of repeatability within 10% at a 90% level of confidence.

As expected the lowest values of water absorption was obtained for specimens cured at 100%RH and 20°C (control condition). A comparison of the OPC mixes indicates that for all conditions of curing, mix 2 has the lowest absorption characteristics. This is what one could expect when comparing mix 2 with mix 3; they contain the same quantity of cement but mix 3 has the higher water/cement ratio. Mix 1 has the same water/cement ratio as mix 2 but contains more cement and therefore a higher cement paste volume. Since cement paste is inherently more porous than the aggregates (in this case the sand) the water absorption of mix 1 is higher than that of mix 2, especially as the curing conditions reduce the availability of water for hydration. The differences in absorption between mixes 1 and 3 for conditions 1, 2 and 4 are very small. This is interesting because mix 1 has the lower water/cement ratio but the benefit from this has apparently been offset by the increased cement content. For all three mixes the worst curing condition is the oven at 50°C which has the effect of increasing the water absorption by between 50 - 65% compared to the figure at 20°C and 100%RH. The increase in absorption values for the three Portland cement mixes when curing conditions are changed from 3 to 1 serves to highlight the importance of early curing. In the case of mix 1 for example, two extra days of protection with polythene at 20°C before subjecting it to the oven reduces the absorption value by more than 70% as compared with that of the same mortar placed in the oven immediately after demoulding.

For all curing conditions, with the exception of 2, the mixes containing pfa or

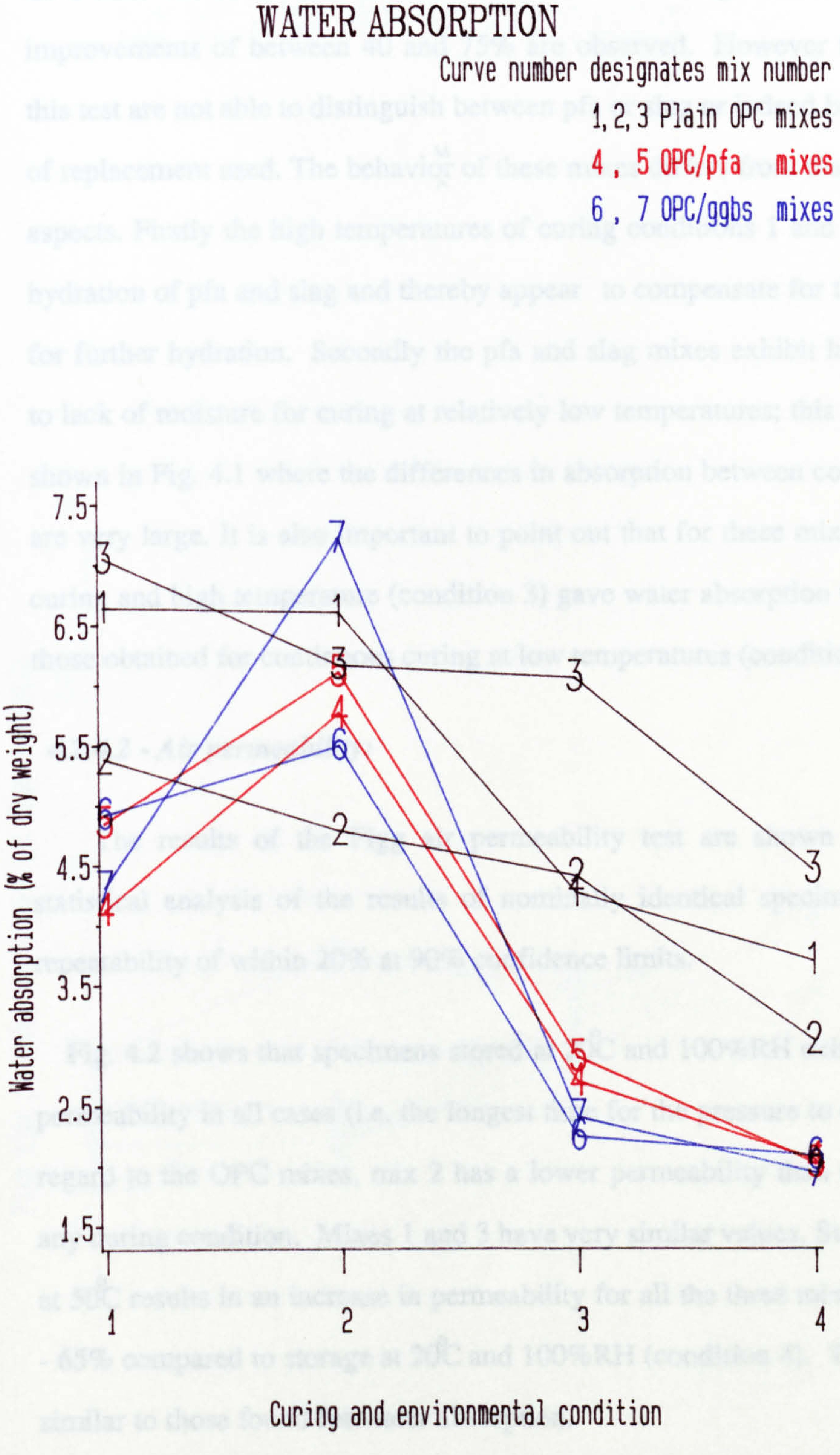


Fig. 4.1 The effects of curing and environmental condition on water absorption results for the mortar specimens

slag (mixes 4, 5, 6, 7) have lower water absorption characteristics than the third OPC mix. The differences are more noticeable for curing condition 3 and 4 where improvements of between 40 and 75% are observed. However the results from this test are not able to distinguish between pfa or slag or indeed between the level of replacement used. The behaviour of these mixes differs from that of OPC in two aspects. Firstly the high temperatures of curing conditions 1 and 3 accelerate the hydration of pfa and slag and thereby appear to compensate for the lack of water for further hydration. Secondly the pfa and slag mixes exhibit higher sensitivity to lack of moisture for curing at relatively low temperatures; this aspect is clearly shown in Fig. 4.1 where the differences in absorption between conditions 4 and 2 are very large. It is also important to point out that for these mixes, limited early curing and high temperature (condition 3) gave water absorption values similar to those obtained for continuous curing at low temperatures (condition 4).

4.2.4.2 - Air permeability:

The results of the Figg air permeability test are shown in Fig. 4.2. A statistical analysis of the results of nominally identical specimen pairs gave a repeatability of within 20% at 90% confidence limits.

Fig. 4.2 shows that specimens stored at 20°C and 100%RH exhibited the lowest permeability in all cases (i.e. the longest time for the pressure to drop 1 kPa). With regard to the OPC mixes, mix 2 has a lower permeability than mixes 1 and 3 at any curing condition. Mixes 1 and 3 have very similar values. Storage in the oven at 50°C results in an increase in permeability for all the three mixes of between 45 - 65% compared to storage at 20°C and 100%RH (condition 4). These findings are similar to those found for water absorption.

The results for the pfa and slag mixes are again similar to those for water absorption although this particular test is apparently capable of distinguishing between pfa and slag and between the level of replacement. In general the pfa

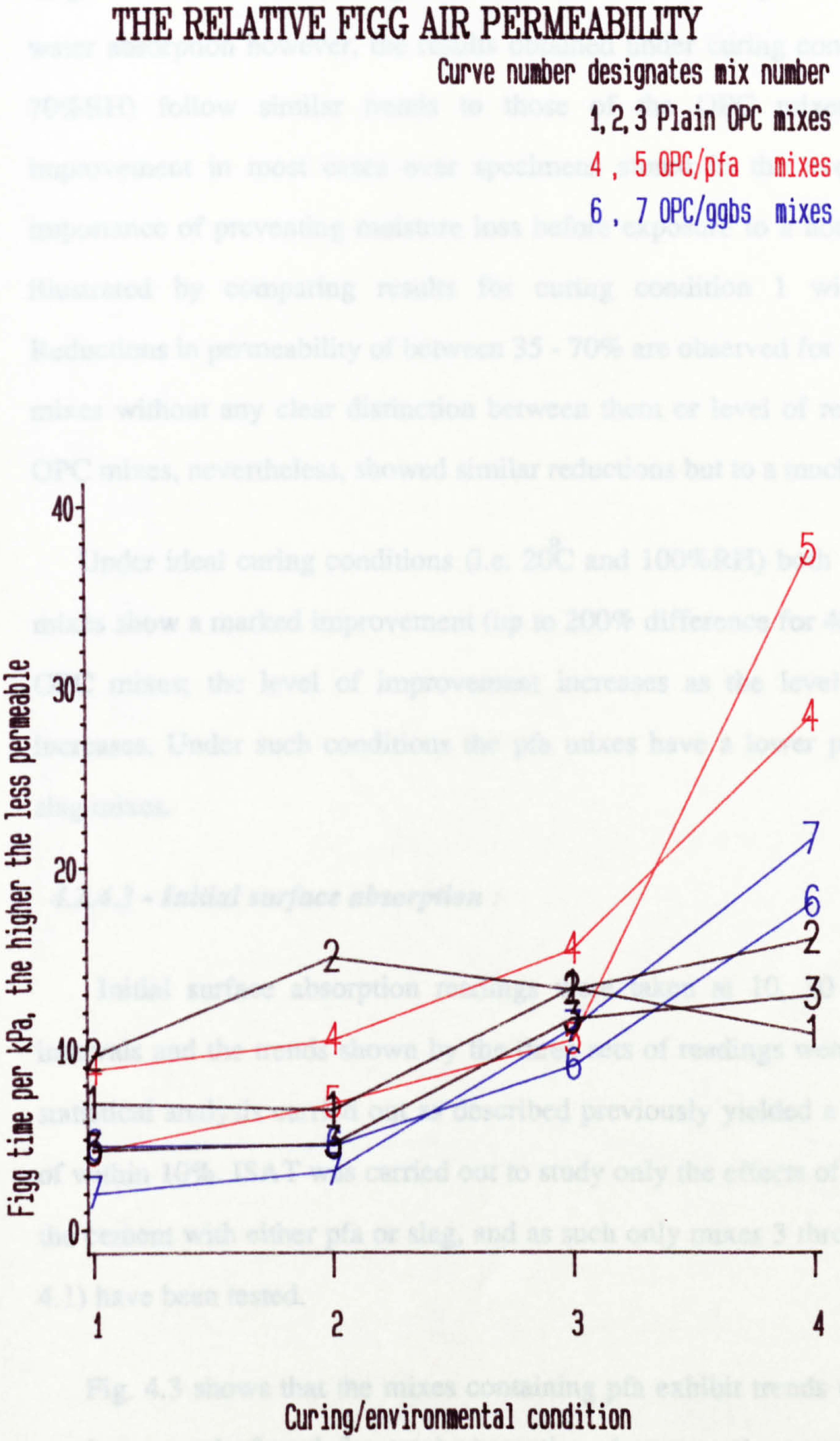


Fig. 4.2 The effects of curing/environmental condition on relative air permeability for the mortar specimens

mixes show lower permeability than the slag mixes; on average the differences range from 20% (curing condition 1) to 80% (curing condition 4). Unlike water absorption however, the results obtained under curing condition 2 (20°C + 70%RH) follow similar trends to those of the OPC mixes, i.e. a slight improvement in most cases over specimens stored in the oven at 50°C. The importance of preventing moisture loss before exposure to a hot environment is illustrated by comparing results for curing condition 1 with those of 3. Reductions in permeability of between 35 - 70% are observed for the pfa and ggbs mixes without any clear distinction between them or level of replacement. The OPC mixes, nevertheless, showed similar reductions but to a much smaller scale.

Under ideal curing conditions (i.e. 20°C and 100%RH) both the pfa and slag mixes show a marked improvement (up to 200% difference for 40% pfa) over the OPC mixes; the level of improvement increases as the level of replacement increases. Under such conditions the pfa mixes have a lower permeability than slag mixes.

4.2.4.3 - Initial surface absorption :

Initial surface absorption readings were taken at 10, 30 and 60 minutes intervals and the trends shown by the three sets of readings were very similar. A statistical analysis carried out as described previously yielded a test repeatability of within 10%. ISAT was carried out to study only the effects of replacing part of the cement with either pfa or slag, and as such only mixes 3 through 7 (see Table 4.1) have been tested.

Fig. 4.3 shows that the mixes containing pfa exhibit trends which are similar to those trends found for total absorption, however the trends for the mixes containing slag show that slag mixes are very sensitive to lack of moisture during curing. In fact mixes 6 and 7 show very large increases, between 80 to 150%, in the surface water absorption when comparing conditions 3 and 1.

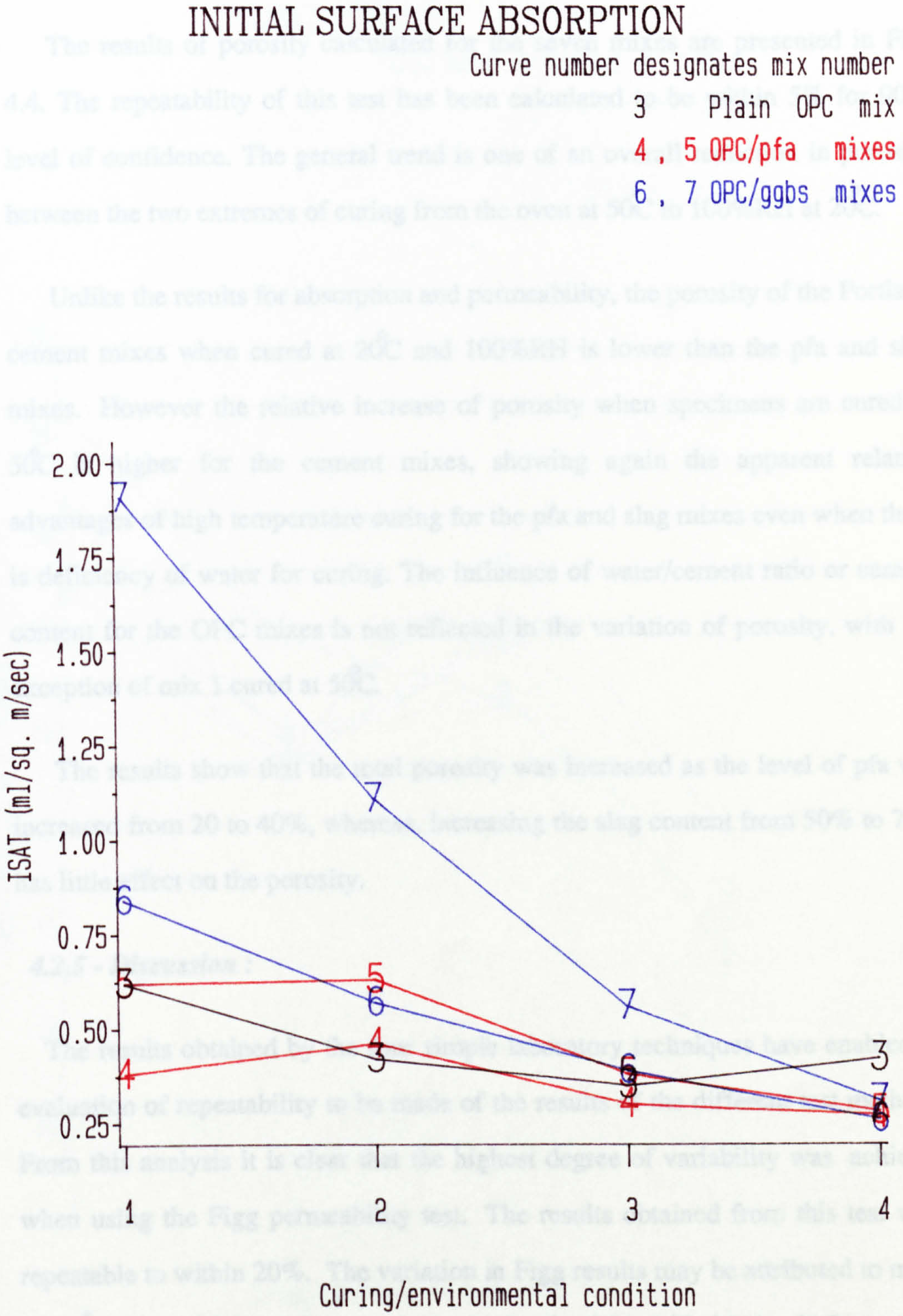


Fig. 4.3 The effects of curing/environmental condition on the initial surface absorption for the mortar specimens

4.2.4.4 - Porosity:

The results of porosity calculated for the seven mixes are presented in Fig. 4.4. The repeatability of this test has been calculated to be within 5% for 90% level of confidence. The general trend is one of an overall reduction in porosity between the two extremes of curing from the oven at 50°C to 100%RH at 20°C.

Unlike the results for absorption and permeability, the porosity of the Portland cement mixes when cured at 20°C and 100%RH is lower than the pfa and slag mixes. However the relative increase of porosity when specimens are cured at 50°C is higher for the cement mixes, showing again the apparent relative advantages of high temperature curing for the pfa and slag mixes even when there is deficiency of water for curing. The influence of water/cement ratio or cement content for the OPC mixes is not reflected in the variation of porosity, with the exception of mix 1 cured at 50°C.

The results show that the total porosity was increased as the level of pfa was increased from 20 to 40%, whereas, increasing the slag content from 50% to 70% has little effect on the porosity.

4.2.5 - Discussion :

The results obtained by the four simple laboratory techniques have enabled an evaluation of repeatability to be made of the results of the different test methods. From this analysis it is clear that the highest degree of variability was achieved when using the Figg permeability test. The results obtained from this test were repeatable to within 20%. The variation in Figg results may be attributed to many factors among which: a) Inaccuracy in the depth of the drilled hole. b) Inaccuracy in the thickness from the surface to the hollow part of the concrete; it is known that specimen depth is an important parameter in calculating the permeability coefficient, see Chapter 3.

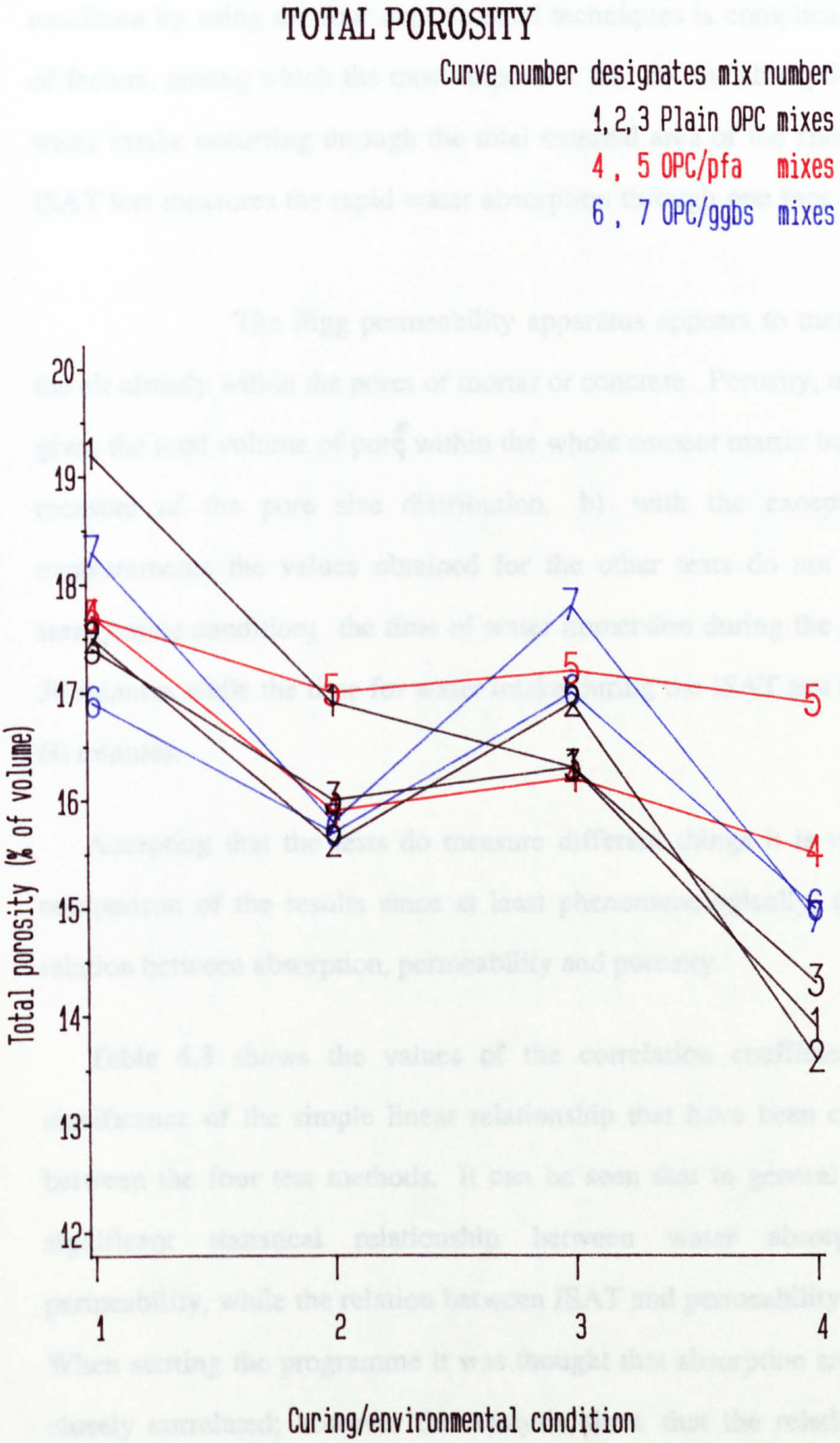


Fig. 4.4 The effects of curing/environmental condition on the total porosity for the mortar specimens

Interpretation of the results obtained for any one mix at any one curing condition by using the four experimental techniques is complicated by a number of factors, among which the most important are: a) the absorption test measures water intake occurring through the total external area of the specimen, while the ISAT test measures the rapid water absorption through one face of the specimen.

The Figg permeability apparatus appears to measure air flow of the air already within the pores of mortar or concrete. Porosity, on the other hand, gives the total volume of pores within the whole cement matrix but does not give a measure of the pore size distribution. b) with the exception of porosity measurements the values obtained for the other tests do not correspond to a steady-state condition; the time of water immersion during the absorption test is 30 minutes while the time for water intake during the ISAT test varies from 10 to 60 minutes.

Accepting that the tests do measure different things it is valid to attempt a comparison of the results since at least phenomenologically, there should be a relation between absorption, permeability and porosity.

Table 4.3 shows the values of the correlation coefficients and level of significance of the simple linear relationship that have been calculated to exist between the four test methods. It can be seen that in general there is a highly significant statistical relationship between water absorption and Figg permeability, while the relation between ISAT and permeability is not significant. When starting the programme it was thought that absorption and ISAT would be closely correlated; however the analysis show that the relationship is poor in statistical terms. This is probably due to the differences highlighted earlier.

The relationship between water absorption and porosity is also significant which is encouraging. Since the evaluation of porosity is repeatable to within 5%,

Table 4.3: Correlation coefficients and level of significance of simple linear relations for the mortar specimens. (Last number in each group in a column indicates number of tests).

test	Figg	Porosity	Water absorption	ISAT
Figg	1.00000 0.0000 36	-0.50364 0.0017 36	-0.83828 0.0001 36	-0.6763 0.0157 12
Porosity	-0.50364 0.0017 36	1.00000 0.00000 37	0.71676 0.0001 37	0.40693 0.1892 12
Water Absorption	-0.83828 0.0001 36	0.71676 0.0001 37	1.00000 0.00000 37	0.68082 0.0148 12
ISAT	-0.67635 0.0157 12	0.40693 0.1892 12	0.68082 0.0148 12	1.00000 0.00000 12

such a test may possibly be incorporated as a routine procedure for quality control.

The relationship between permeability and porosity is poor which is probably related to the fact that permeability is not so much a function of total pore volume but rather of the nature of the pore size distribution.

It was very encouraging to see that the different curing environments were seen to have a measurable influence on the durability properties of mortars. The 50°C + 15%RH environment is considered to be far too extreme and a more realistic hot environment, such as 40°C and 60%RH, would have to be simulated and this will be examined in the following section with concrete.

The results of the three OPC mixes showed that higher cement content mixes with the same water/cement ratio resulted in more permeable and more absorptive specimens. This is expected since, at the same water/cement ratio, the higher cement content mixes contain more cement paste which is known to be inherently more porous than the sand. It would be very useful to explore how curing environments will influence concrete mixes having the same workability but different cement contents. This will be demonstrated in the next section.

The OPC/pfa and OPC/ggbs mixes showed better results than that of plain OPC at relatively low temperatures, 20°C, when continuously cured. However when curing for short periods and placing in hot environments, an advantageous behaviour, as far as hot countries are concerned, was seen when pfa or slag were included. This is an interesting point which needs to be explored further. Therefore, concrete mixes containing pfa and ggbs will be examined in the next part of this initial investigations.

Different levels of OPC replacement by either pfa or slag exhibited similar trends of results. Hence, one OPC/pfa and one OPC/ggbs mix are considered to be sufficient in explaining the effects of curing environments. Furthermore, the inclusion of pfa is known to enhance the workability and a reduction in the water/cement ratio is therefore possible if workability is to remain constant. These different parameters will be studied using concrete mixes having the same workability as measured by the slump test.

4.3 - Analysis of Concrete:

4.3.1 - Mixing and Casting:

The concrete mixes used in this part of the investigations were designed on the basis of constant workability to reflect the situation likely to occur in practice. These mixes followed from the discussion at the end of the previous section. The mix proportions used in this part are shown in Table 4.4. Mixing was carried out as described previously and for each mix cast, the following specimens were made:

1 - (16) 100X100X500 mm prisms for the dynamic modulus of elasticity;

2 - (16) 100 mm cubes for the evaluation of compressive strength at 28 days and six months of age. These cubes were also used to measure the total porosity.

3 - (16) 100 mm cubes for the water absorption test at 28 days and six months.

4 - (8) 100 mm cubes for the ISAT and Figg method to be tested at 28 days. The six-month tests were performed on cubes sliced out of the prisms used for the dynamic modulus of elasticity. Two vertical faces of each cube were tested, one by ISAT and the other one by Figg test.

4.3.2 - Curing/Environmental Conditions:

Four laboratory curing/environmental conditions were chosen to simulate a range of site conditions under which fresh concrete may harden. The casting and demoulding procedures are identical to those in the mortar part. Immediately after demoulding, i.e. at an age of one day, the specimens were subjected to one of the conditions described in Table 4.5.

Table 4.4: Concrete mix proportions by mass

mix number	OPC	sand	gravel	pfa	ggbs	water
1	1	2	4	0	0	0.55
2	1	1.25	2.5	0	0	0.38
3	0.7	1.25	2.5	0.3	0	0.36
4	0.4	1.25	2.5	0	0.6	0.38

Note: Workability was constant for all mixes, 50-75mm of slump

Table 4.5: Details of the curing/environmental conditions

condition No.	Description
1	Uncovered in oven at 50°C + 15%RH
2	Uncovered in an environmental chamber at 40°C + 60%RH
3	AS 2 but wrapped in polythene for the first two days
4	Uncovered at 20°C + 100%RH

4.3.3 - Tests Carried Out:

The tests carried out in this part of the investigation were: water absorption, Figg relative air permeability, initial surface absorption (ISAT), total porosity by the helium method, compressive strength and dynamic modulus of elasticity, for details of tests procedures see Chapter 3. The 28-day testing procedure is identical to that described in Chapter 3. Testing at 6 months followed the plan shown in Chapter 3 with the exception that specimen conditioning started at 180 days of age.

4.3.4 - Results

The actual 28-day results for each of the tests are shown graphically in Fig. 4.5 - 4.10. Table 4.6 shows the 28-day and 6-month results for all the tests.

4.3.5 - Discussion

4.3.5.1 - Statistical Relationships

4.3.5.1.1 - Durability - Related Tests:

It is important to recall that significant linear relations were found in the previous mortar programme between water absorption and Figg permeability, and water absorption and porosity. Table 4.7 shows the values of the correlation coefficients and level of significance of simple linear relationship for concrete specimens. It can be seen that in general there exist a highly significant linear relations between water absorption and ISAT see Fig. 4.11. Moreover, Table 4.7 shows that the relationship between Figg and the reciprocal of water absorption results is more significant than that between Figg and water absorption (see Fig. 4.12). A similar observation was also seen for the relationship between Figg and ISAT (see Fig. 4.13). This shows that higher air permeability is accompanied by an increase in water absorption to a certain limit beyond which any additional

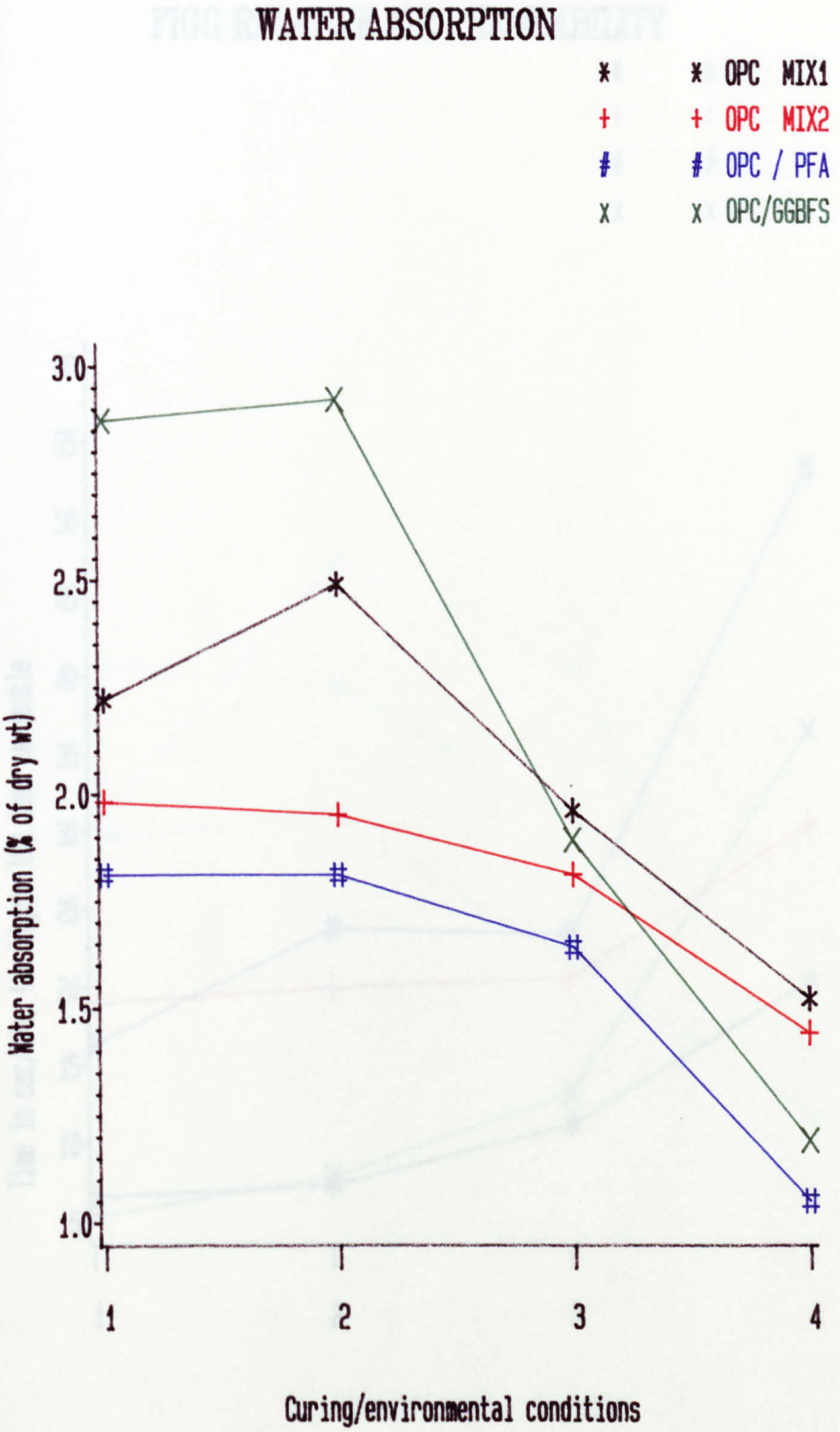


Fig. 4.5 The effects of curing/environmental condition on the water absorption for the concrete specimens

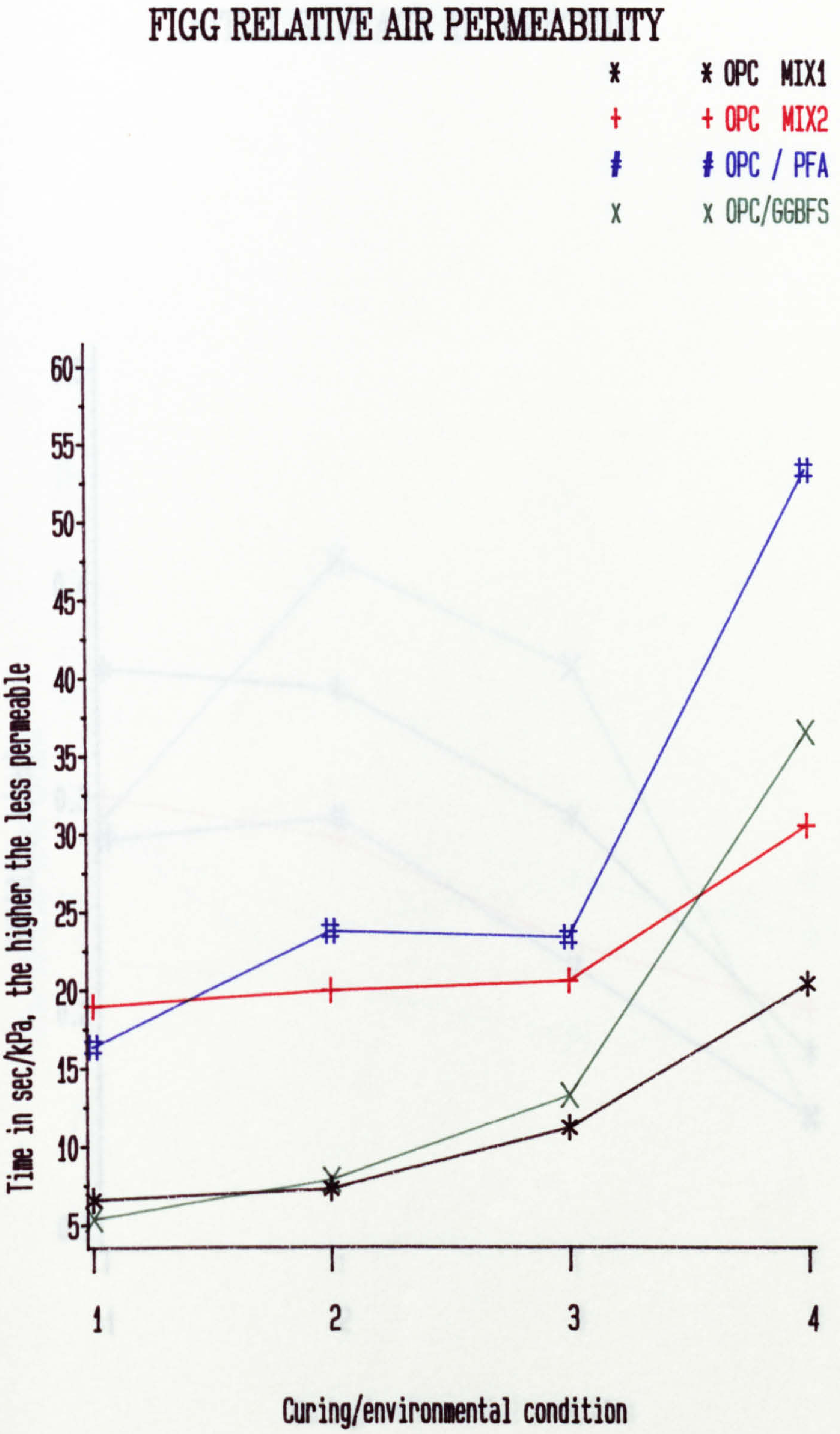


Fig. 4.6 The effects of curing/environmental conditions on the relative air permeability for the concrete specimens

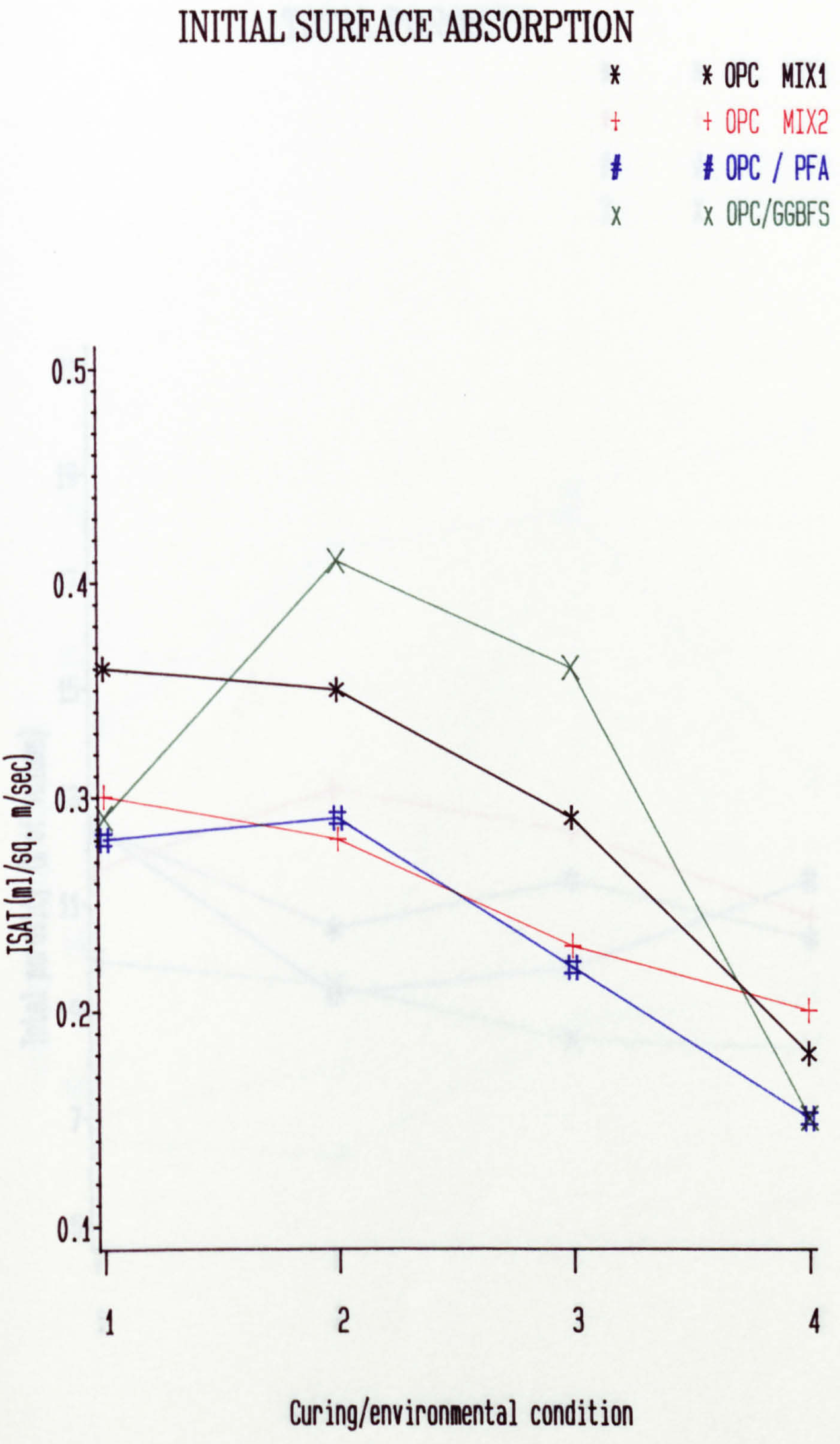


Fig. 4.7 The effects of curing/environmental conditions on the initial surface absorption for the concrete specimens

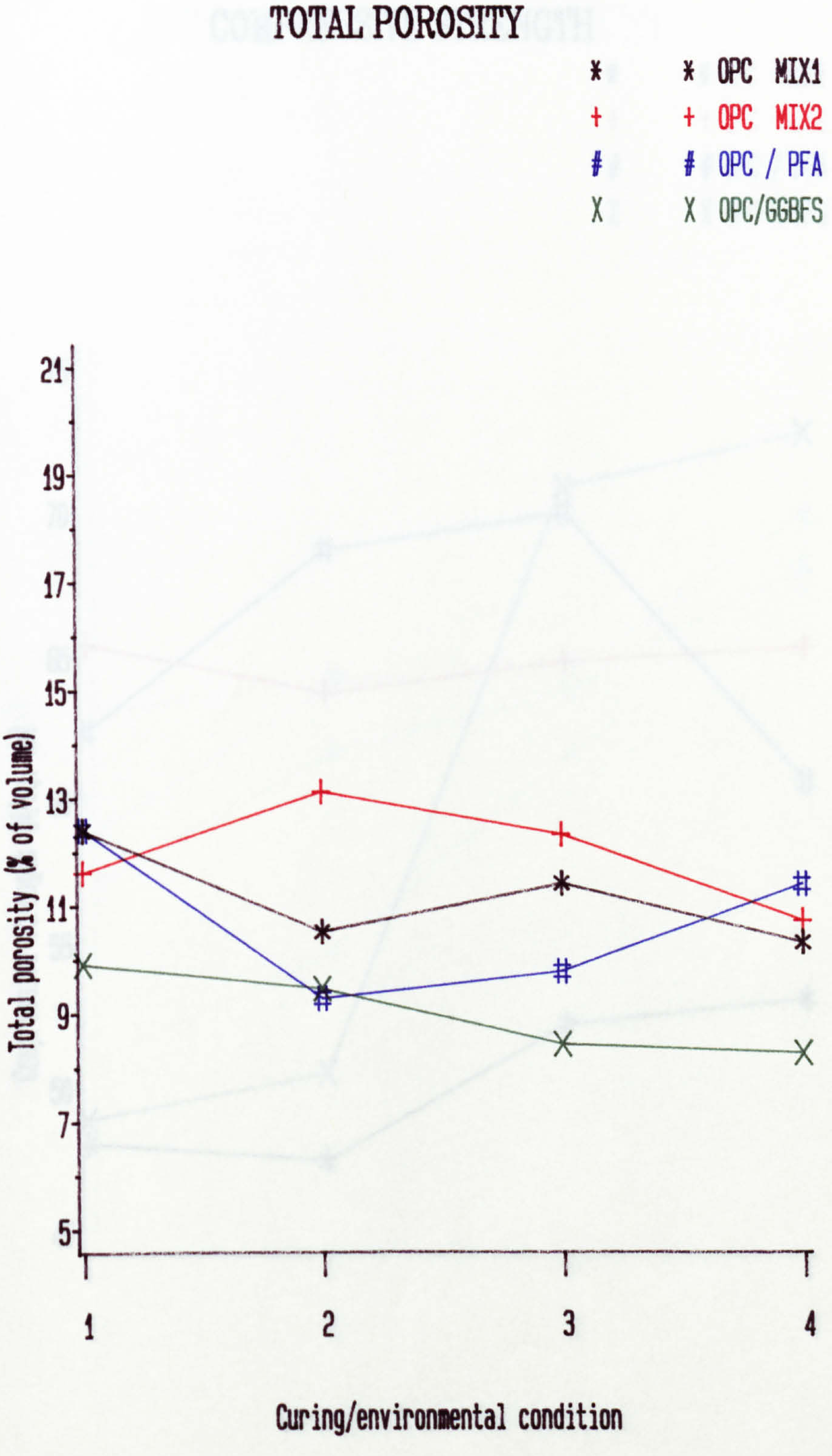


Fig. 4.8 The effects of curing/environmental conditions on the total porosity for the concrete specimens

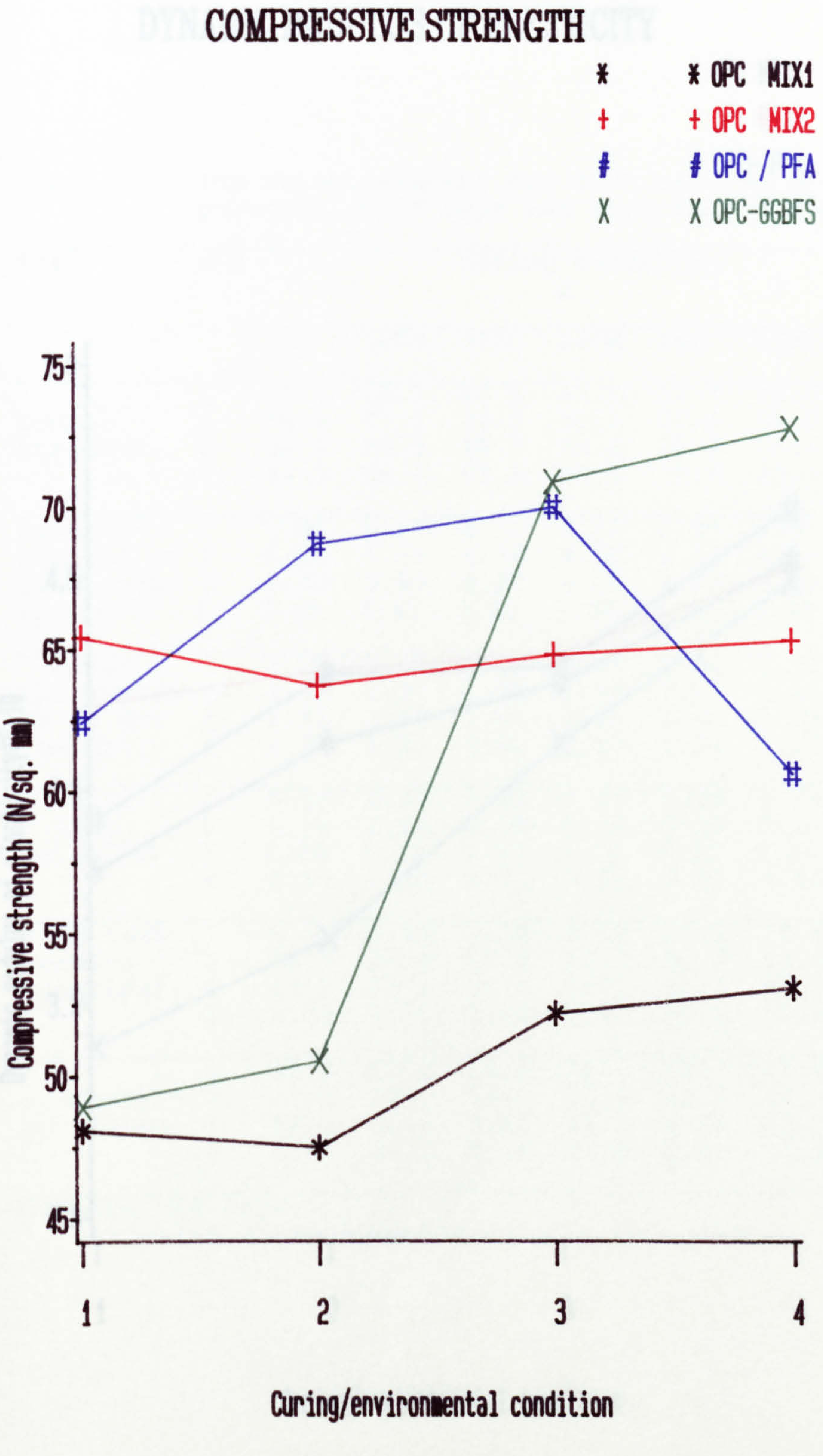


Fig. 4.9 The effects of curing/environmental condition on the compressive strength for the concrete specimens

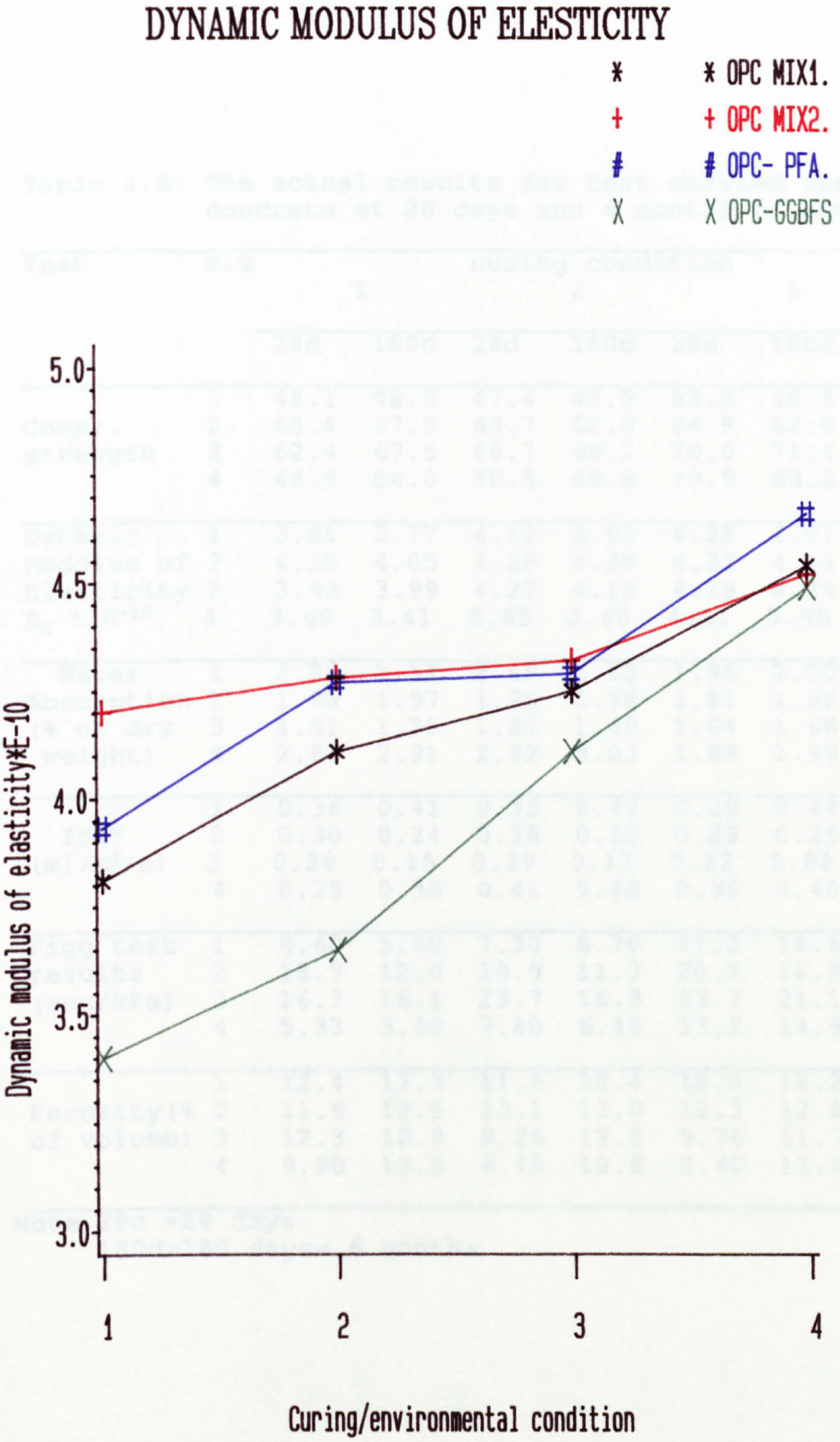


Fig. 4.10 The effects of curing/environmental condition on the dynamic modulus of elasticity for the concrete mixes

Table 4.6: The actual results for test carried out on concrete at 28 days and 6 months of age.

Test	mix	curing condition							
		1		2		3		4	
		28d	180d	28d	180d	28d	180d	28d	180d
Compr. strength	1	48.1	48.0	47.4	42.5	52.2	46.4	53.1	61.1
	2	65.4	67.5	63.7	62.0	64.8	62.0	65.3	75.3
	3	62.4	67.5	68.7	68.2	70.0	71.4	60.6	79.0
	4	48.9	54.8	50.5	49.8	70.9	63.8	72.7	78.6
Dynamic Modolus of Elasticity E_d $*10^{-10}$	1	3.81	3.77	4.11	3.92	4.25	4.01	4.54	4.79
	2	4.20	4.05	4.28	4.38	4.32	4.14	4.52	4.86
	3	3.93	3.99	4.27	4.18	4.29	4.24	4.66	4.96
	4	3.40	3.41	3.65	3.60	4.11	3.95	4.49	4.97
Water Absorption (% of dry weight)	1	2.22	2.31	2.49	2.65	1.96	2.10	1.52	1.32
	2	1.98	1.97	1.95	1.98	1.81	1.85	1.44	1.22
	3	1.81	1.75	1.81	1.80	1.64	1.66	1.05	0.95
	4	2.87	2.91	2.92	3.03	1.89	1.99	1.19	1.05
ISAT ($ml/m^2/s$)	1	0.36	0.41	0.35	0.48	0.29	0.44	0.18	0.10
	2	0.30	0.24	0.28	0.26	0.23	0.25	0.20	0.10
	3	0.28	0.15	0.29	0.11	0.22	0.08	0.15	0.05
	4	0.29	0.30	0.41	0.60	0.36	0.40	0.15	0.14
Figg test results (sec/kPa)	1	6.60	5.80	7.30	8.70	11.2	10.6	20.4	24.8
	2	18.9	12.0	19.9	11.3	20.5	16.0	30.5	38.7
	3	16.3	16.1	23.7	16.9	23.3	21.1	53.3	51.7
	4	5.33	3.60	7.80	6.40	13.2	14.9	36.5	34.8
Porosity(% of volume)	1	12.4	13.3	11.5	12.4	10.4	12.2	10.3	11.6
	2	11.6	12.5	13.1	13.0	12.3	12.2	10.7	11.2
	3	12.3	12.0	9.26	12.5	9.76	11.7	11.3	10.5
	4	9.90	13.8	9.40	12.8	8.40	11.2	8.24	11.2

Note 28d =28 days
180d=180 days= 6 months

Table 4.7: correlation coefficients and levels of significance for linear relations.

	strength	DME	WA	Figg Test	ISAT	porosity	1/WA	1/ISAT
strength	1.0 0.0	.269 .3141	-.392 .1330	.380 .1467	-.444 .085	-.448 .0816	.470 .0663	.568 .0218
DME	.269 .3141	1.0 0.0	-.898 .0001	.785 .0003	-.726 .0014	.004 .9890	.826 .0001	.710 .0021
WA	-.392 .1330	-.898 .0001	1.0 0.0	-.861 .0001	.819 .0001	.051 .8510	-.941 .0001	-.805 .0002
Figg test	.380 .1470	.785 .0003	-.861 .0001	1.0 0.0	-.811 .0001	-.084 .7560	.953 .0001	.859 .0001
ISAT	-.444 .0850	-.726 .0014	-.819 .0001	-.811 .0001	1.0 0.0	.096 .724	-.852 .0001	-.957 .0001
porosity	-.448 .0816	.004 .9890	.051 .8510	-.084 .7560	.096 .7240	1.0 0.0	-.137 .6135	-.202 .453
1/WA	.470 .0663	.826 .0001	-.941 .0001	.953 .0001	-.852 .0001	-.137 .6135	1.0 0.0	.907 .0001
1/ISAT	.568 .0218	.710 .0021	-.805 .0002	.859 .0001	-.957 .0001	-.202 .4530	.907 .0001	1.0 0.0

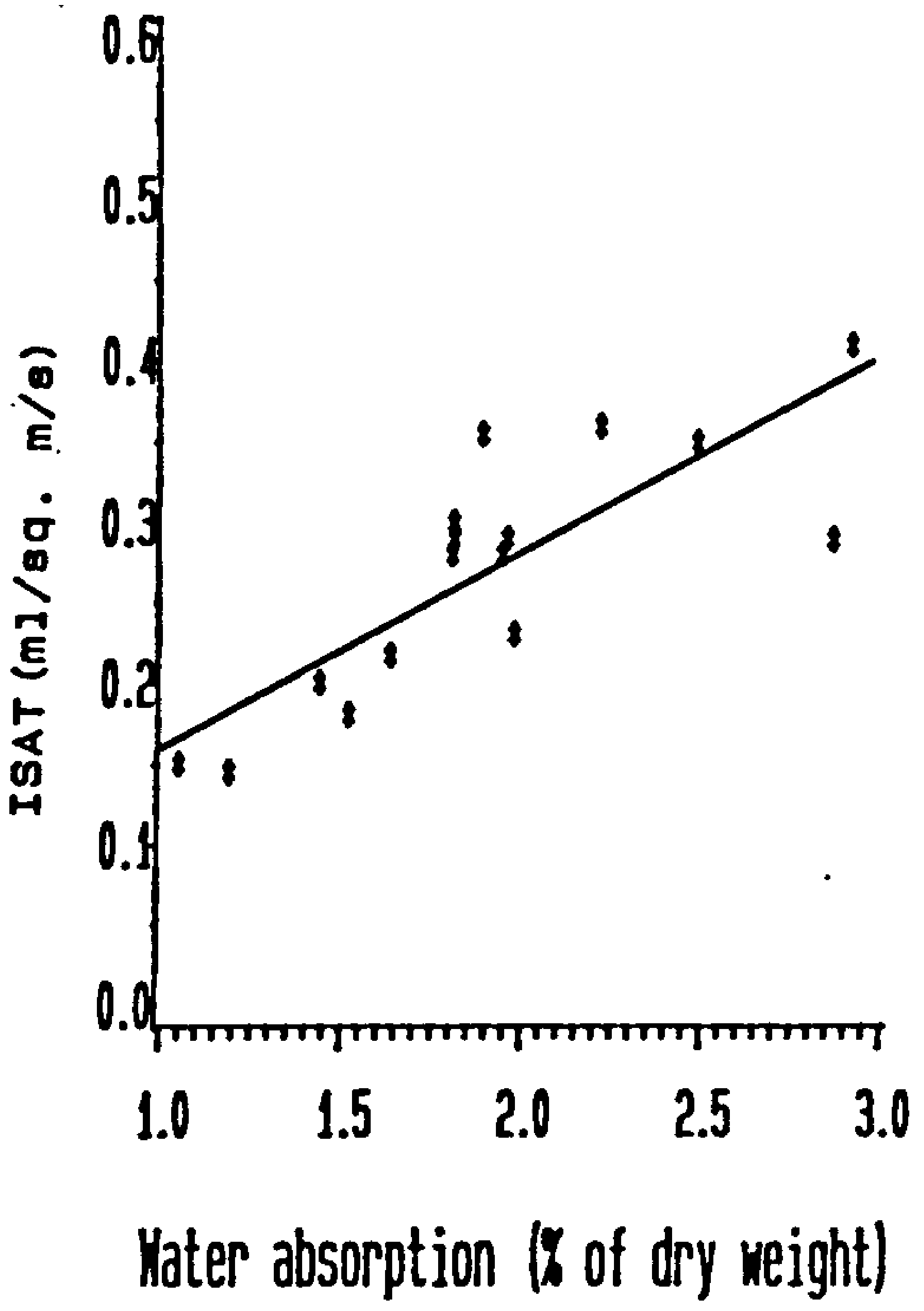


Fig. 4.11

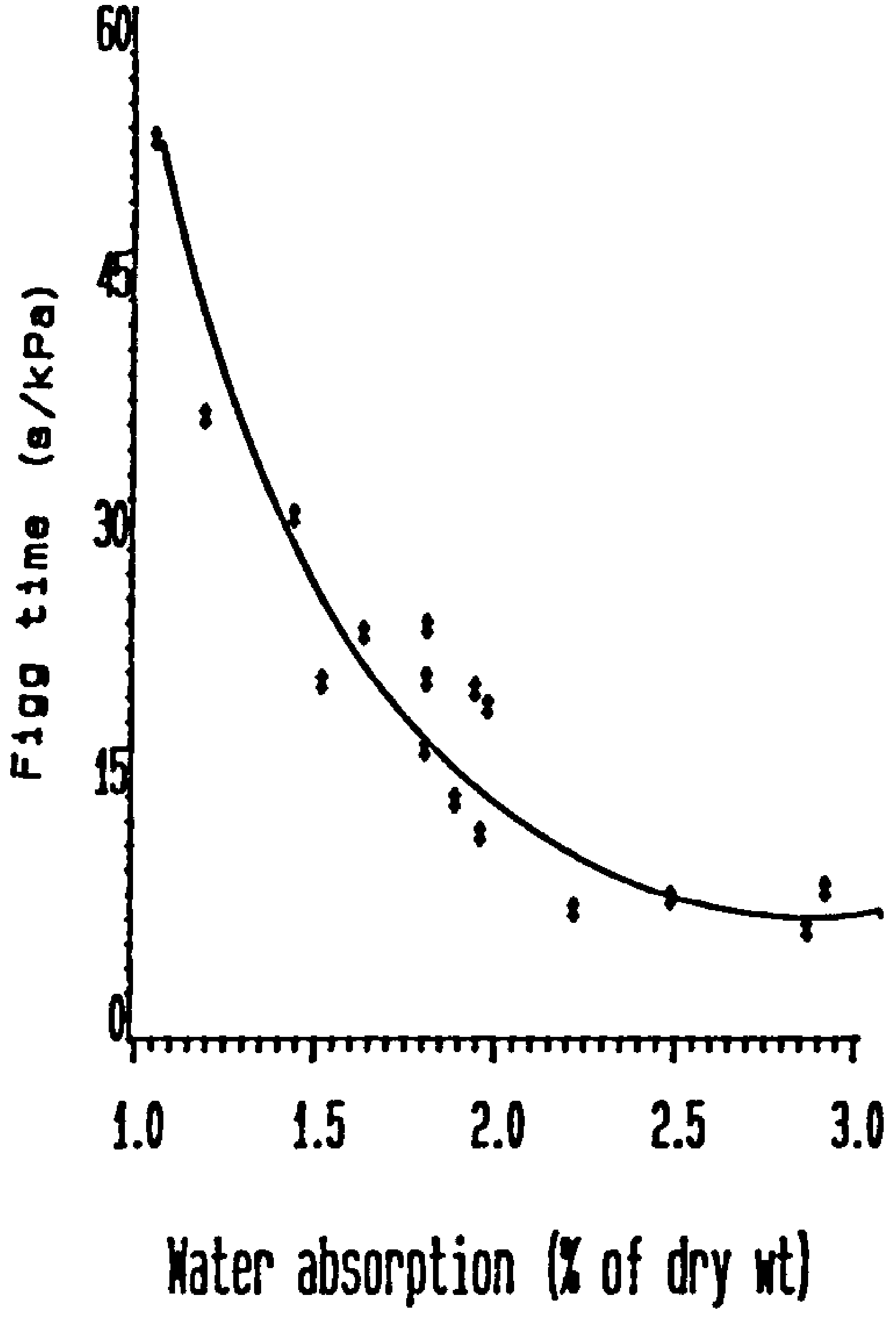


Fig. 4.12

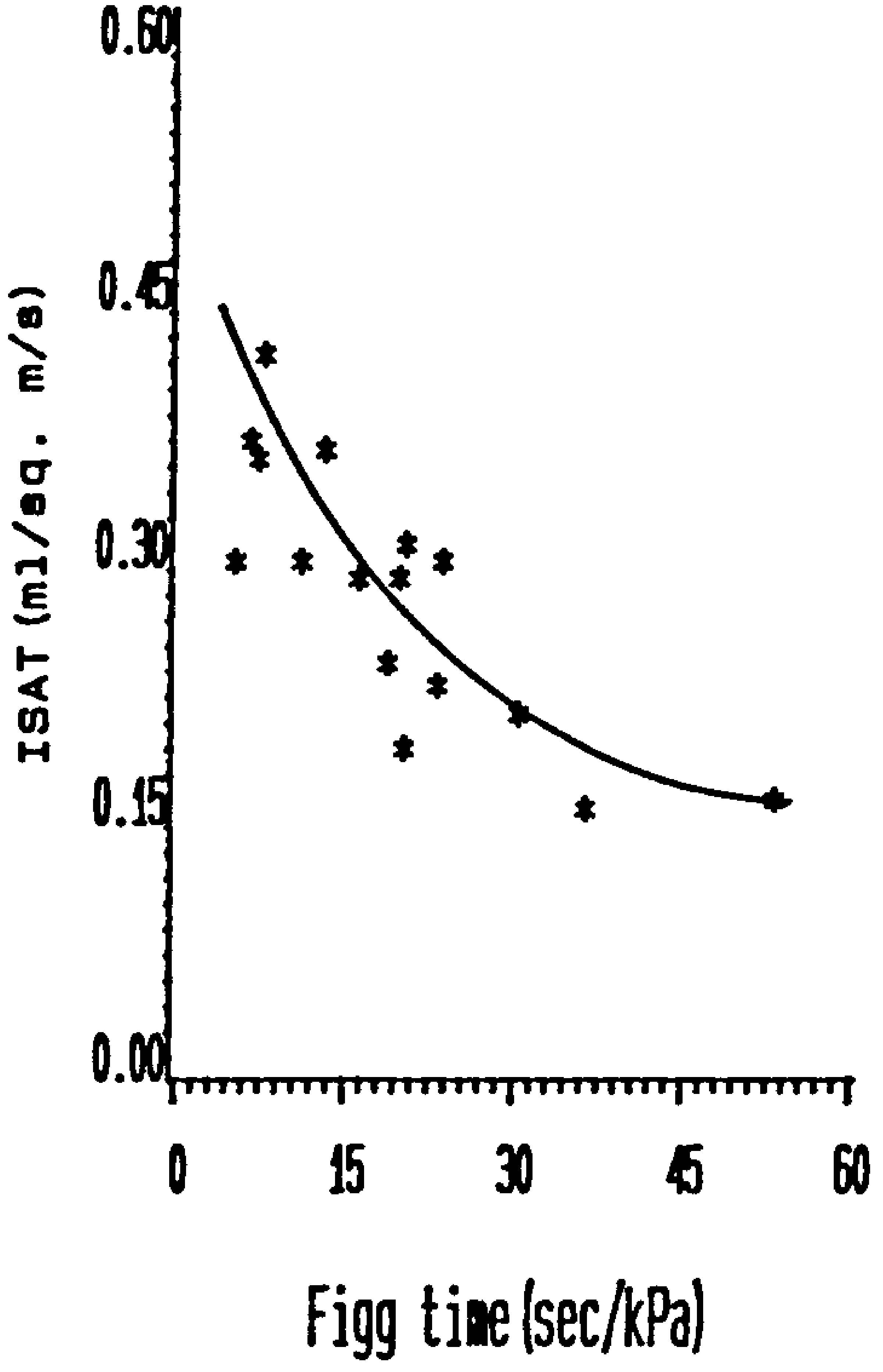


Fig. 4.13

The relationships between water absorption and ISAT, water absorption and Figg test and ISAT and Figg test significant increases in permeability is followed by small increases in absorption.

4.3.5.1.2 - Strength and Durability:

The relationships, on the other hand, between compressive strength and durability tests were, expectedly, insignificant. It is due to the different trends in the results provided by compressive strength test from those by the other tests. Nevertheless, changes in the strength of all mixes were not followed by similar changes in the durability-related tests, see Fig. 4.14, 4.15 and 4.16. Big changes in strength were accompanied by small changes in absorption and permeability and vice versa. That is, a weak concrete is able to produce lower absorption and lower permeability results if cured properly than uncured samples of significantly stronger concrete.

4.3.5.2 - The effects of Curing/Environmental Conditions:

1 - Durability- Related properties:

The general trend of curing and environmental condition effects on the durability tests conducted on concrete is similar to that seen with mortar. Improving the curing conditions effectively produced better concrete, e.g. curing for 2 more days showed relatively a similar improvement to that seen earlier with mortar.

2 - Strength

The different curing and environmental conditions had little effect on the strength of OPC concretes. The sensitivity, however, of the two mixes containing cement replacement materials was bigger than that of plain OPC especially when 60% of ggbs was used. It was however interesting to see that continuously cured OPC/pfa samples at 20°C were weaker than those kept in the other conditions despite the lower relative humidity. Apparently the pozzolanic reactions of the pfa were accelerated significantly by the higher temperatures.

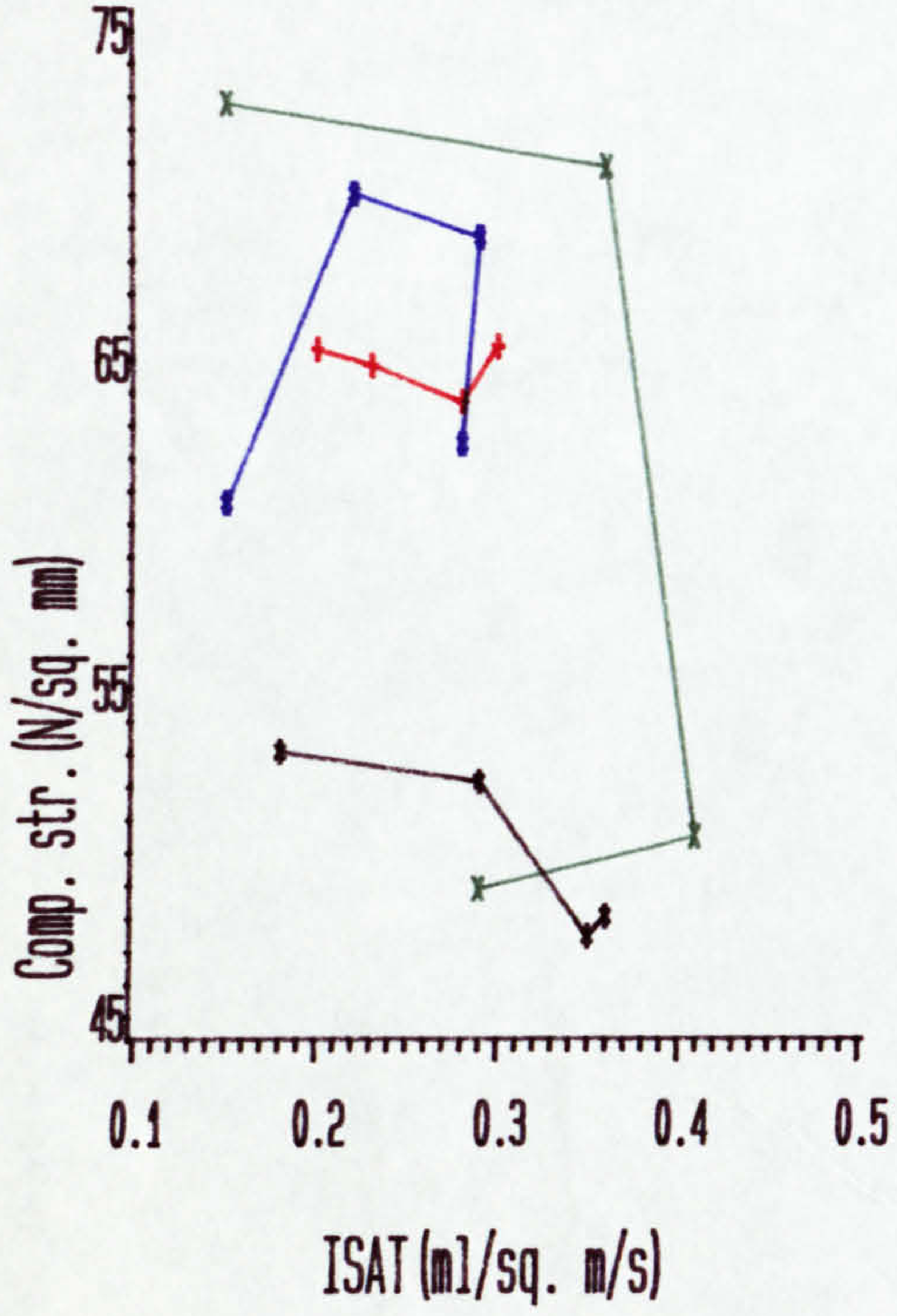


Fig. 4.14

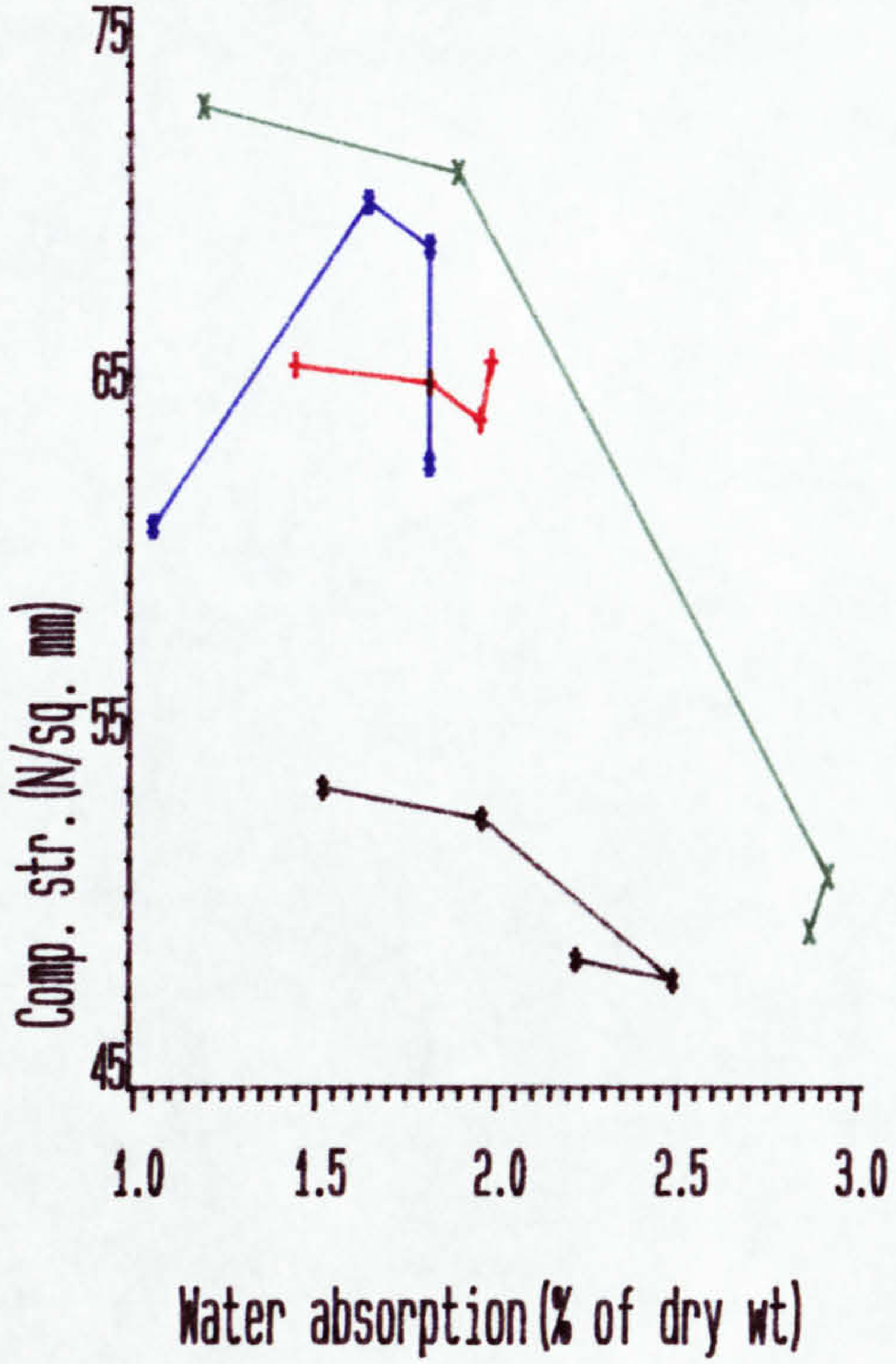


FIG. 4.15

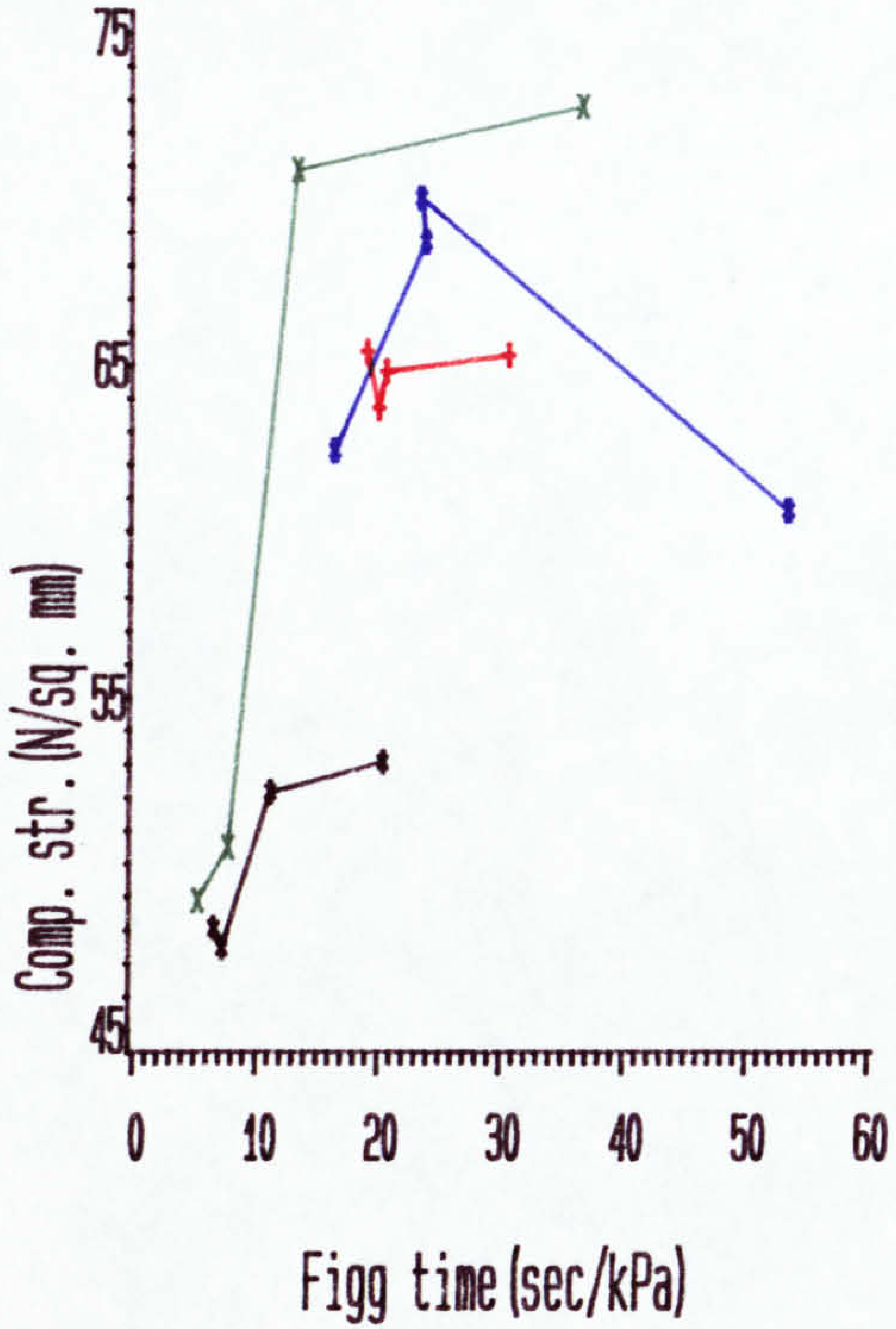


FIG. 4.16

The relationships between compressive strength and either ISAT, water absorption and Figg test

*** OPC mix1 +++ OPC mix2 ### OPC/pfa xxx OPC/ggbs

4.3.5.3 - The Effects of OPC Content:

Increasing the cement content or water/cement ratio of the mortar mixes while keeping the other parameters constant resulted in higher absorption and permeability values. However, for constant workability concretes, increasing the cement content gave better concrete specimens from absorption, permeability and compressive strength points of view despite the higher porosity results. This shows that water absorption and permeability of concrete mixes are controlled by the quality of the pore structure rather than the total pore volume.

4.3.5.4 - The Effects of Cement Type:

1 - Durability - Related Properties:

The effects of the pfa and ggbs on the durability properties of the concrete mixes are in line with those of the mortars.

2 - Strength

The use of pfa to replace 30% of the OPC resulted in similar results to those of mix 2 for oven-cured samples but weaker samples when storing at 20°C+100%RH. This shows that the effect of the high temperature of 50°C on strength on the pfa samples is more significant than that of 100%RH at 20°C after 28 days of age. On the other hand, pfa produced stronger samples than the OPC mix 2 at conditions 2 and 3. Eventually, the combination of the high temperature of 40°C and the 60%RH is more effective than either the oven at 50°C or the 100%RH at 20°C interms of compressive strength.

Due to the lack of curing time in conditions 1 and 2, high temperatures and the high level of OPC replacement, the slag samples were about 30% weaker than OPC mix 2. However, curing for 2 more days in the 40°C room was seen to be sufficient to trigger the hydration reaction to a level resulting in significantly stronger samples than those of mix 2. In addition to this, slag specimens stored at

20°C+100%RH were stronger than the plain OPC or OPC/pfa samples when similarly cured.

4.3.5.5 - The effects of Age

The previous six tests performed on the concrete mixes at 28 days of age were also carried out at 6 months. Samples tested were from the same batch as those tested at 28 days. As expected, continuously cured samples of all mixes showed significant increase in strength and significant reductions in the results of ISAT and water absorption with age. Nonetheless, continuous curing for six months was ineffective in reducing the relative air permeability significantly as measured by Figg's method, see Table 4.6.

The results of those samples kept in the 50°C oven were practically unchanged as measured by all tests. Nevertheless, the behaviour of OPC mix 1 and of the OPC/slag mix in the 40°C+60%RH chamber, i.e. conditions 2 and 3, showed slight reduction in the strength and the dynamic modulus of elasticity and significant increase in the water absorption and ISAT results. On the other hand, the OPC mix 2 and the OPC/pfa mix were the least affected by the 40°C+60%RH in which the results of all tests were statistically similar to those found at 28 days of age except for the ISAT values of the pfa mix which were even lower.

Despite the slight reduction in the quality of some concrete mixes at 40°C+60%RH when comparing the 6 months results to those found at 28 days of age, the general trend is found to be the same. The trends found at 28 days were found to hold true at 6 months.

4.4 - Guidelines for the Primary Investigations:

4.41 - Curing Environments:

As was the case with mortar, curing/ environmental conditions had measurable effects on the durability properties and strength of OPC, OPC/pfa and

OPC/slag concretes. It was encouraging therefore to carry out a preliminary study of the effects of curing environments and curing lengths on some durability-related properties and strength of cement mixes. From these initial investigations, it was recommended to simulate moderate, hot and very hot environments (similar to those found in actual life) as follows:

1 - 20°C + 70%RH (i.e. normal;
2 - 35°C + 70%RH (i.e. hot) and
3 - 45°C + 30%RH (i.e. extremely hot).

4.4.2 - Mix Proportions and Cement Type

Concretes with higher cement content were seen to be superior to those of low cement content in terms of strength and durability-related properties if designed at the same workability. In addition to this, some researchers (5) have suggested that the addition of about 10% more water to compensate for evaporation has no apparent influence on strength. This point requires further investigation and its effects on durability need to be evaluated.

The inclusion of pfa or ggbs showed interesting behaviour in hot environments. Incorporating pfa and slag in this research is therefore seen to be of great significance especially when these materials are being used in many hot countries.

4.4.3 - Summary of Tests:

A further evaluation of the influence of curing environments and curing duration on the pore structure of an OPC, OPC/pfa and OPC/ggbs mixes is seen to be essential for the development of this research. Steady-state permeability and water absorption tests along with a study of the pore structure by the mercury intrusion porosimeter (MIP) are considered to be important to perform, in order to identify how they are related. Mortar mixes were used in this part because the MIP results are known to be more repeatable and more accurate than for concrete samples.

The cube strength test was seen to be able to distinguish between the two OPC mixes but not between the different curing/environmental conditions. However the durability- related tests(i.e. ISAT, water absorption and Figg test) showed the opposite. Therefore, for the concrete specimens compressive strength as well as some durability -related tests are seen to be essential if both of the mix proportions and curing programme are to be verified.

4.4.4 - Age of Testing

The major trends in the results found at 6 months of age were seen to be similar to those found at 28 days of age. Therefore, testing either concrete or mortar samples in the primary investigations will be carried out at 28 days of age only.

CHAPTER FIVE

POROSITY AND PORE STRUCTURE, PERMEABILITY AND WATER ABSORPTIONS OF OPC, OPC/PFA AND OPC/GGBS MORTARS

5.1 - Introduction:

The main purpose of the work reported in this chapter was to investigate the effects of curing environments and duration of curing on the durability of mortars made from OPC and combinations of OPC/pfa and OPC/ggbs. Durability was assessed using a variety of tests including: mercury intrusion porosimetry(MIP), permeability to oxygen (using the cell described in Chapter 3), and helium pycnometry for total porosity measurement. The portable air permeability test (see section 3.3.9) was also carried out on the same samples tested for oxygen permeability. In addition to this, a simple test for water absorption was also carried out to see whether such a test could be used successfully to assess the quality of mortars in the same way as MIP and permeability. In the light of the results, a discussion is presented covering the following:

1 - relationships between the results of the pore structure and those of the permeability and water absorption tests;

2 - statistical and mathematical analyses of the relationship between the oxygen permeability and the portable air permeability results.

3 - evaluation of the effects of curing duration on the different durability related properties.

4 - explanation of the way in which hot environments affect the properties of mortars and how this behaviour is affected by the inclusion of pfa or ggbs.

5.2 - Mix Proportions:

The mortar mixes used in this part of the investigations were made from OPC and blends of OPC/pfa and OPC/ggbs. Details of the mix proportions are given in Table 5.1.

Mixing was performed as described in Chapter 3 and with each mix cast the following test specimens were prepared:

1 - Ten 50mm cubes for the assessment of permeability;

2 - Ten 50mm cubes for the test for water absorption. At the appropriate age, these specimens were then cored, sliced and prepared following the procedure described in Chapter 3 for the measurement of the total porosity using the helium pycnometer.

3 - Ten 50mm cubes for the evaluation of pore size distribution.

5.3 - Curing and Environmental Conditions:

Three different environments were chosen, two to simulate Middle Eastern conditions and one less aggressive more temperate environment, details are given in Table 5.2,

In an attempt to control the mix temperatures as close as possible to that of the curing environments, all materials were stored at the respective environmental temperature for one week before casting. Because of size limitations of the environmental room, all casting had to be carried out in the laboratory at 20°C ± 2°C. However, immediately after casting, specimens were returned to their respective environments. The initial temperatures of the mortar mixes at casting are shown in Table 5.3.

The samples were demoulded at an age of one day and all sides, except the top-as-cast face, were covered to the day of testing using polythene sheet sealed with cellotape. With the exception of those samples to be kept in an uncured condi-

Table 5.1: Mortar mix proportions(by weight)

mix	OPC	pfa	slag	sand	water
1	1	0	0	2.3	0.45
2	0.7	0.3	0	2.3	0.45
3	0.4	0	0.6	2.3	0.45

Table 5.2: Details of curing environments

Environment	Description
1	20°C ±2°C + 70%RH ± 5%RH
2	35°C ±2°C + 70%RH ± 5%RH
3	45°C ±2°C + 30%RH ± 5%RH

Table 5.3: The Initial mix temperatures of the mortar mixes.

mix	environment	
	35°C+70%RH	45°C+30%RH
1	29°C	38°C
2	30°C	37°C
3	29°C	37°C

tion, the top-as-cast faces of all specimens were covered immediately after casting with polythene sheet. Wet hessian was applied at approximately 6 hours of age and was kept wet throughout the curing period. Curing durations were divided into five categories; uncured, one-day, three-day, seven-day and continuous curing.

5.4 - Tests Carried Out:

The five tests used to assess the influence of curing duration and environments were:

1 - mercury intrusion porosimetry (MIP),
2 - total porosity by the helium pycnometry method,
3 - oxygen permeability;
4 - water absorption; and
5 - the portable air permeability.

Tests were performed when specimens were 28 days old following the procedures described in Chapter 3.

5.5 - Results:

5.5.1 - Porosity and Pore Structure:

5.5.1.1 - Total Porosity by Helium Pycnometry:

Fig. 5.1 illustrates the effect of curing duration, environment and cementitious materials on the total porosity of the three mixes as measured by helium pycnometry. The statistical analysis performed on the results showed that this test was repeatable to within 5% for a 95% level of confidence.

Increasing the curing duration resulted in a reduction in the porosity of all mixes in all environments.

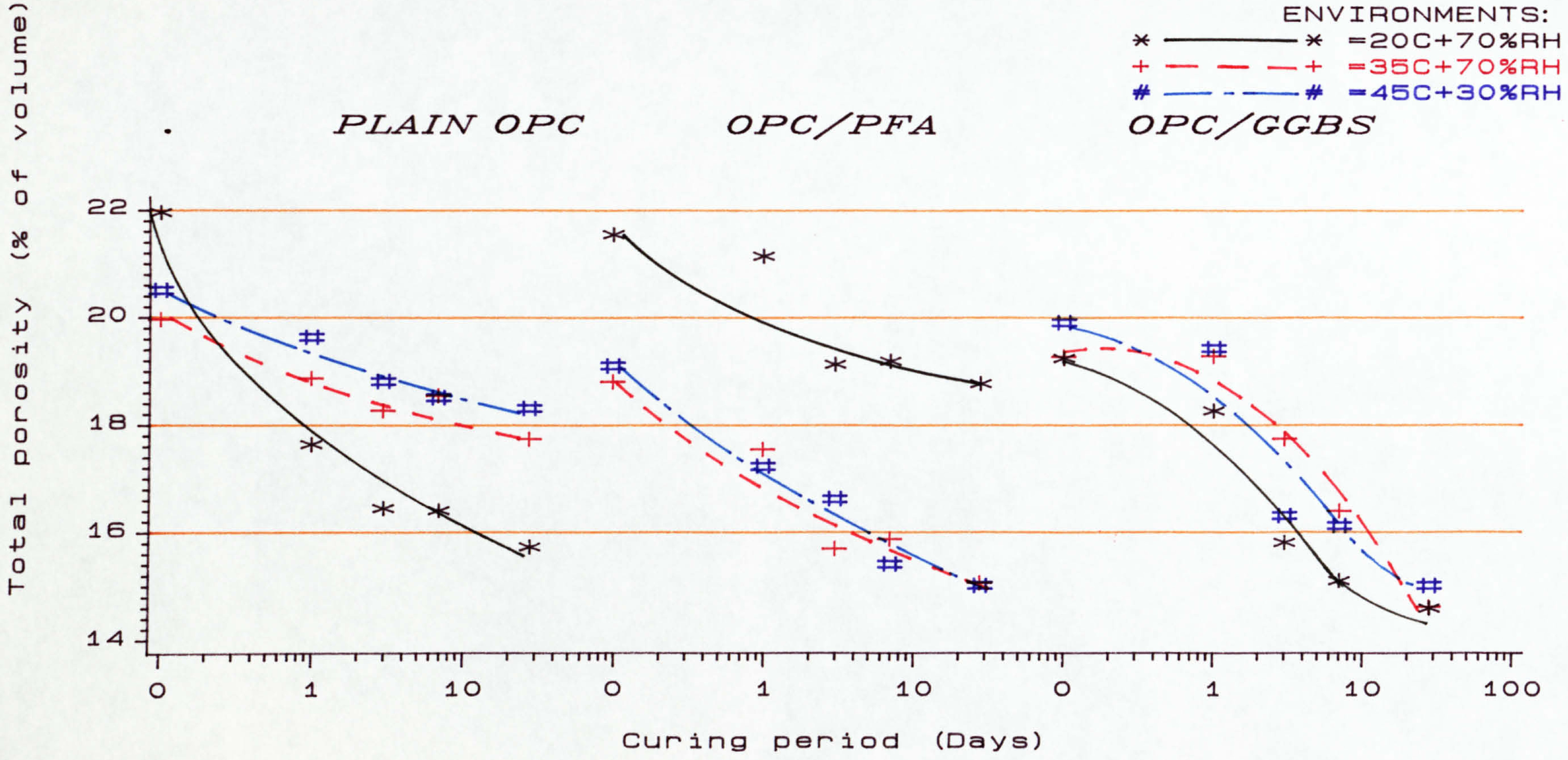


FIG. (5.1) The effects of curing period and environment on the total porosity as measured by the helium method (Tests carried out at 28 days of age)

Hotter environments than 20°C increased the porosity for those plain OPC mixes which were cured for a period of one day or more. However in contrast, the total porosities of the OPC/pfa samples were seen to be lowered by hotter environments, i.e. 35°C+70%RH and 45°C+30%RH as opposed to 20°C+70%RH. In spite of this, the porosities of the pfa samples stored in the two hot environments were not significantly different from each other. It is interesting however to see that for a given curing period the results of the OPC/ggbs specimens were similar in all environments, as seen in Fig. 5.1.

For any given curing period, with the exception of uncured samples, the porosities of the OPC/pfa samples were higher than those of plain OPC at 20°C+70%RH but were generally lower in the other two environments. The OPC/slag samples produced lower porosity results than the plain OPC samples at 35 and 45°C but were generally similar at 20°C+70%RH. A comparison of the two mixes containing cement replacement materials shows that the porosities of OPC/ggbs samples were lower than those of pfa at 20°C+70%RH but were generally similar in the other two environments.

5.1.2 - Mercury Porosimetry Analysis:

Using mercury intrusion porosimetry it is possible to calculate several parameters that can be used to explain characteristics related to the pore structure of hydrated cement pastes. These parameters, which are calculated from the pore size distribution by the use of pore volume and pore surface area, are as follows:

1 - pore surface area (PSA);
2 - median pore diameter by pore volume (MPD-V);
3 - average pore diameter (APD);
4 - median pore diameter by pore surface area (MPD-A); and
5 - total porosity.

A full description of the above parameters is given in Chapter 3. However, because of the difficulty involved in trying to discuss the results in terms of the pore size distribution, it is proposed to show the general trends by means of the pore surface area (PSA) and median pore diameter by volume (MPD-V) and substantiate the more important trends by selected pore size distribution curves. Pore surface area (PSA) is, as explained previously, a parameter related to the volume and sizes of pores. For example, at constant total porosity, the bigger the PSA the greater the number of smaller pores. On the other hand, the median pore diameter by volume relates to the relative volume of smaller pores in the cement matrix,i.e. the greater the MPD-V , the greater the volume of larger pores.

The actual results of all of the above parameters are given in Tables 5.4-5.6. The results which will be used in the discussion of the pore structure are shown in Figs. 5.2- 5.10. The statistical analyses performed on the MIP results shows that the median pore diameter and the pore surface area are repeatable to within 10% for a 90% level of confidence.

- The Effect of Curing Duration:

The effects of curing duration on the pore structure of all mixes were similar to those on total porosity; longer curing periods resulted in finer pore structures as shown by the increase in PSA (Fig. 5.2), the reduction in MPD-V (Fig. 5.3) and the decrease in the volume of bigger pores (Figs. 5.4 to 5.6).

-The Effect of Curing Environment:

Environments hotter than 20°C+70%RH were seen to adversely affect the pore structure of uncured samples of all mixes, see Fig. 5.7.

The hotter environments of 35°C+70%RH and 45°C+30%RH produced a lower PSA for the OPC mix than that achieved at 20°C+70%RH at all curing periods. This infers either a larger number of larger pores or smaller number of smaller ones or both.

Table 5.4: The actual pore structure results as measured by MIP for the plain OPC mix in the three environments.

Environment	Porosity (% of vol)	PSA	MPD-V	MPD-A	APD	curing period (days)
20°C+70%RH	14.700	8.8911	0.1824	0.0056	0.0356	0
	14.950	12.483	0.1457	0.0052	0.0305	1
	15.000	10.341	0.1107	0.0054	0.0297	3
	13.900	10.411	0.1063	0.0055	0.0290	7
	14.300	12.945	0.0906	0.0066	0.0254	28
35°C+70%RH	17.900	5.2277	0.2734	0.0175	0.0683	0
	17.900	6.3422	0.1153	0.0293	0.0571	1
	18.000	7.1388	0.1075	0.0264	0.0526	3
	17.000	6.6259	0.1060	0.0328	0.0543	7
	18.700	6.8615	0.1063	0.0418	0.0584	28
45°C+30%RH	16.700	3.8280	0.3498	0.0339	0.0847	0
	17.600	4.4586	0.2073	0.0350	0.0781	1
	17.500	7.0096	0.1350	0.0201	0.0500	3
	16.900	7.7355	0.1098	0.0183	0.0452	7
	15.400	8.8334	0.0947	0.0146	0.0368	28

PSA = pore surface area (m^2/g)
MPD-V = median pore diameter by pore volume (µm)
MPD-A = median pore diameter by pore surface area (µm)
APD = average pore diameter (µm)

Table 5.5: The actual pore structure results as measured by MIP for the OPC/pfa mix in the three environments.

Environment	Porosity (% of vol)	PSA	MPD-V	MPD-A	APD	curing period (days)
20°C+70%RH	16.100	4.7345	0.1717	0.0255	0.0673	0
	16.300	5.7723	0.1232	0.0210	0.0569	1
	15.600	4.8901	0.0991	0.0522	0.0643	3
	15.800	5.9094	0.1071	0.0312	0.0536	7
	15.000	6.6651	0.1013	0.0233	0.0474	28
35°C+70%RH	15.200	10.815	0.1845	0.0060	0.0318	0
	15.100	12.602	0.1578	0.0050	0.0277	1
	14.400	10.753	0.1194	0.0063	0.0302	3
	15.000	13.968	0.1075	0.0052	0.0245	7
	14.400	14.816	0.0909	0.0051	0.0224	28
45°C+30%RH	13.600	9.9359	0.3058	0.0045	0.0295	0
	12.400	17.927	0.0488	0.0056	0.0170	1
	11.600	21.008	0.0449	0.0052	0.0144	3
	12.258	18.363	0.0478	0.0055	0.0165	7
	9.6000	24.497	0.0316	0.0049	0.0117	28

PSA = pore surface area (m^2/g)
MPD-V = median pore diameter by pore volume (μm)
MPD-A = median pore diameter by pore surface area (μm)
APD = average pore diameter (μm)

Table 5.6: The actual pore structure results as measured by MIP for the OPC/ggbs mix in the three environments.

Environment	Porosity (% of vol)	PSA	MPD-V	MPD-A	APD	curing period (days)
20°C+70%RH	14.600	4.6547	0.5007	0.0093	0.0651	0
	13.200	7.3345	0.3505	0.0048	0.0380	1
	10.800	9.1866	0.1907	0.0049	0.0272	3
	11.300	11.984	0.1554	0.0042	0.0217	7
	10.400	11.893	0.1366	0.0042	0.0205	28
35°C+30%RH	15.100	6.0242	0.5980	0.0062	0.0553	0
	14.100	10.431	0.3394	0.0043	0.0300	1
	13.200	10.516	0.3011	0.0041	0.0303	3
	14.700	10.179	0.3097	0.0044	0.0319	7
	12.400	11.189	0.1801	0.0043	0.0248	28
45°C+30%RH	15.600	3.1034	1.1808	0.0086	0.0991	0
	11.110	14.685	0.1353	0.0041	0.0182	1
	10.700	13.702	0.1091	0.0041	0.0185	3
	10.400	5.9616	0.1270	0.0012	0.0370	7
	11.000	15.189	0.1031	0.0042	0.0177	28

PSA = pore surface area (m^2/g)
MPD-V = median pore diameter by pore volume (μm)
MPD-A = median pore diameter by pore surface area (μm)
APD = average pore diameter (μm)

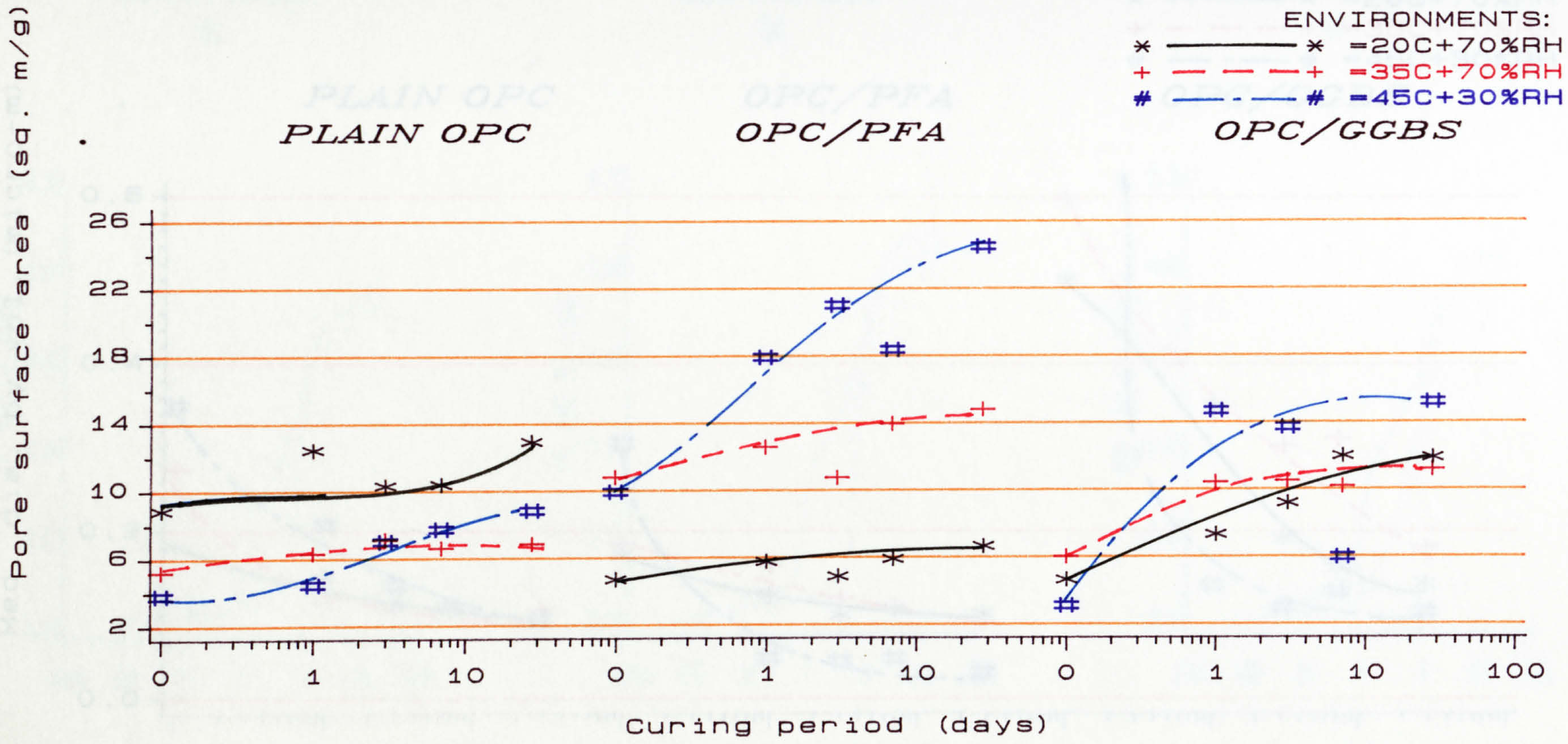


FIG. (5.2) The effects of curing period and environment on the pore surface area (sq. m/g)
(Tests carried out at 28 days of age)

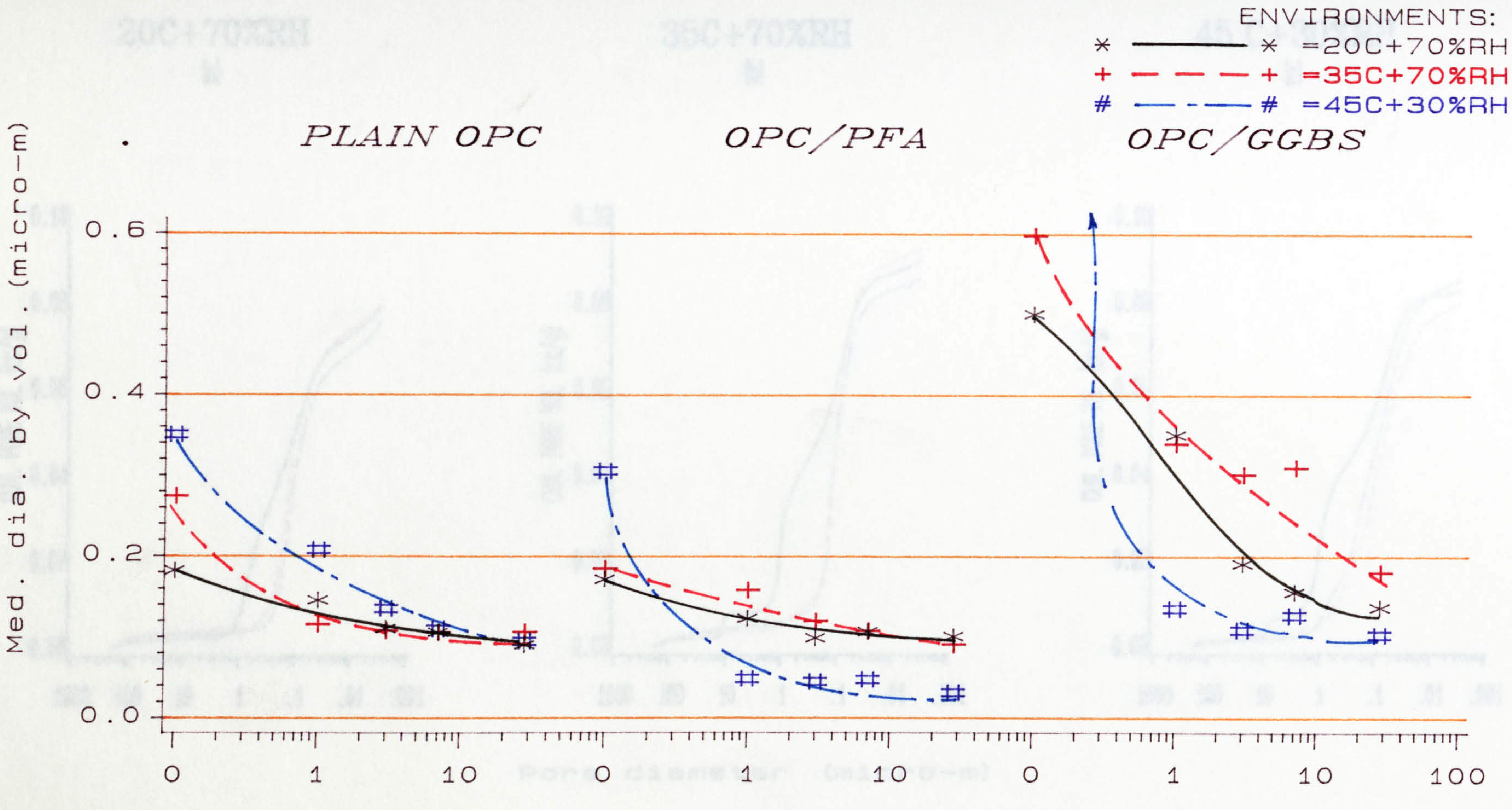


FIG. (5.3) The effects of curing period and environment on the median pore diameter by volume (Tests carried out at 28 days of age)

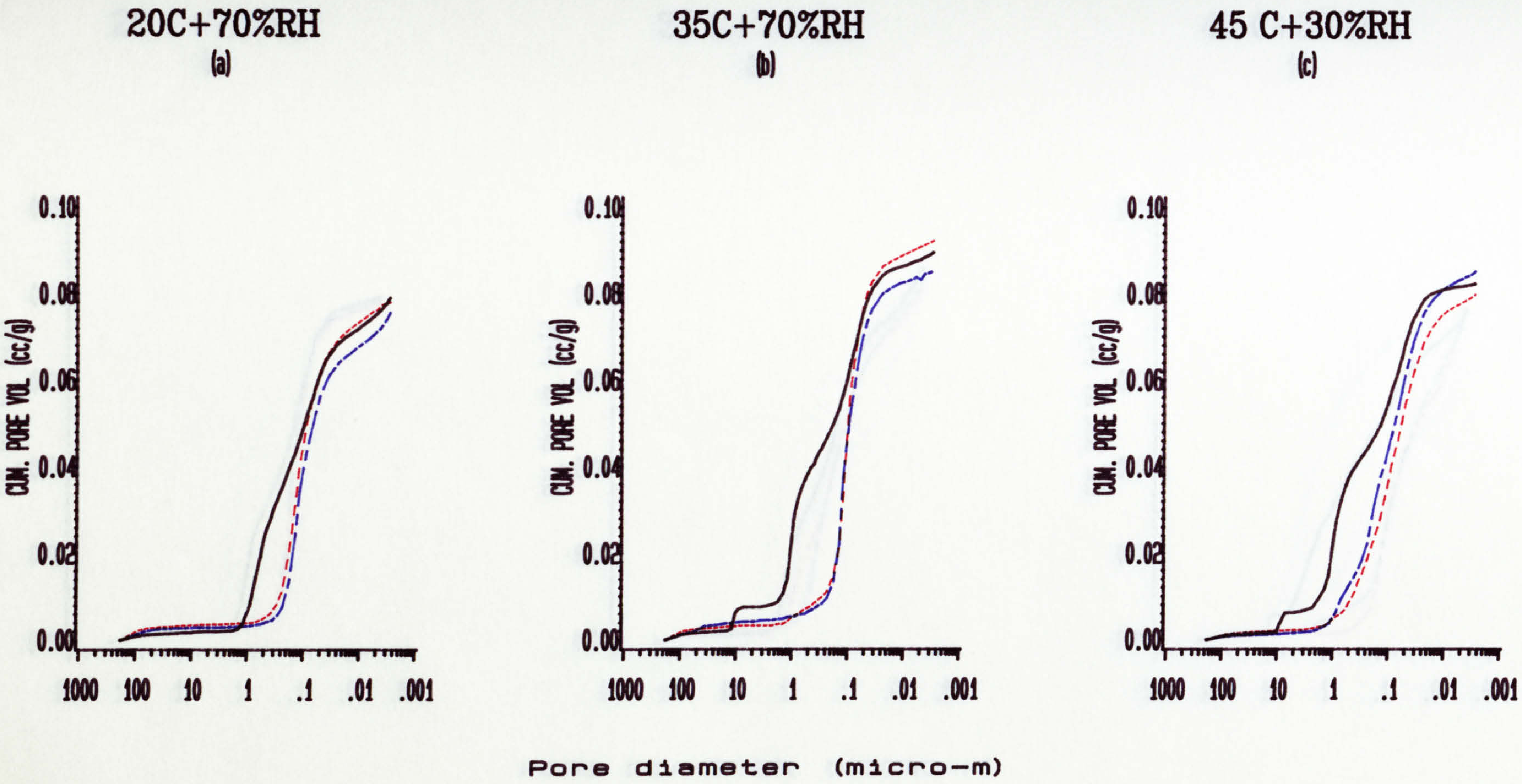


Fig. (5.4) The effects of curing period on the pore size distribution of ordinary Portland cement

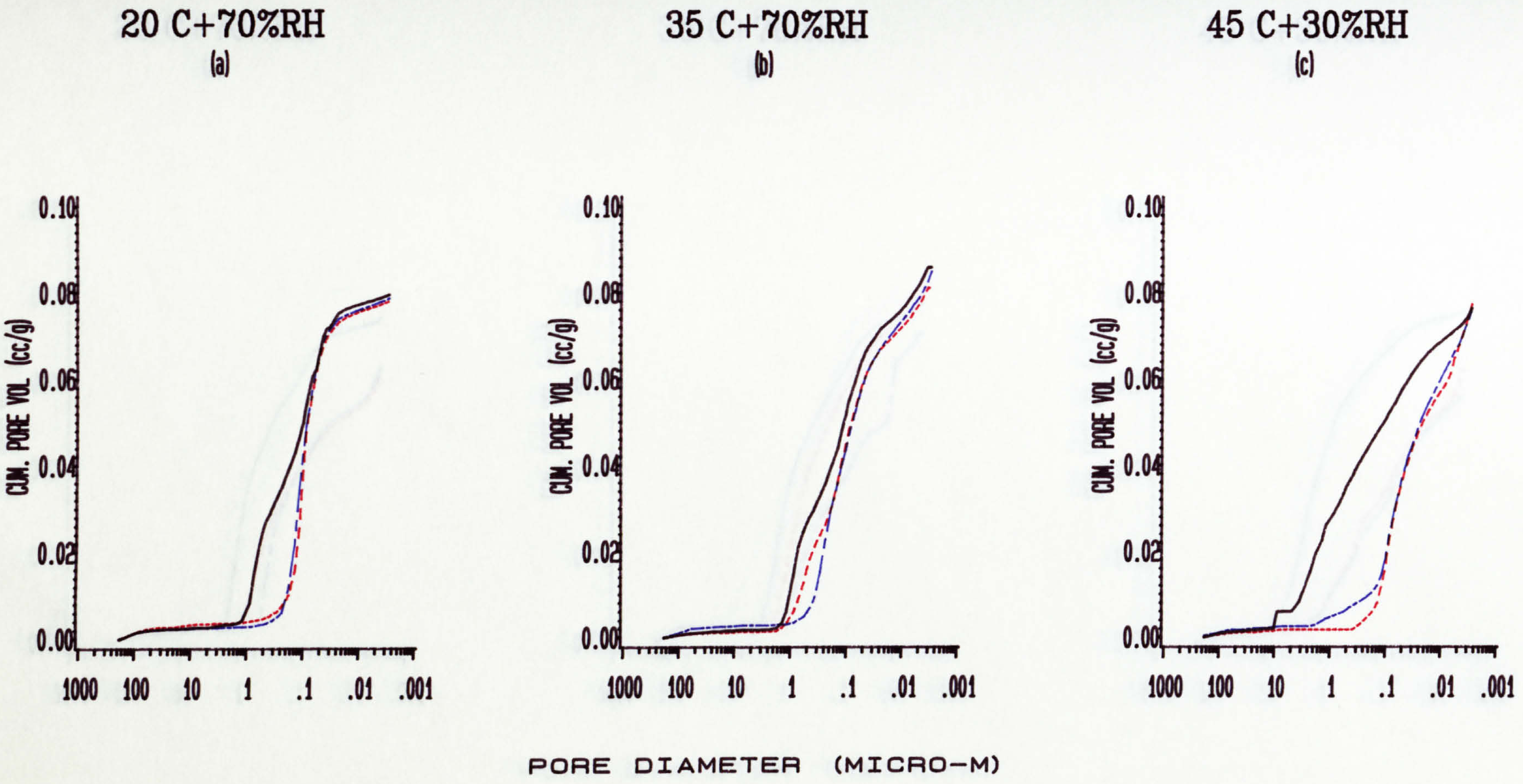


Fig. (5.5) The effects of curing lengths on the pore size distribution of ordinary Portland cement/fly ash mortars

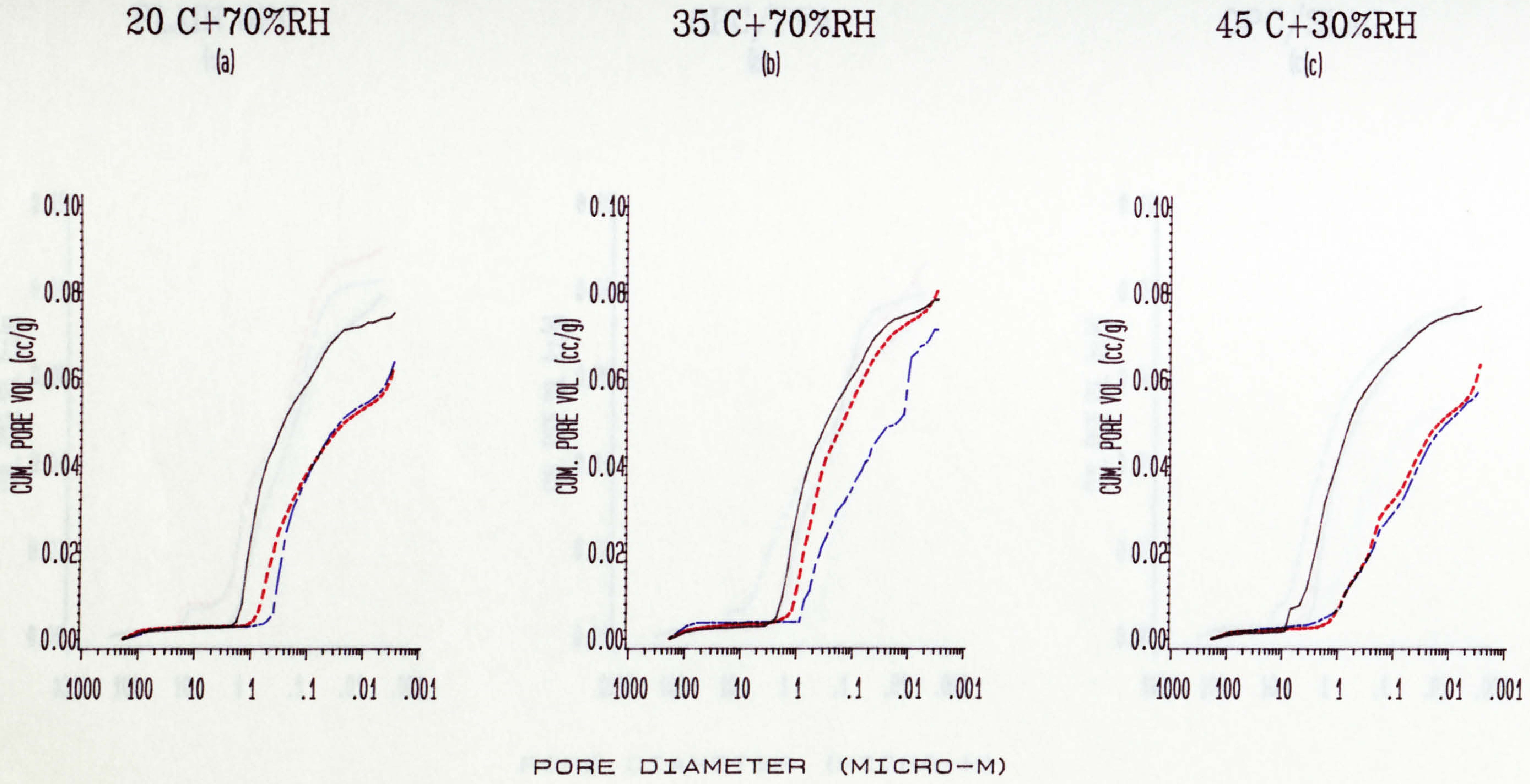


Fig. (5.6) The effects of curing lengths on the pore size distribution of ordinary Portland cement/slag mortars

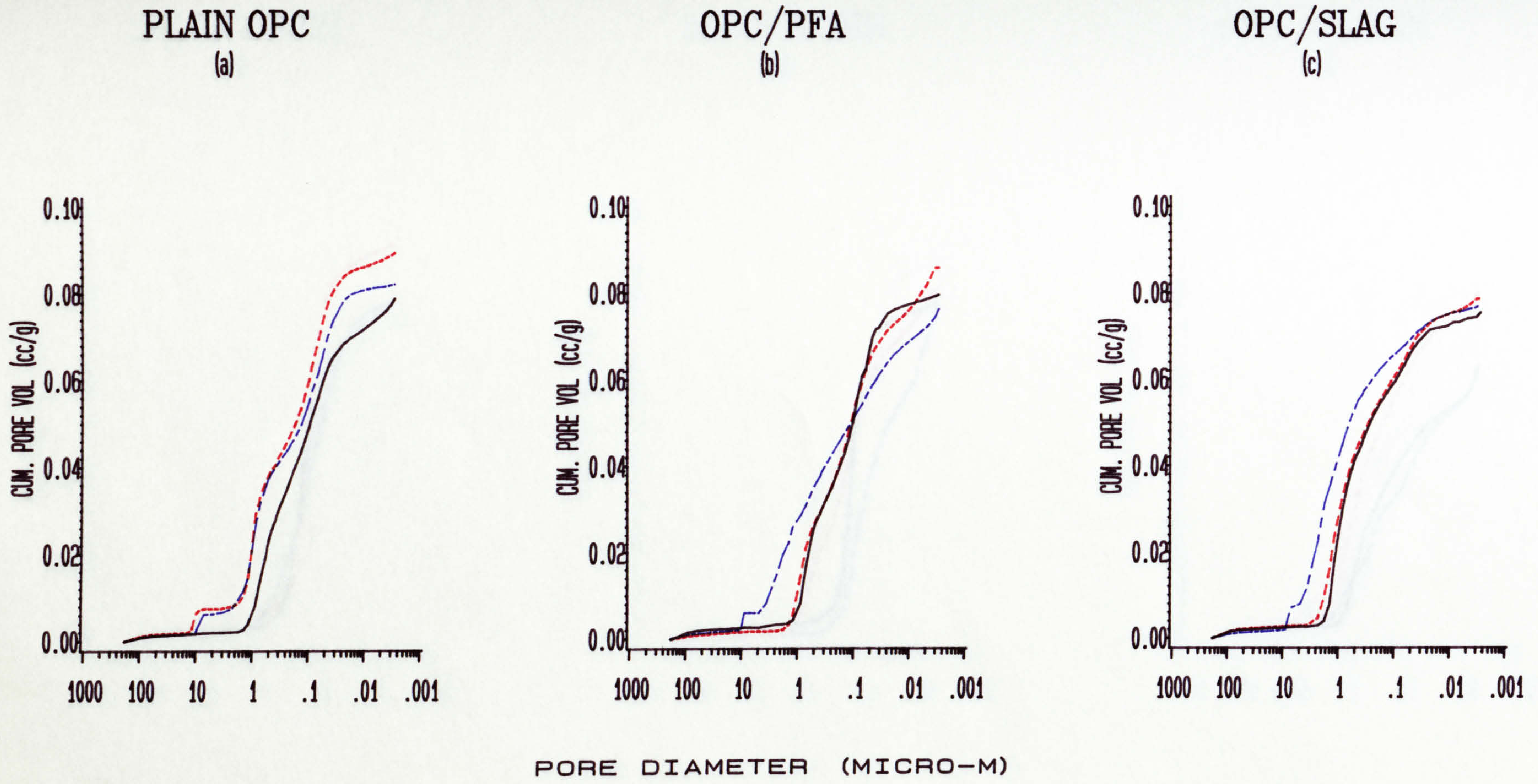


Fig. (5.7) The effects of environments on the pore size distribution of uncured mortar samples

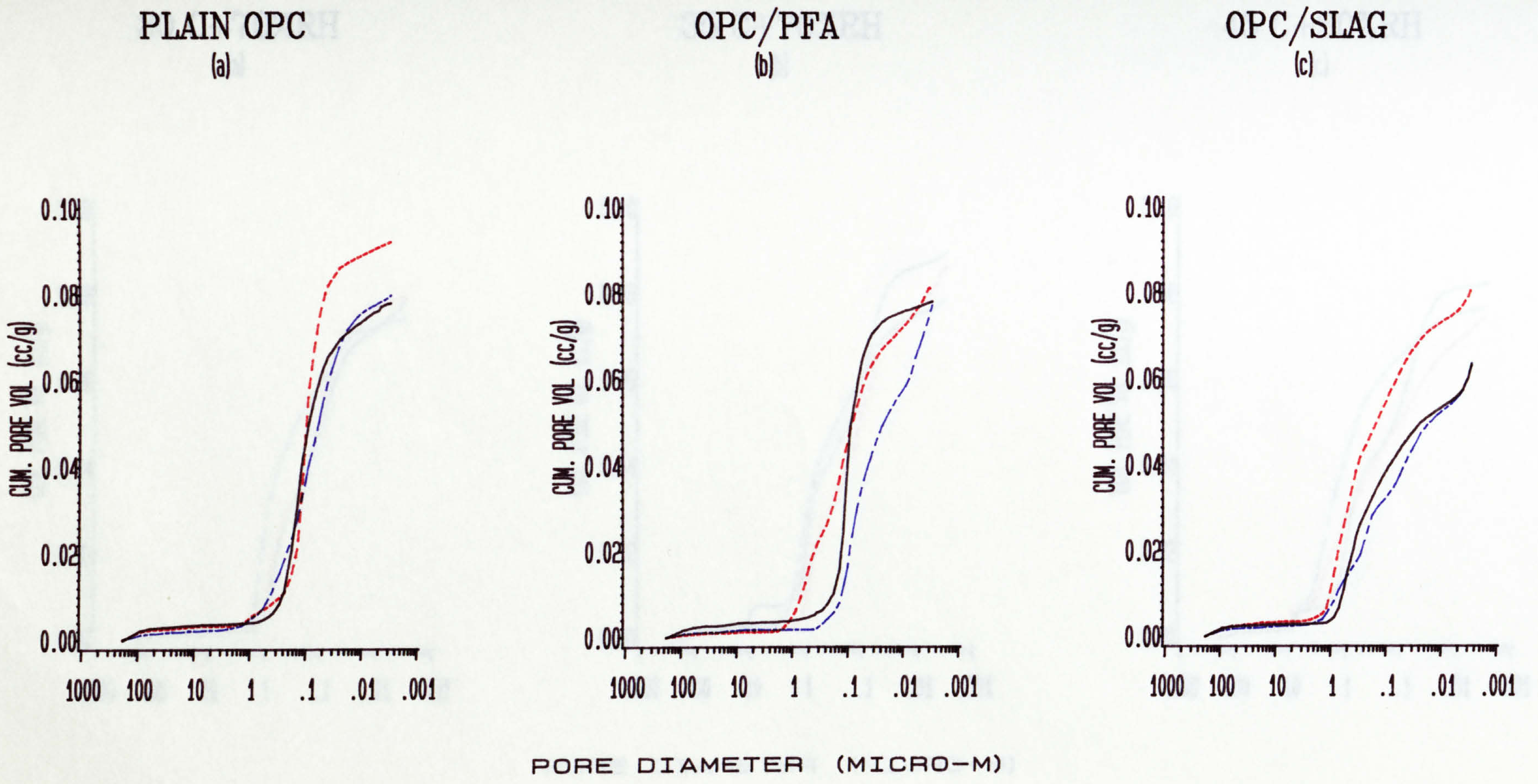


Fig. (5.8) The effects of environments on the pore size distribution of three day cured mortar samples

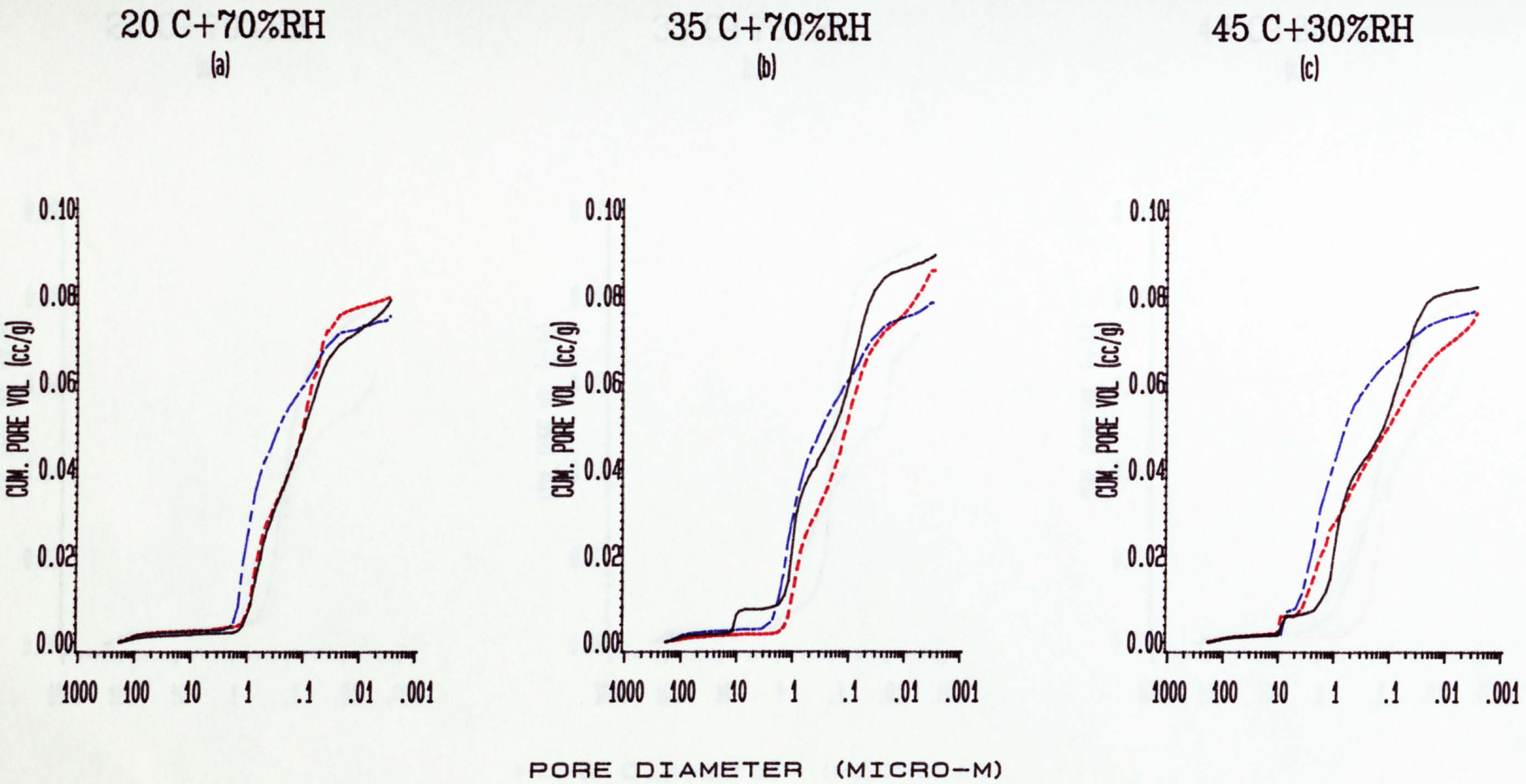


Fig. (5.9) The effects of cement type on the pore size distribution of uncured mortar samples

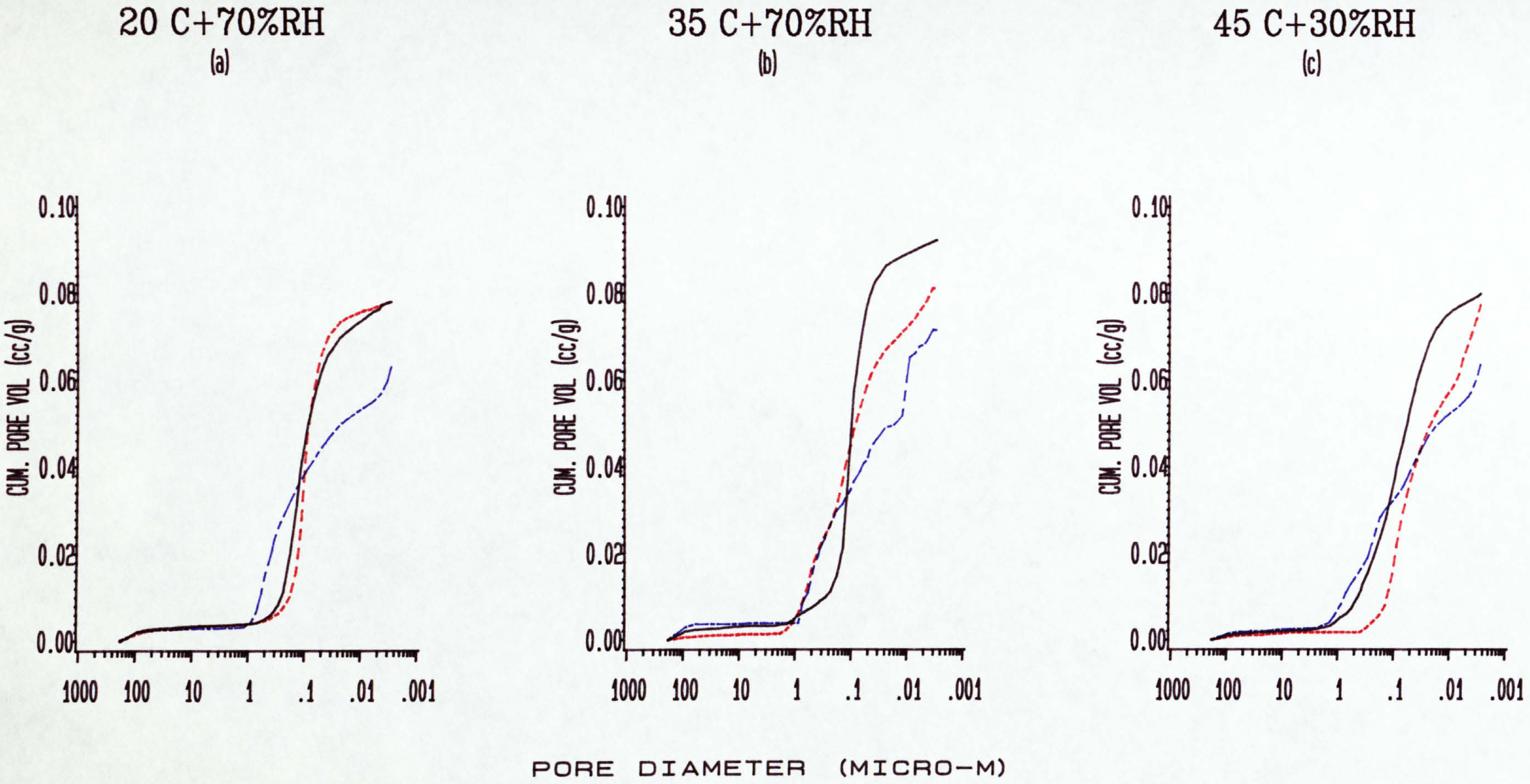


FIG. (5.10) The effects of cement type on the pore size distribution of three days cured mortar samples

—— OPC - - - OPC/PFA —·— OPC/SLAG

The MPD-V values of the pfa samples cured at 35°C+70%RH were similar to those kept at 20°C+70%RH although PSA values were approximately doubled. This indicates that the inclusion of pfa at 35°C results in a greater number of smaller diameter pores than at 20°C, as seen from the PSA results, even though the relative volumes of pores greater than or smaller than the MPD-V remained unchanged. This can clearly be seen in Fig. 5.8b. Fig. 5.3 shows that while uncured OPC/pfa samples at 45°C+30%RH obtained higher MPD-V values than those uncured at 20°C+70%RH, the MPD-V results of one-day cured samples and over at 45°C+30%RH were significantly lower than those found in the 20°C and 35°C environments for similar curing periods.

Curing the OPC/ggbs samples at 35°C+30%RH increased the MPD-V results (Fig. 5.3) significantly for curing periods of one day and longer over those similarly cured at 20°C+70%RH, hence resulting in a greater volume of bigger pores. Nevertheless, the one-day and over cured specimens at 45°C+30%RH produced significantly higher PSA results than at 20°C+70%RH or at 35°C+70%RH and this means a greater volume of smaller diameter pores.

- The Effect of Cement Type:

The replacement of 30% of the OPC by pfa resulted, at 20°C+70%RH, in a smaller PSA value, i.e. coarser pore structure, than that of the OPC mix at all curing periods, see Fig. 5.2. Also comparing the OPC/pfa results with those of the plain OPC samples kept at 35°C+70%RH or 45°C+30%RH, the PSA values of the OPC/pfa mixes were significantly increased suggesting a finer pore structure than plain OPC.

A comparison of the cured OPC and OPC/ggbs samples shows that the latter produced a coarser or similar pore structure for all curing periods in the first two environments, i.e. 20°C+70%RH and 35°C+70%RH, see Fig. 5.2, 5.3, 5.9, and 5.10, although the total porosity was lower. Nevertheless, Figs. 5.2 and 5.9 show that while uncured samples stored at 45°C+30%RH produced a greater volume of bigger pores than plain OPC, the pore structures of cured specimens were finer, see Fig. 5.10c.

A comparison of the two mixes containing cement replacement materials shows that, at the normal temperature of 20°C, one-day and over cured slag specimens produced slightly finer pore structure, see Fig. 5.10,but uncured specimens showed the opposite (Fig. 5.9a). However in the hot environments of 35°C and 45°C, the pfa samples contained a greater number of smaller pores for both cured and uncured conditions as can be seen in Figs. 5.2 and 5.3.

5.5.2 - Permeability to Oxygen:

The actual results of this test are shown in Fig. 5.11. The statistical analyses conducted on these results show that they are repeatable to within 10% for 95% level of confidence.

-The Effect of Curing Period:

Fig. 5.11 shows that curing the samples for the first day only reduced the permeability by more than 50%. A further less dramatic reduction was observed for an additional two days of curing but little if any change was observed for any further increase in curing periods.

- The Effect of Curing Environment:

The permeabilities of the plain OPC samples cured in environments 2 and 3 (i.e.35°C+70%RH and 45°C+30%RH) were generally greater than samples stored in the 20°C+70%RH environment for similar curing periods, see Fig. 5.11.

The lowest permeabilities for one-day and over cured pfa samples were for those stored in the 45°C+30%RH environment followed by those at 20°C+70%RH.

Fig. 5.11 shows that the hot environment of 35°C+70%RH was also seen to

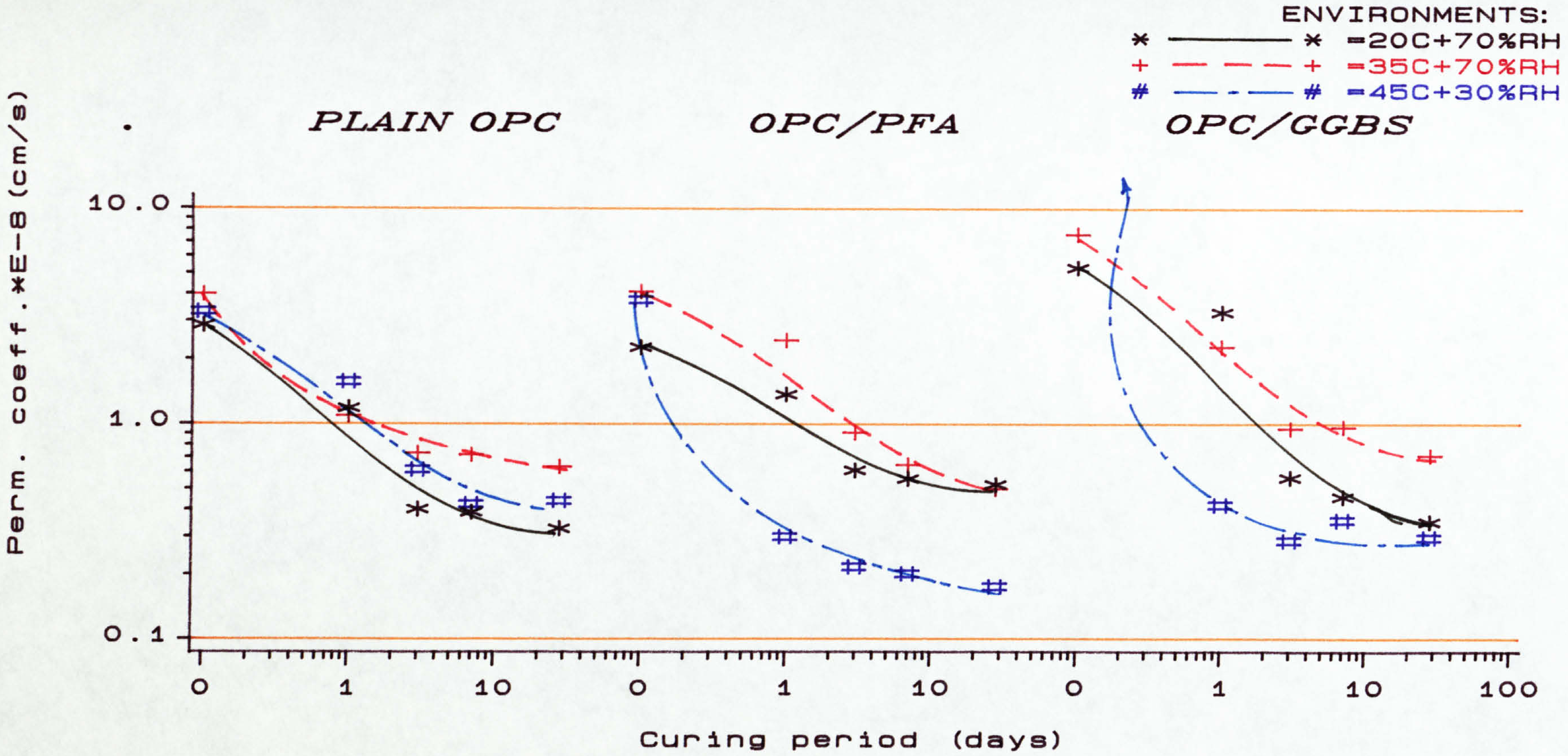


FIG. (5.11) The effects of curing period and environment
on the oxygen permeability
(Tests carried out at 28 days of age)

produce significantly more permeable slag samples when compared with the results achieved at 20°C+70%RH.

Uncured slag specimens at 45°C+30%RH showed more than twice the permeability of those uncured and stored at 20°C+70%RH and at 35°C+70%RH. However, curing for one day only at 45°C+30%RH produced results which were less than one fifth of those cured for the same time at 20°C+70%RH and at 35°C+70%RH.

- The Effect of Cement Type:

Fig. 5.12 shows that the inclusion of pfa at 20°C+70%RH produced higher permeability results than plain OPC for curing periods of 3 days or less but similar or lower results for curing periods longer than three days. Fig. 5.12 also shows that compared to OPC, the inclusion of pfa at 45°C+30%RH lowered the permeability considerably for all those specimens which were cured for one day and over.

Fig. 5.13 shows that at 20°C+70%RH and 35°C+70%RH, OPC/slag samples produced generally higher results, i.e. over 10%, than the OPC samples. At 45°C+30%RH, the OPC/ggbs samples produced lower results than plain OPC samples from one day of curing and over.

Furthermore, Fig. 5.14 shows that in almost all cases the permeability of OPC/ pfa samples was either similar to or lower than the OPC/ggbs specimens in all environments.

5.5.3 - The Test for Water Absorption:

The actual results of tests for water absorption are given in Figs. 5.15 and 5.16. The statistical analyses carried out on the results of this test show that it is repeatable to within 10% for a 95% level of confidence.

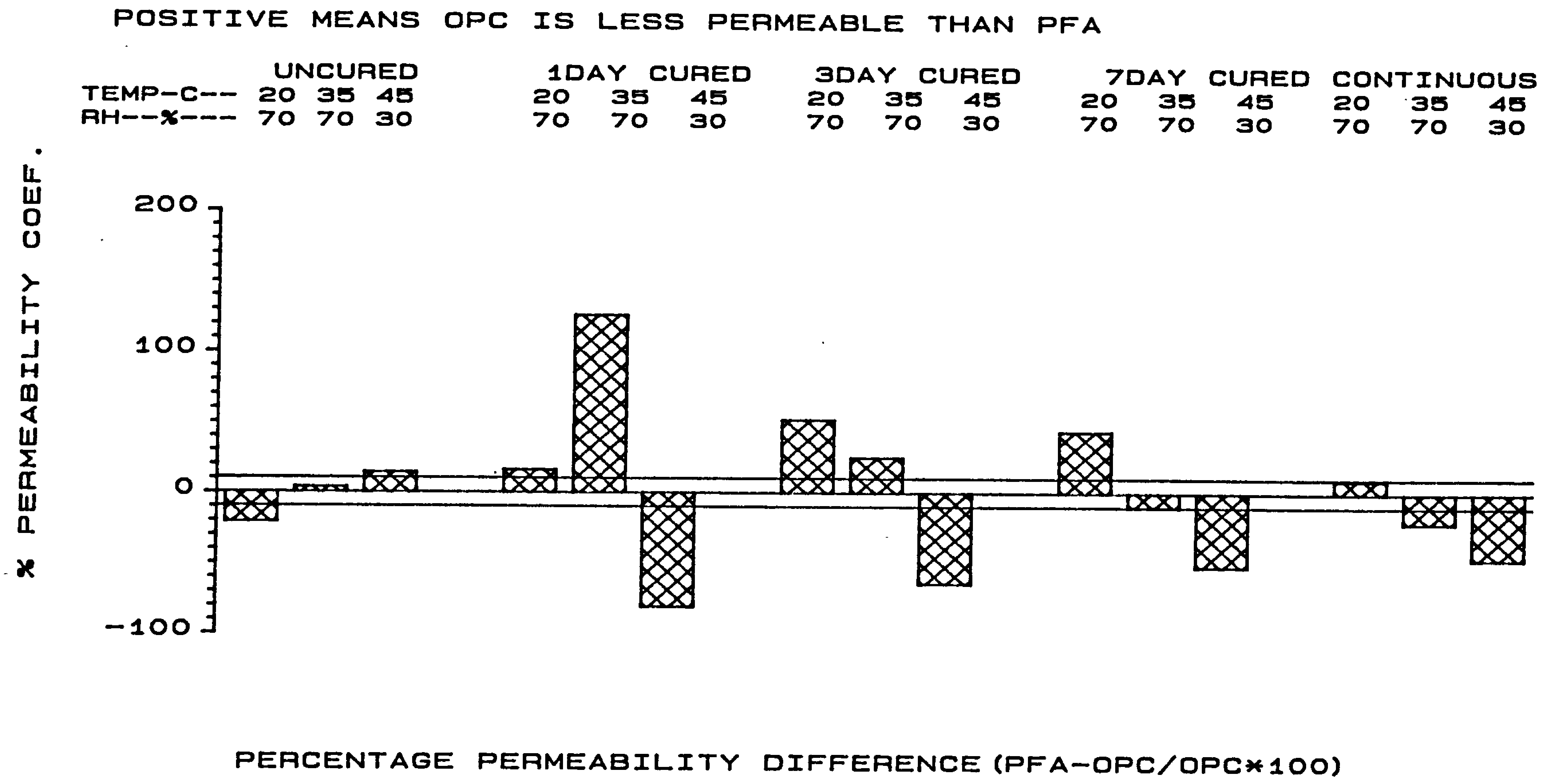


FIG. (5.12) The permeability difference between pfa and OPC mortars in different environments and under various curing periods (Tests carried out at 28 days of age)

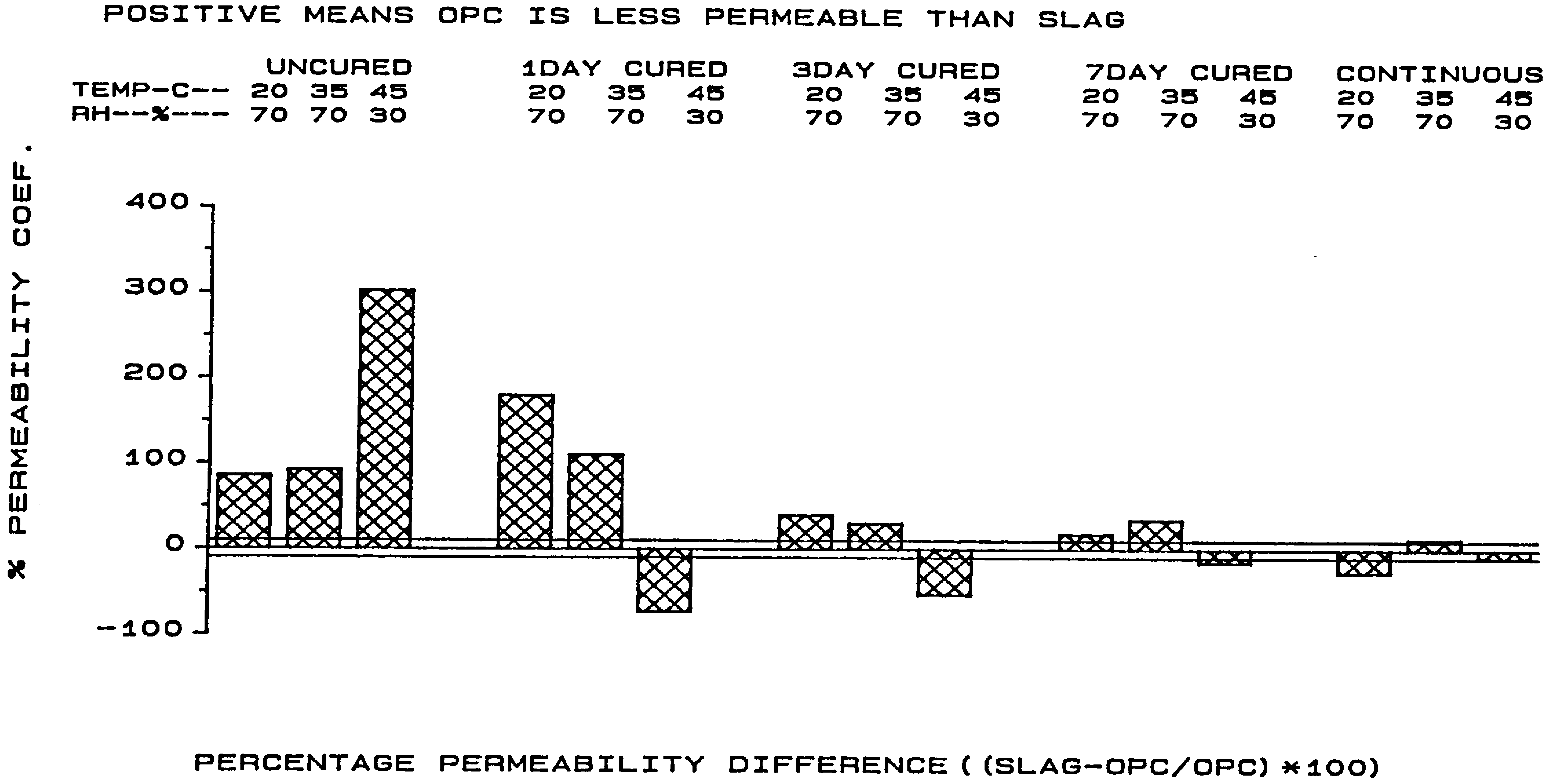
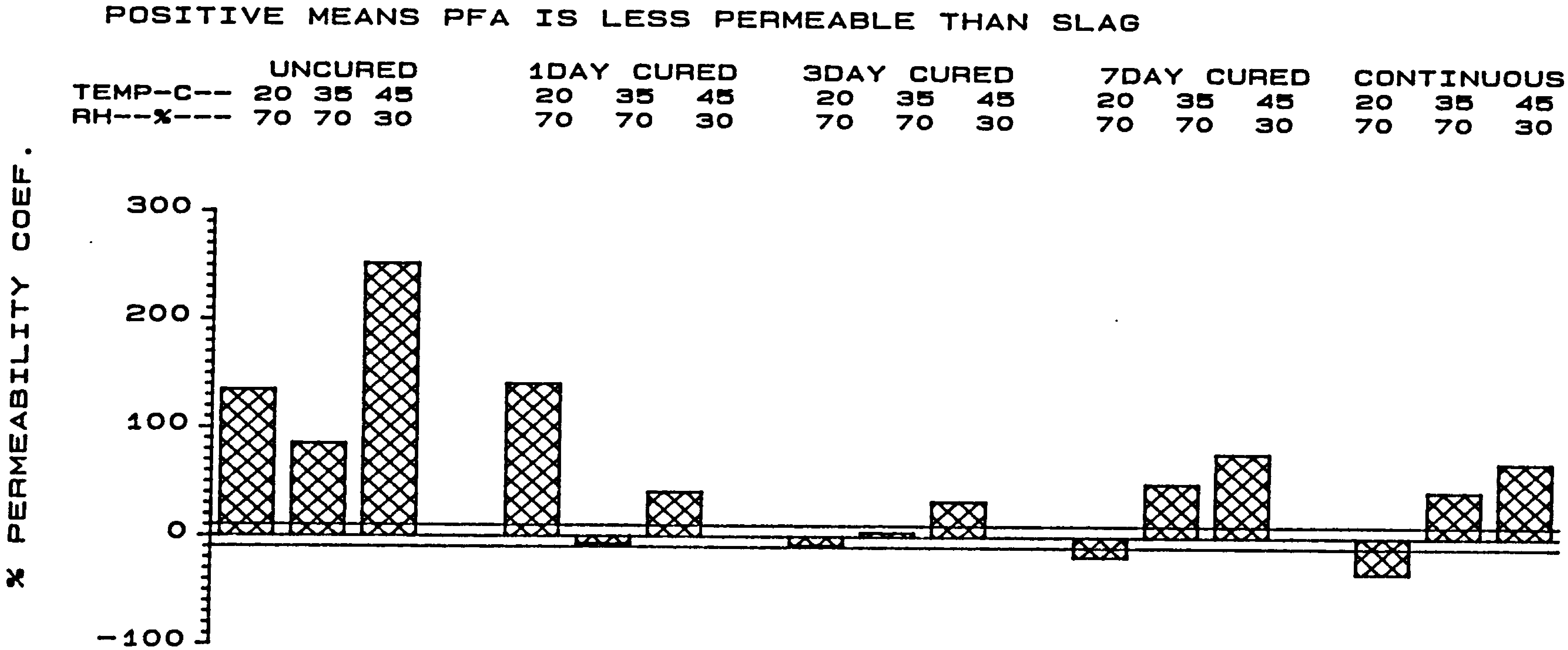


FIG. (5.13) The permeability difference between ggbs and OPC MORTARS in different environments and under various curing periods (Tests carried out at 28 days of age)



PERCENTAGE PERMEABILITY DIFFERENCE (SLAG-PFA/PFA*100)

FIG. (5.14) The permeability difference between ggbs and pfa mortars in different environments and under various curing periods (Tests carried out at 28 days of age)

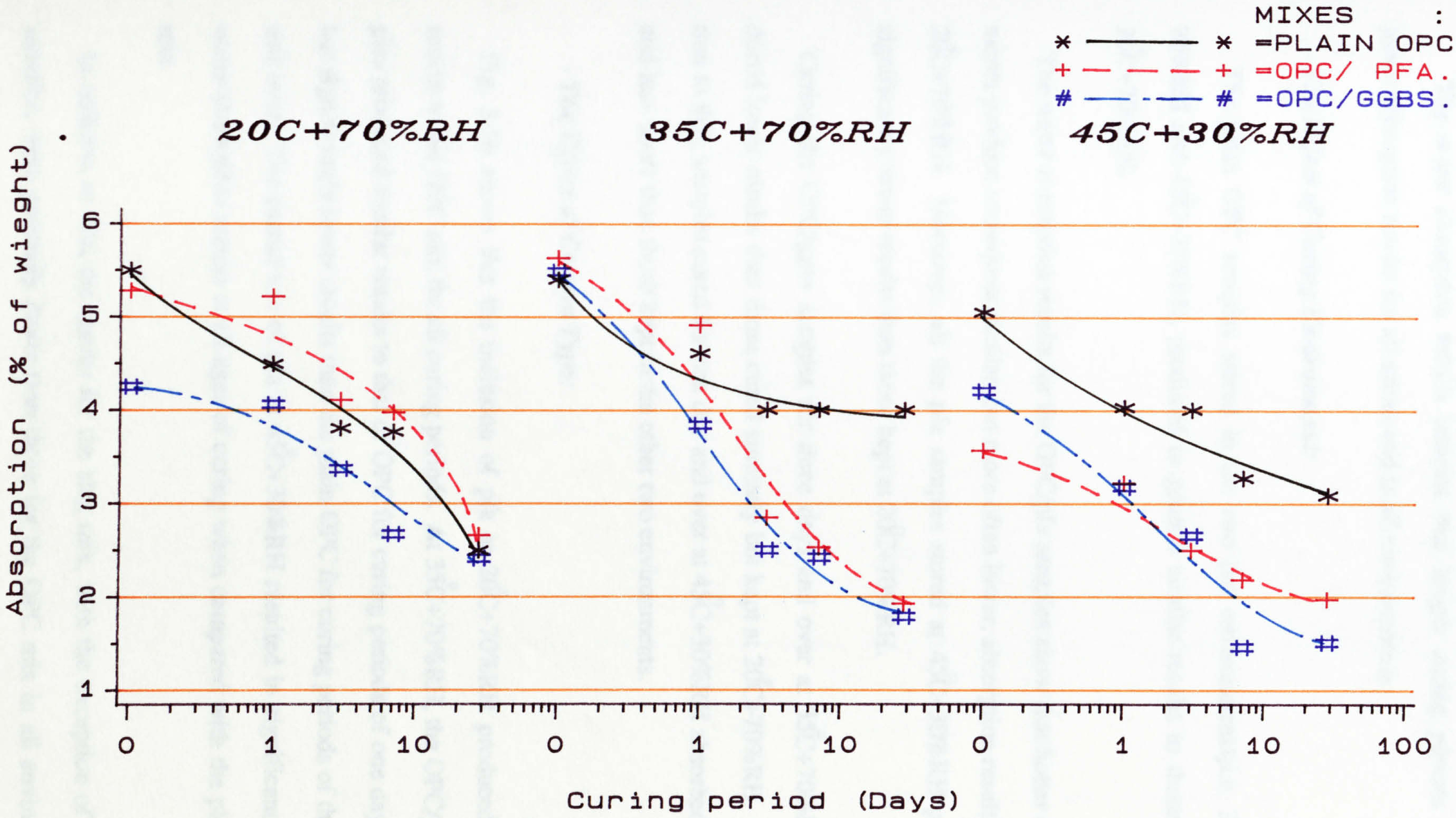


FIG. (5.15) The effects of curing period and cement type on the test for water absorption (Tests carried out at 28 days of age)

- The Effect of Curing Duration:

The water absorption results indicate that longer curing periods produce lower absorption results for all mixes and in all environments.

- The Effect of Curing Environment:

The plain OPC samples stored in the two hot environments,i.e. 35°C+and 70%RH and 45°C+30%RH, produced in general similar results to those kept at 20°C+70%RH.

The water absorption results for the OPC/pfa samples show that hotter environments produce sometimes similar, but more often lower, absorption results than at 20°C+70%RH. Moreover, all the pfa samples stored at 45°C+30%RH produced significantly lower results than those kept at 20°C+70%RH.

Curing the OPC/ggbs samples for three days and over at 35°C+70%RH produced lower results than those cured similarly but kept at 20°C+70%RH. In addition to this, samples cured for one day and over at 45°C+30%RH absorbed in general less water than those kept in the other two environments.

- The Effect of Cement Type:

Fig. 5.16 shows that the inclusion of pfa at 20°C+70%RH produced similar results to the OPC mix for all curing periods. At 35°C+70%RH, the OPC/pfa samples produced similar results to that of OPC for curing periods of one day or less, but significantly lower results than the plain OPC for curing periods of three days and over. The partial use of pfa at 45°C+30%RH resulted in significantly lower water absorption results at all ages of curing when compared with the plain OPC mix.

In addition to this, the results for the slag mix, with the exception of uncured samples, were generally lower than those for the OPC mix in all environments,

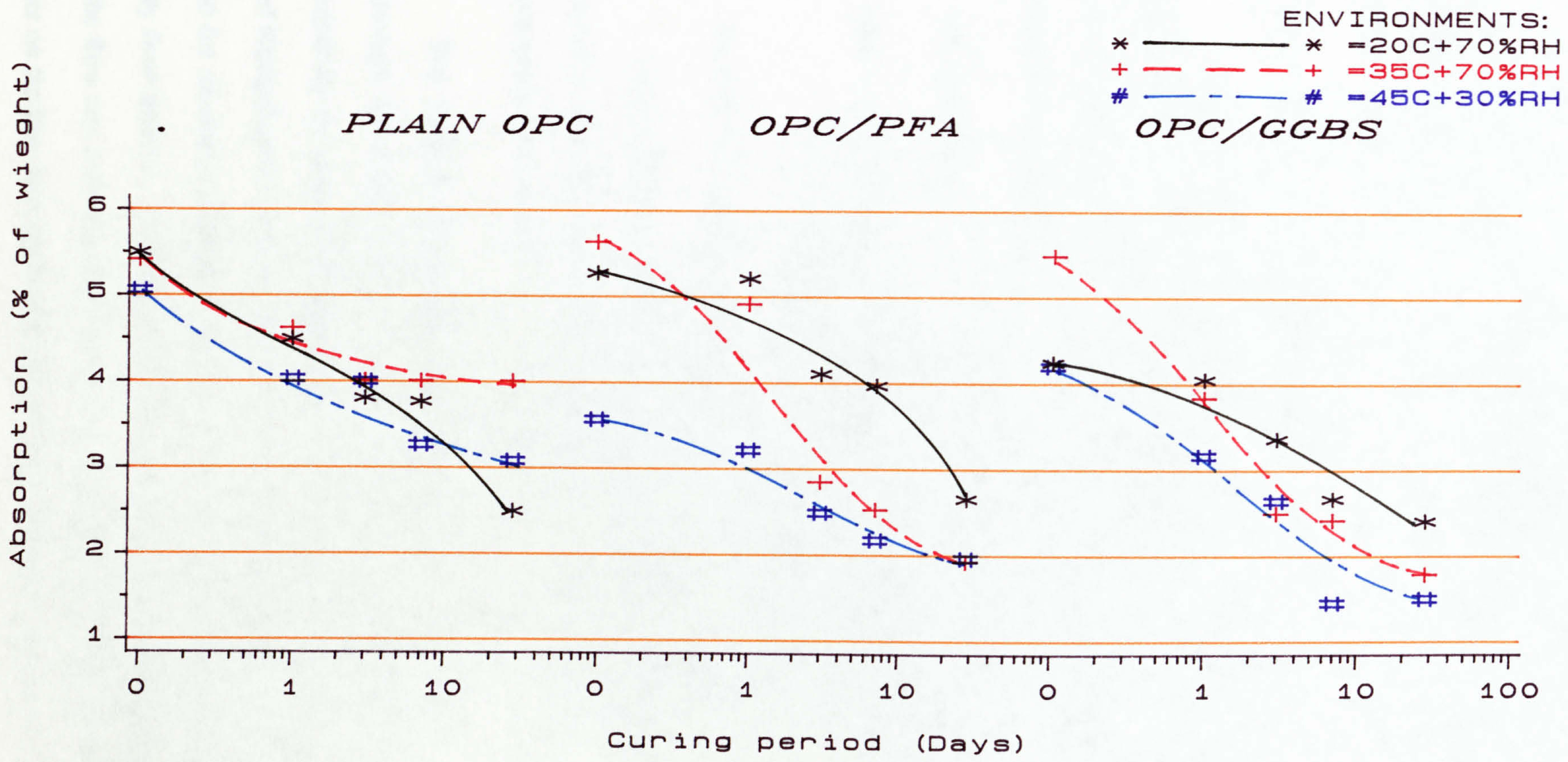


FIG. (5.16) The effects of curing period and environment on the test for water absorption (Tests carried out at 28 days of age) see Fig. 5.16.

A comparison of the two mixes containing pfa and ggbs shows that as far as water absorption results are concerned, the OPC/slag samples produced the lowest results when stored at 20°C+70%RH but showed similar values to the pfa mix in the other two environments.

5.5.4 - The Portable Air Permeability:

The length of times recorded by the portable air permeability apparatus and the corresponding flow rate as measured by the oxygen test are shown in Table 5.7. These results will be used later in the discussion to correlate this test with the oxygen permeability test.

5.6 - Discussion:

5.6.1 - The Relationship Between the Pore Structure and Permeability Results:

5.6.1.1 - Theoretical Relationship

The permeability results shown above as well as the results for pore structure indicate that they are greatly affected by curing duration, environment, and cementitious materials.

The oxygen permeability test measures the steady-state flow of oxygen through the sample and it is logical to assume that permeability can be lowered either by the presence of blocked pores, or by narrower pores or both. The effect of blocked pores on permeability is obvious and the reduction in permeability due to the existence of smaller diameter pores at a constant porosity can be explained by flow theories. According to the theory of fluid mechanics, smaller pores lower the flow rate even though porosity may be unchanged. The effects of pore diameter on the flow rate can be estimated by the following equation(115):

Table 5.7: The portable air permeability results (sec) and the corresponding flow rates (cm^3/sec) measured using the oxygen permeability cell. (oxygen flow rate/portable test results)

Curing duration (days)	Environment	Mix		
		1	2	3
0	20°C+70%RH	0.0217/21.3	0.1902/25.2	0.0498/9.64
1		0.0099/46.3	0.0116/40.0	0.0312/17.7
3		0.0040/115.	0.0050/93.0	0.0045/96.0
7		0.0033/136.	0.0046/101.	0.0038/108.
28		0.0046/111.	0.0044/103	0.0030/160.
0	35°C+70%RH	0.0329/17.1	0.0325/15.0	0.0650/6.48
1		0.0090/50.5	0.0200/24.1	0.0190/23.4
3		0.0060/79.7	0.0084/59.3	0.0078/66.0
7		0.0059/79.3	0.0058/77.8	0.0081/55.1
28		0.0051/89.1	0.0041/98.4	0.0059/74.3
0	45°C+30%RH	0.0287/15.5	0.0334/13.4	0.1170/4.60
1		0.0138/34.5	0.0026/172.1	0.0037/116.4
3		0.0054/43.2	0.0019/238.0	0.0025/182.4
7		0.0037/120.	0.0018/244.4	0.0031/143.6
28		0.0029/155.	0.0015/288.0	0.0026/181.5

$$\text{Head loss} = \frac{4LFV^2}{2gD} \tag{5.1}$$

where

L= length of the pore;

F= friction coefficient;

D= diameter of the pore;

V= flow velocity; and

g= gravity.

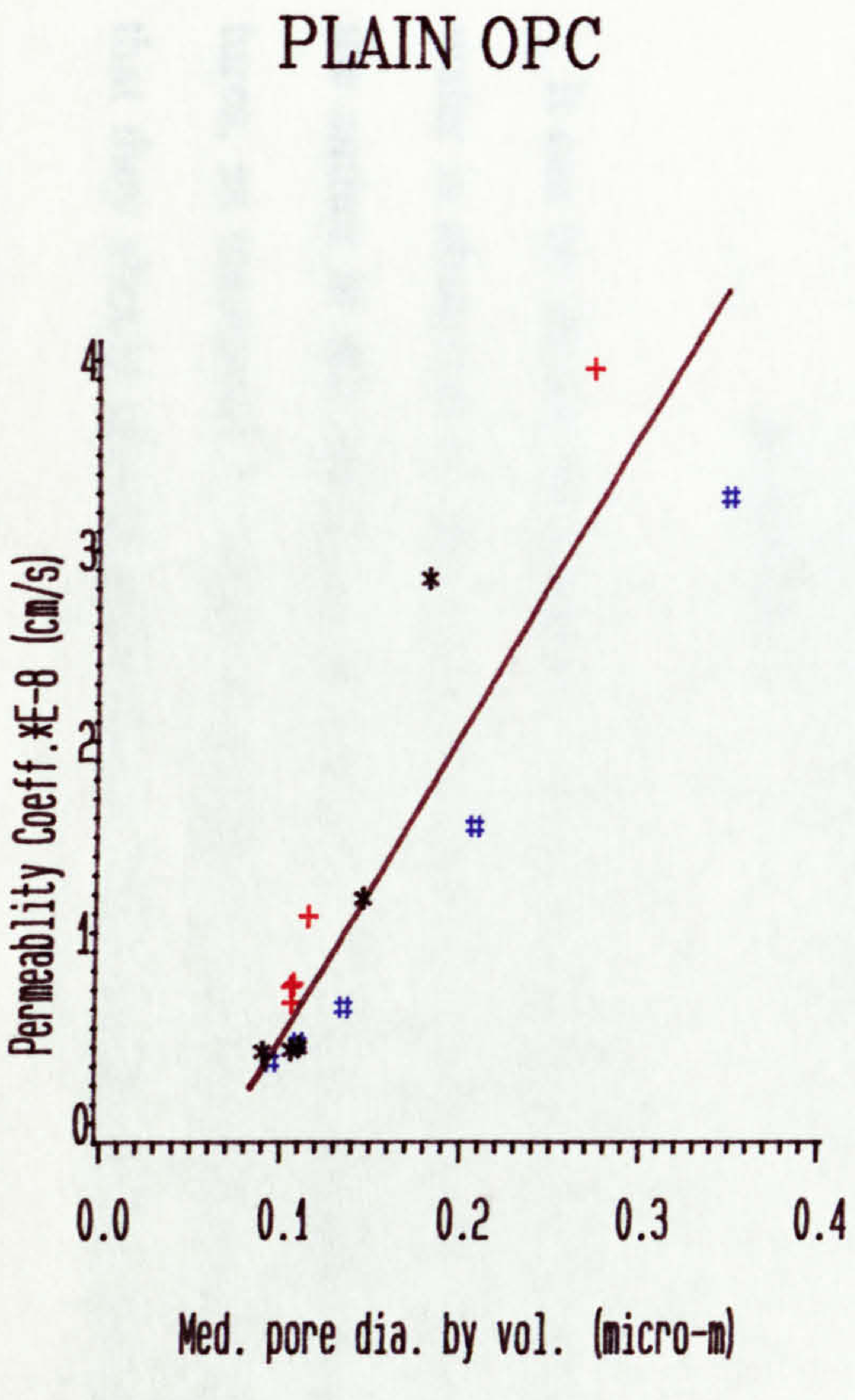
Since there is a direct, proportional relationship between flow rate and permeability, this equation can be used to show that finer pore systems exhibit lower flow rates and hence lower permeabilities, although the total volume of the pores remains constant.

5.6.1.2 - Experimental Relationship

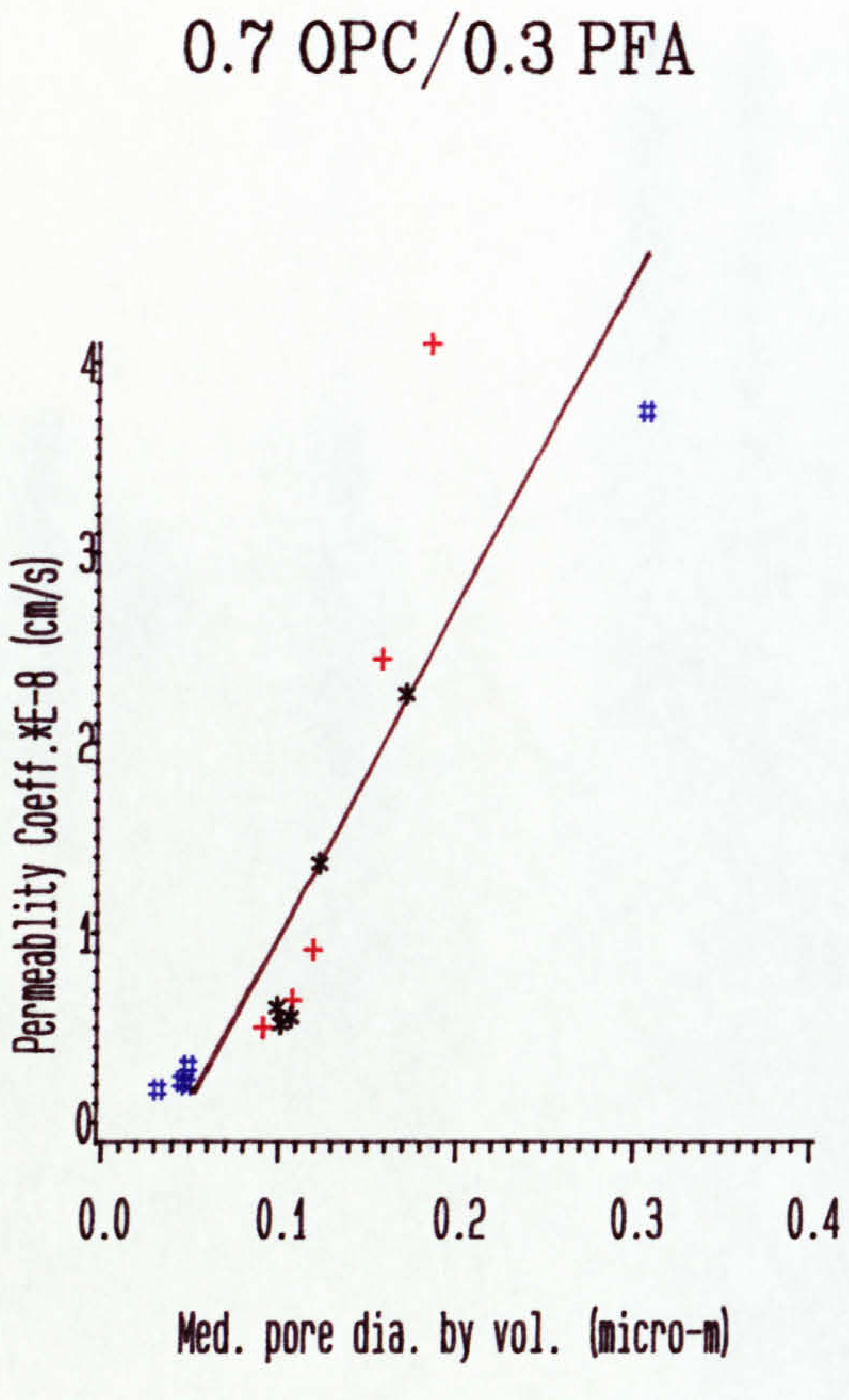
Curing duration, curing environment and the two cement replacement materials were seen to mainly influence the volume of the pores in excess of 0.1 μm in diameter (Figs. 5.4 - 5.10). A statistical analysis was performed on the relation between permeability and several parameters used to explain the changes in the pore structure such as PSA, MPD-V, and the volume of pores in excess of 0.1 μm in diameter. The statistical analyses performed on the results shows that permeability is best related to the MPD-V (Table 5.8). This is confirmed by the graphical representation of the relationships between the permeability and pore structure which are shown in Figs. 5.17-5.19 for the plain OPC, OPC/pfa and OPC/ggbs mixes respectively. It is seen from the figures that the higher the MPD-V the greater the permeability. In addition to this, while MPD-V is seen to be better than PSA in describing the effects of curing lengths, the opposite is true in some

Table 5.8: The correlation coefficients and significance limits of linear relation between the tests discussed in this chapter.

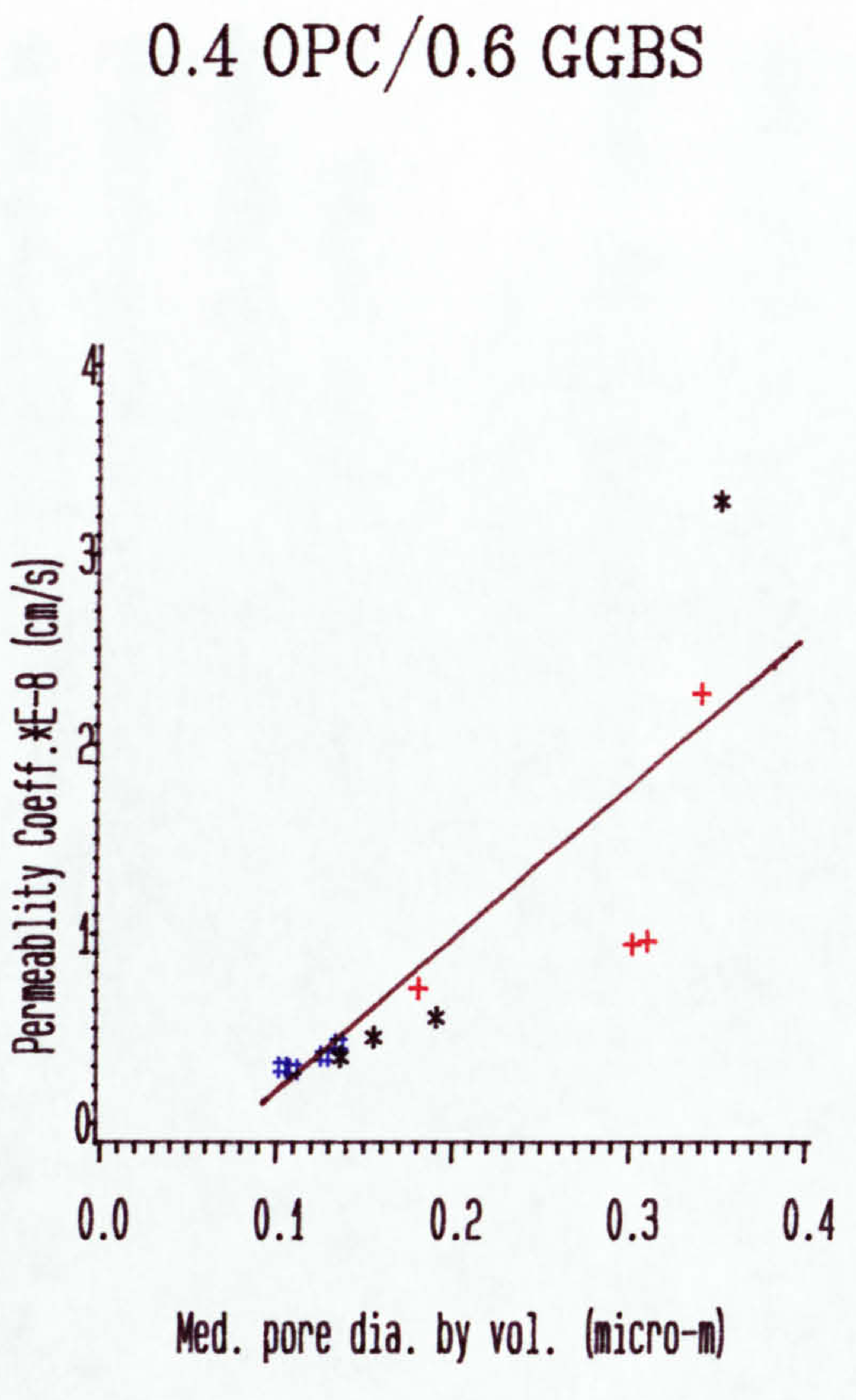
Relationship	plain OPC	OPC/pfa	OPC/ggbs	all mixes
w. absorption with permeability	0.83098 0.0001	0.69562 0.0040	0.71201 0.0029	0.49790 0.0005
w. absorption with square root of permeability	0.86072 0.0001	0.75183 0.0012	0.79790 0.0004	0.63475 0.0001
w. absorption with total porosity	0.76620 0.0009	0.81864 0.0002	0.8404 0.0001	0.82059 0.0001
permeability with total porosity	0.75470 0.0011	0.48361 0.06780	0.6411 0.0100	0.45906 0.0015
w. absorption with PSA	-0.47453 0.0739	-0.64486 0.0094	-0.56344 0.0287	-0.57037 0.0001
permeability with PSA	-0.48705 0.0656	-0.36464 0.1815	-0.75616 0.0011	-0.42825 0.0033
w. absorption with MPD-V	0.69382 0.0041	0.54577 0.0353	0.65798 0.0077	0.31259 0.0366
permeability with MPD-V	0.89897 0.0001	0.88922 0.0001	0.97946 0.0001	0.93980 0.0001
permeability with volume pores greater than .5micro-m	0.8298 0.0001	0.9298 0.0001	0.8845 0.0001	0.8217 0.0001
permeability with volume of pores greater than .1micro-m	0.7059 0.0033	0.6491 0.0088	0.8165 0.0002	0.6123 0.0001


PLAIN OPC

(Fig. 5.17)


0.7 OPC/0.3 PFA

(Fig. 5.18)


0.4 OPC/0.6 GGBS

(Fig. 5.19)

The relationship between permeability coefficient and median pore diameter by volume for plain OPC, OPC/pfa and OPC/ggbs mortar mixes

***=20C+70%RH +++=35C+70%RH ###=45C+30%RH cases of the effects of curing environments on permeability, see Figs. 5.2, 5.3 and 5.11. Therefore, both the PSA and the MPD-V will be used in explaining the effects of the different parameters on the pore structure of mortars.

5.6.2 - The Relationship Between the Pore Structure and Water Absorption Results:

The test for water absorption measures the weight of water absorbed as a percentage of the dry weight of the sample. Because of the small water head used in this test, its effect on the penetration into the sample by water is small. Hence, in this particular test the water absorption is greatly influenced by the capillary forces arising from surface tension. According to the theory of surface tension, the smaller the diameter the greater the water rise is in the capillary tube. The relation between the pore diameter and the rise in the capillary tube is governed by the following equation (115):

$$H = \text{Capillary rise} = \frac{4S}{\omega D g} \tag{5.2}$$

where,

S= surface tension;

D= diameter of the pore;

ω = density of the fluid; and

g= gravity.

It can be shown by equation 5.2 that for systems with constant porosity, more water is absorbed by the system containing finer pores. The results reported by the author in this work are in conflict with this. Samples with finer pore structures, as measured by MIP, absorbed less water whereas equation 5.2 suggests that they should absorb more water. This suggests that the phenomena of finer pores might not be the important parameter here. Therefore, the pore structure results measured by MIP may not be appropriate to explain the trends in water absorption results. Figs. 5.2, 5.3 and 5.15 show that the changes taking place in the pore structure were not followed by similar changes in water absorption. In the following argument, an attempt will be made to explore the importance of other factors:

1 - The Influence of Blocked Pores:

A preliminary investigative study was made to try and measure the effect of curing periods on the depth of water penetration into the mortar samples. The 50 mm cubes were broken open at the end of the water absorption test and the depth of penetration was measured. Table 5.9 shows the results of the depth of penetration for samples cured under different conditions in which it can be seen that increasing the curing periods resulted in smaller depths of penetration.

Table 5.9: Depth of water penetration (mm) after 30 minutes of total submersion in water of OPC/pfa samples, 50 mm cubes. (20°C + 70% RH).

face	curing periods (days)				
	0	1	3	7	continuous
top	12	9	8	5	3
side	9	4	4	4	3
bottom	3	2	2	2	2

These data suggest that, in addition to the reduction in pore sizes, as measured by MIP, and in the total porosities, more pores nearer to the Protected surfaces become blocked by the hydration products of the OPC and ggbs or the additional precipitants of the pfa or ggbs an effect which is not clearly shown by the MIP results.

Moreover, because the top-as-cast face, which was the only face exposed to the different ambient conditions ,(the other sides were sealed until the day of testing), absorbed more water than either the side or bottom faces. These results seem to be similar to those published by Senbetta and Scholer (22) who have shown that the top layer of plain OPC samples absorbed more water than the bottom one, a trend also confirmed by Payne and Dransfield (44).

2 - The Influence of Total Porosity:

In addition to the effects of blocked pores on the water absorption, the statistical analysis performed on the relationship between porosity and water absorption shows that lower porosities result in lower water absorption results. Table 5.8 shows that porosity and water absorption are closely related as seen from the correlation coefficients of linear relations for the three mixes. This suggests that in addition to the effects of blocked pores on the water absorptions as shown above, water absorptions are also lowered by lower porosities.

The water absorption results of the three mixes are generally seen to conform best with the total porosity results. For example, the total porosities of uncured plain OPC and OPC/pfa samples were generally similar at 20°C+70%RH and so were the water absorption results. The specimens containing slag were seen at 20°C+70%RH to exhibit smaller total porosities and lower water absorption results than the other two mixes kept in the same environment. In addition to this, the total porosities of the OPC/pfa and OPC/ggbs, which were generally similar, were lower than those of the plain OPC at 35°C+70%RH and 45°C+30%RH and so were the results of the test for water absorption.

In conclusion, the water absorption results become lower (in the case of finer pores) only when the influences of more blocked pores and lower total porosity exceed that of the increase in capillary suction due to the increase in surface tension.

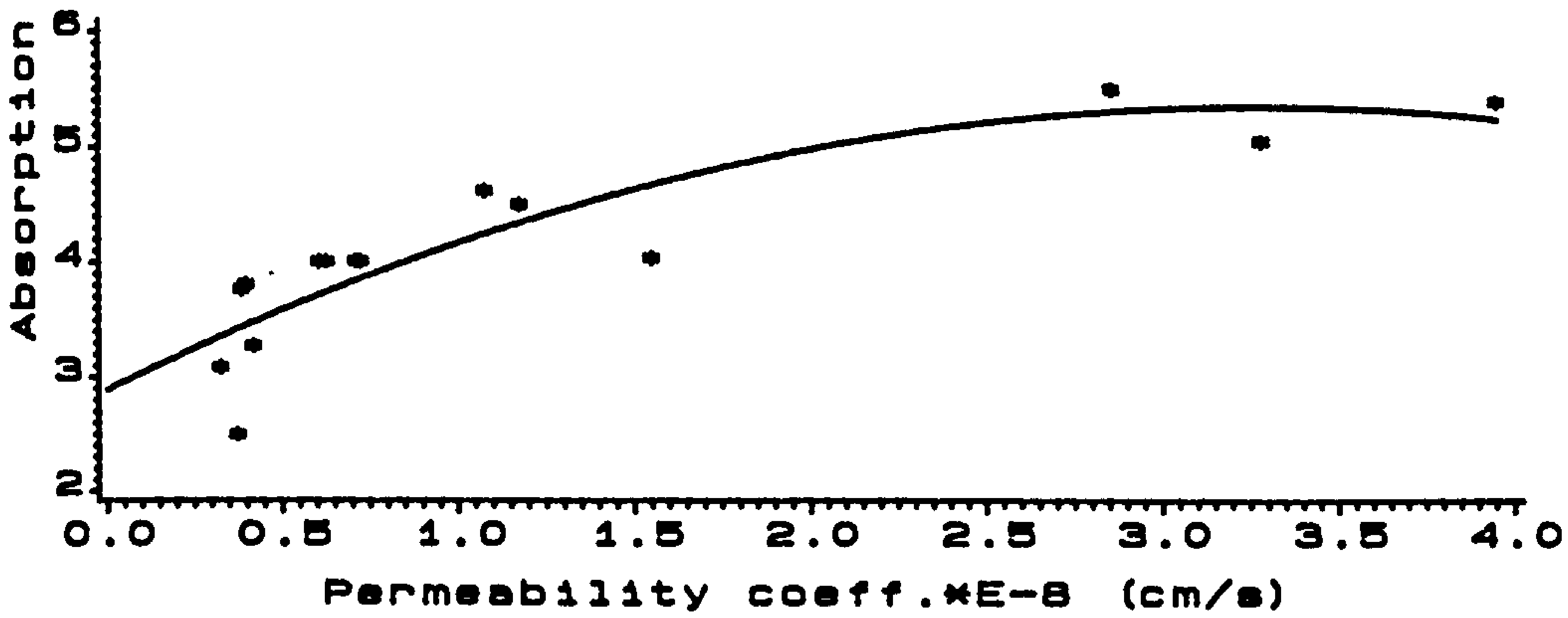
5.6.3 - The Relationship Between the Permeability and Water Absorption Results:

The statistical analysis performed on the relation between water absorption and oxygen permeability shows that a square root function is a better representation than linear function. Table 5.8 shows that in general the correlation coefficient between absorption and the square root of permeability is more significant than that between permeability and absorption. In spite of this, the graphical representations shown in Figs. 5.20-5.22 indicate that there is poor correlation between the results for relatively lower permeabilities. Therefore, it can be concluded from this that there is no clear relationship between both tests. The reason for this can be attributed as discussed earlier to the fact that while blocked pores lower the permeability and water absorption, finer pores reduce the permeability while at the same time increase the water absorption results. Therefore, the oxygen permeability test is seen to be better than the water absorption test in explaining the changes taking place in the pore structure. In addition, permeability results along with those of the pore structure will be the only ones used in the discussion of the effects of curing periods, curing environments or cement type.

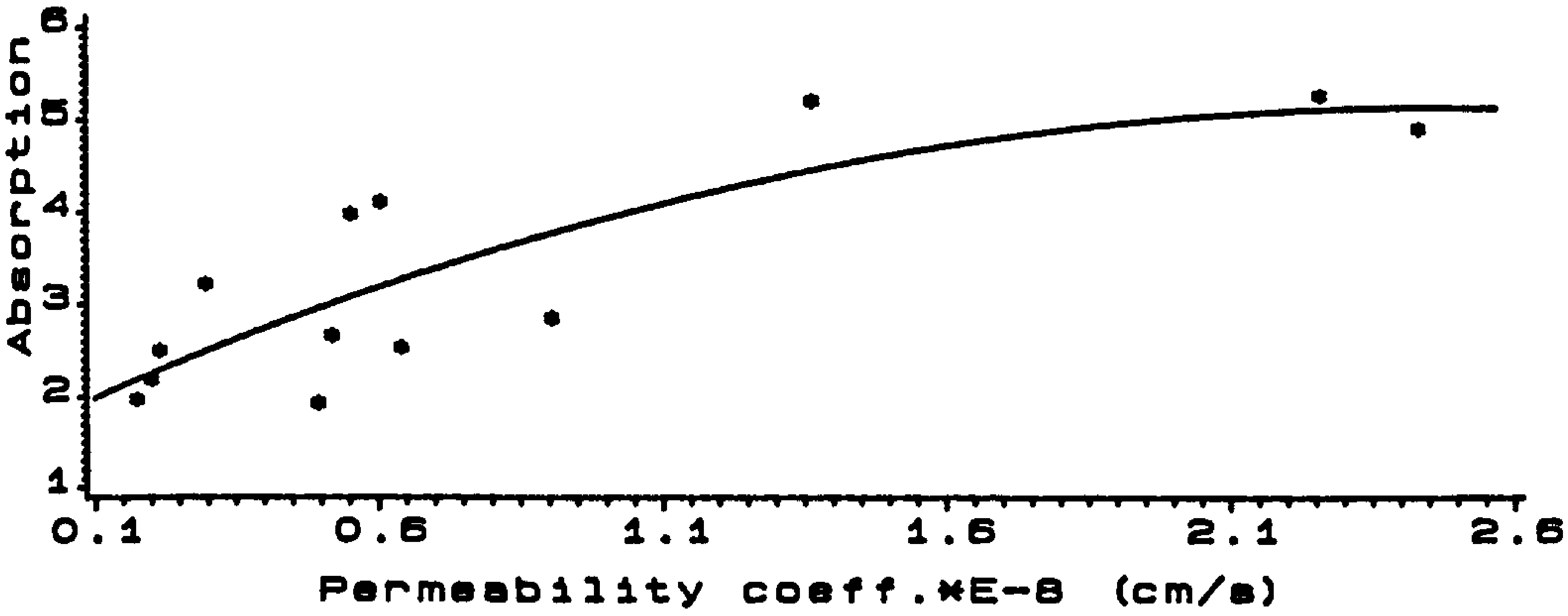
5.6.4 - The Relationship Between The Oxygen Permeability and The Portable Air Permeability Results:

The statistical analysis conducted on the flow rate measured by the oxygen permeability test and the lengths of time recorded by the portable air permeability test indicate that they are closely related. A highly significant linear relation was found between the flow rate and the reciprocal of time with a correlation coefficient of 0.996 and a significant limit of 0.0001, see Fig. 5.23. Using the limited data found by the author, the relation between the two tests is governed by the following equation:

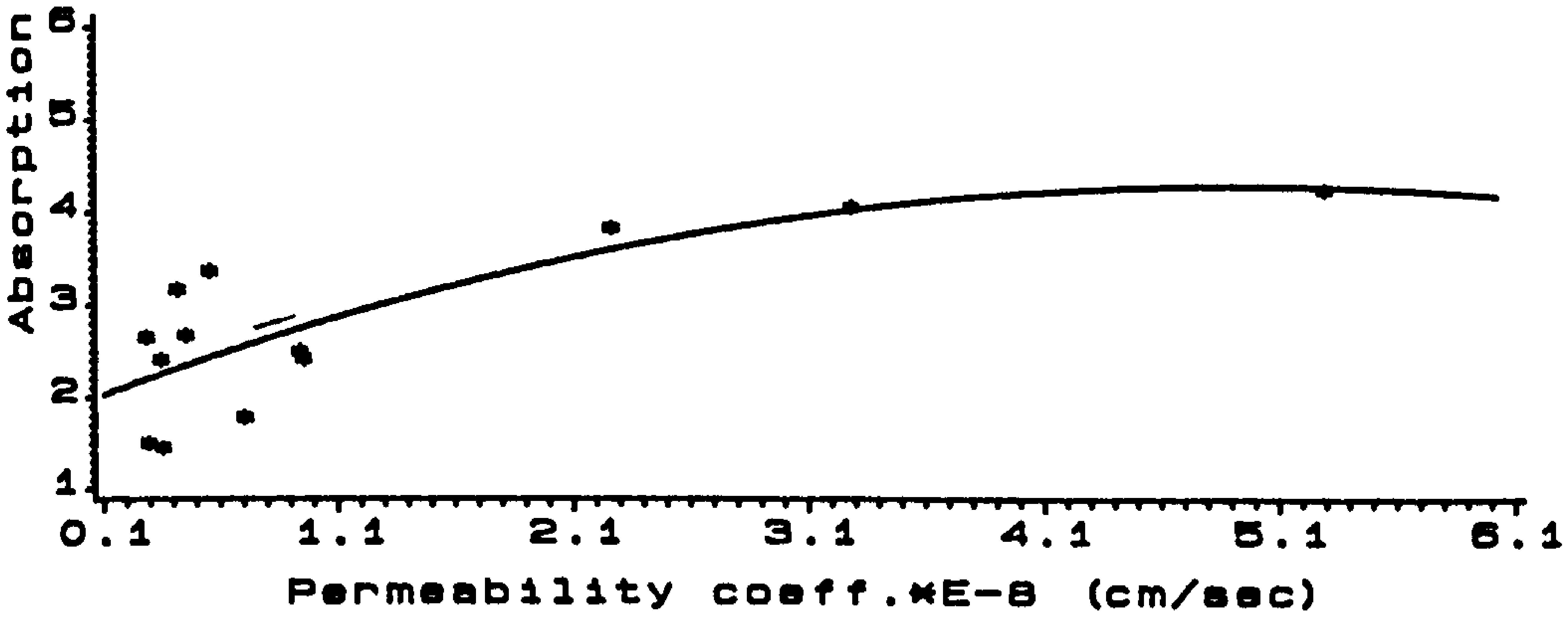
PLAIN OPC
FIG. 5.20



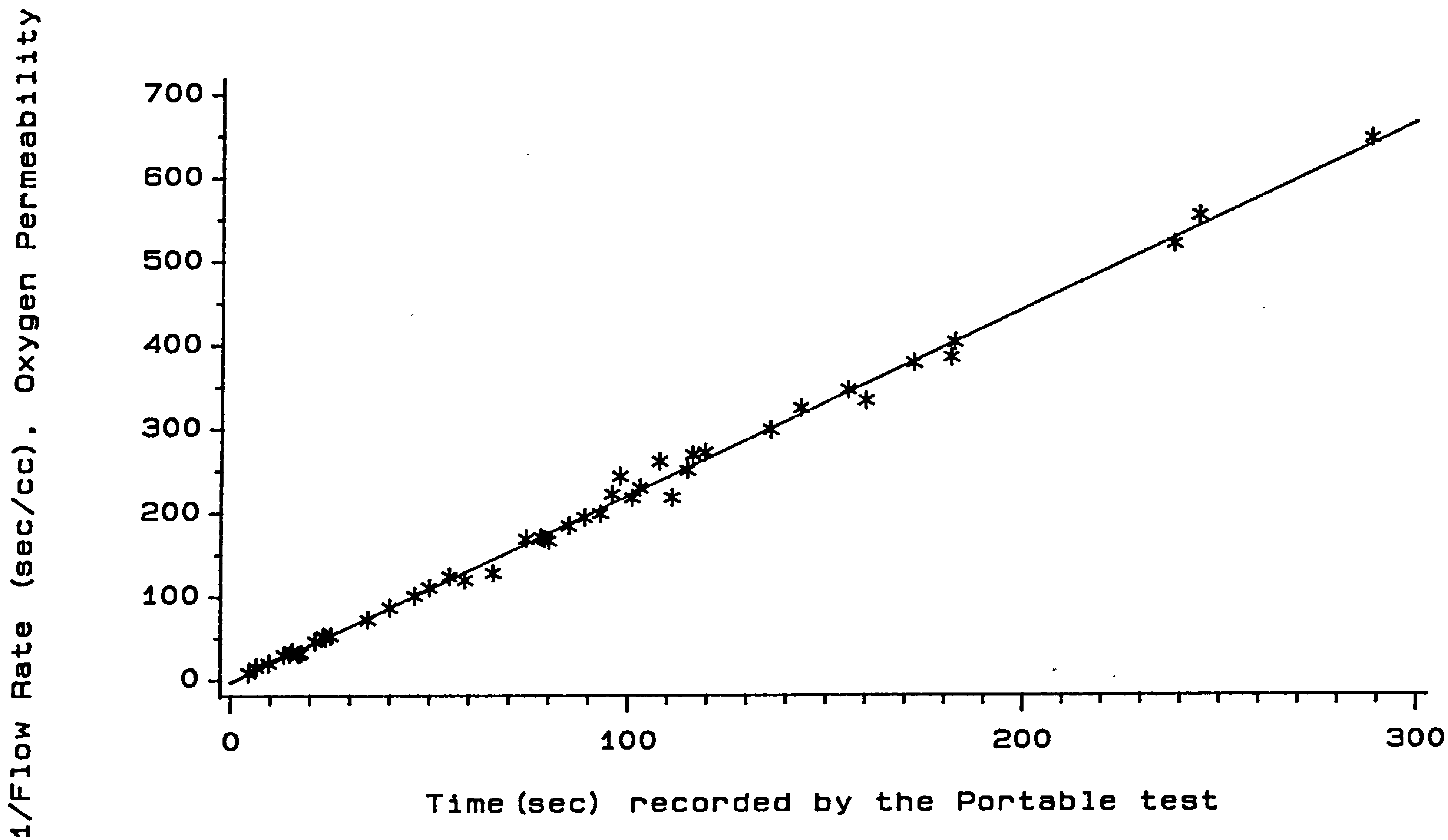
0.3 PFA/0.7 OPC
FIG. 5.21



0.6 GGBFS/0.4 OPC
FIG. 5.22



The relationship between permeability coefficient and water absorption
(Tests carried out at 28 days of age)



CORRELATION COEFFICIENT=0.9964
LEVEL OF SIGNIFICANCE = 0.0001

FIG. 5.23 The relationship between oxygen permeability method and the periods of time recorded by the portable air permeability

$$Q = \frac{0.45}{T} \tag{5.3}$$

Where

Q = the measured oxygen flow rate (cc/sec)

T = the recorded time measured by the portable air permeability apparatus(sec).

Therefore, the flow rate can then be easily and confidently estimated by equation 5.3 and used in the following equation to calculate the permeability coefficient (see Chapter 3):

$$K = \frac{2L\omega QP_2}{(P_1^2 - P_2^2)A} \tag{3.6}$$

where;

K = permeability coefficient;

L = length of the sample;

ω = unit weight of the oxygen;

A = cross sectional area;

P_1 and P_2 are the pressure at both ends of the sample.

Then,

$$K = \frac{2L\omega Q(1.033)}{(2.05^2 - 1.033^2)A}$$

$$= \frac{0.659L\omega Q}{A}$$

using equation 5.3, the following equation is derived

$$K = \frac{0.297L\omega}{AT} \qquad (5.4)$$

Example:

a sample of

$L = 5.17$ cm

$A = 5.0669$ cm^2

$\omega = 1.43$x 10^{-6} kg/cm^3

$T = 78$ seconds

$Q = 0.005845$ cm^3/sec

then

using equation 3.6:

$K = 0.5620$x 10^{-8} cm/sec

and using equation 5.4

$K' = 0.556$x 10^{-8} cm/sec

The permeability coefficient corresponds to that measured at an applied pressure of 1 bar over atmospheric. Because of the highly significant correlation between the results of both the portable air permeability and oxygen permeability tests, the later will be used in the discussion of the effects of curing periods, curing environments and cement type.

Conclusion:

From the limited data available, the portable air permeability test succeeded, as seen from the statistical analysis, in estimating the permeability coefficient confidently. The apparatus has therefore the potential of replacing the conventional oxygen permeability apparatus because of the following:

1 - Lighter in weight and can be carried around.

2 - cheaper; and

3 - estimates the permeability coefficient correctly.

5.6.5 - The Effect of Curing Period:

An examination of the above results indicate that increasing the curing period in all environments produces lower porosities (Fig. 5.1) and finer pore structures (Figs. 5.4, 5.5 and 5.6) for all three mixes. Results of this nature are to be expected since longer curing periods result in a greater degree of hydration and hence lower porosities, a trend shown by others including Ramazanianpour (18) and March (60). Nyame (52) has shown that the pore surface area of plain OPC mixes increased with longer hydration periods and a similar effect was also mentioned by Goto and Roy (46). The effects of curing duration on the pore structure were also studied by Lach and Rosova (14) who produced SEM-micrographs of hydrated cement pastes and showed that denser hydration products became more abundant as the curing period increased. Similar trends to these have also been found for the OPC/pfa and OPC/ggbs mixes by other researchers such as Cabrera (58), Ramazanianpour (18), March (60) and Roy and Parker (21). The results presented here by the author confirm the above findings reported by these various researchers. For example, the PSA values (Fig. 5.2) of uncured OPC samples were about 40-75% of those continuously cured in the three environments and similar trends were seen by the MPD-V results, see Fig. 5.3.

The size range of pores most affected by curing duration was seen to be influenced by both the curing environment and the type of cement. This can be clearly seen in Figs. 5.4 to 5.6 and Table 5.10. For example, the range of pores in which the most significant volume reductions as a result of curing all mixes for one day or more at 20°C+70%RH was approximately between 0.5 and 1.0 µm in diameter. Nonetheless, at 45°C+30%RH this range was increased to cover pores in the region of 0.5-10 µm in diameter.

Continued curing, which results in a greater degree of hydration, reduces the total porosity and increases the probability of the pore being either blocked or narrowed down by the continued formation of hydration products. The effect of curing periods on the properties of mortars showed that in all cases, the three-day cured samples exhibited finer pore structure and lower total porosities resulting in lower permeability results than those uncured. A confirmation of the above observation on the effect of pore structure on permeability is clearly seen when comparing the MPD-V and permeability results. The results of each mix in any one environment indicate that lower permeabilities (Fig. 5.11) were seen for samples showing lower MPD-V (Fig. 5.3), i.e. a finer pore structure. Longer curing periods resulted in a finer pore structure which in turn resulted in lower permeability results. The Concrete Society (44), Grube (44) and many other researchers have also reported similar trends as to the effects of curing on the permeability.

As to the effects of curing duration, the two blended cement mixes cured at 45C+30%RH exhibited a more sensitive behaviour than either plain OPC in all environments or OPC/pfa and OPC/ggbs in the other two environments, see Figs. 5.2, 5.3 and 5.11. Table 5.11 shows this clearly using permeability results. Moreover, the percentage increase in the PSA results of one-day cured OPC/pfa and OPC/ggbs samples, when compared with those uncured, were two to three times larger at 45°C+30%RH than at 20°C+70%RH or 35°C+70%RH, see Fig. 5.2; corresponding reductions in the MPD-V and permeability results were also observed (Figs. 5.3 and 5.11). The reason for this increased sensitivity in the hotter environment 45°C+30%RH, when compared with the other two environments, can be attributed to the fact that while higher evaporation rates (as a result of higher temperatures, lower relative humidities or both) have greater adverse effects on uncured samples, the hydration of slag or the pozzolanic reactions of the pfa are accelerated by higher temperatures in the presence of moisture due to curing for one day or more.

Table 5.10: The size range of pores most significantly reduced in volume by increasing curing periods (μm)

cement Type		environments	
	20°C+70%RH	35°C+70%RH	45°C+30%RH
plain OPC	0.5 to 1	0.5 to 10	0.5 to 10
OPC/pfa	0.5 to 1	0.5 to 1	0.5 to 10
OPC/ggbs	0.5 to 1	0.5 t0 7	0.5 to 10

Table 5.11: Percentage decrease in permeability between uncured and one-day cured samples ((one-day cured - uncured)/uncured)*100%

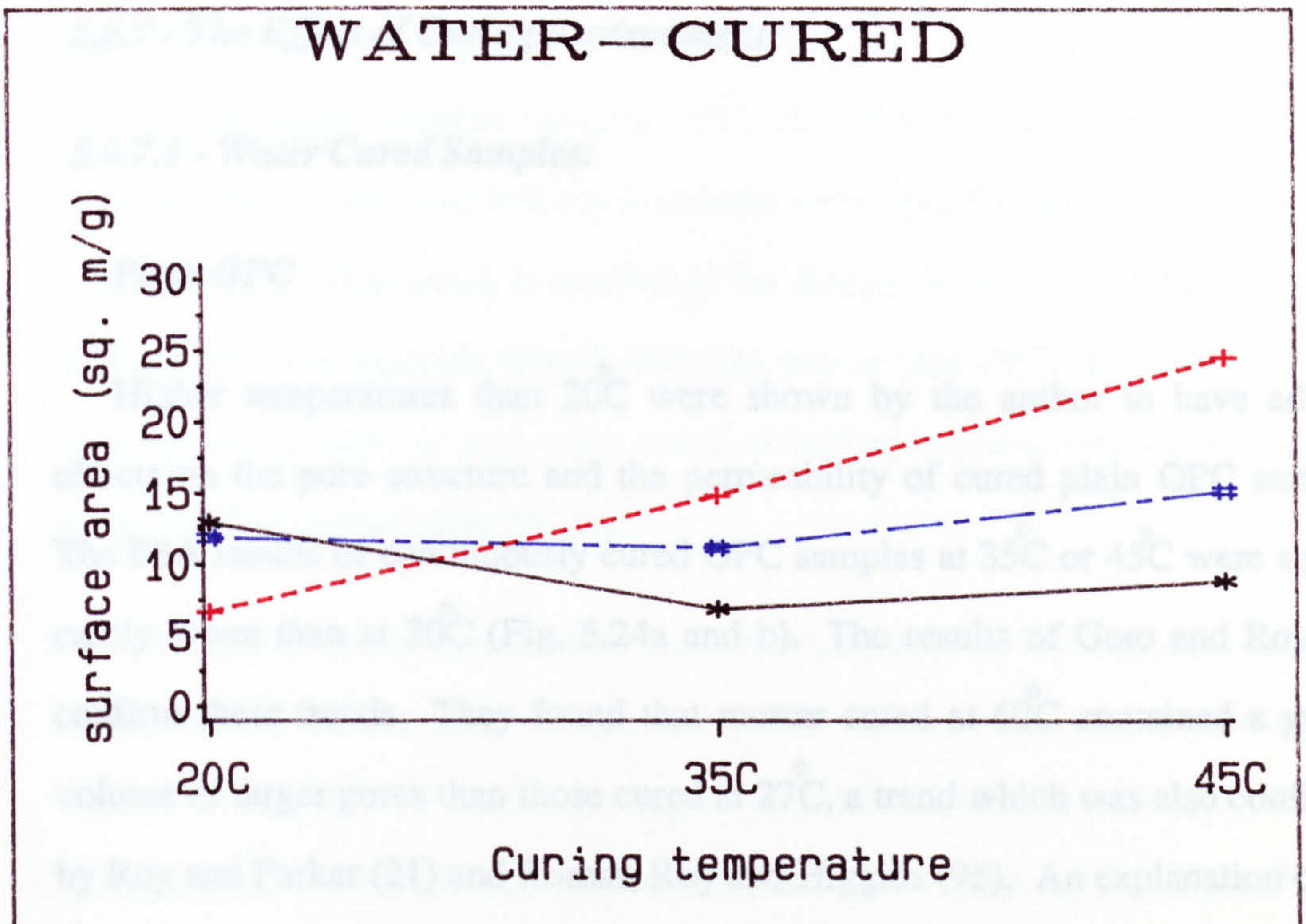
MIX	20°C+70%RH	35°C+70%RH	45°C+30%RH
Plain OPC	58.9	72.7	52.7
OPC/pfa	39.6	40.6	92.0
OPC/ggbs	38.0	70.1	97.0

5.6.6 - Critical Curing Duration:

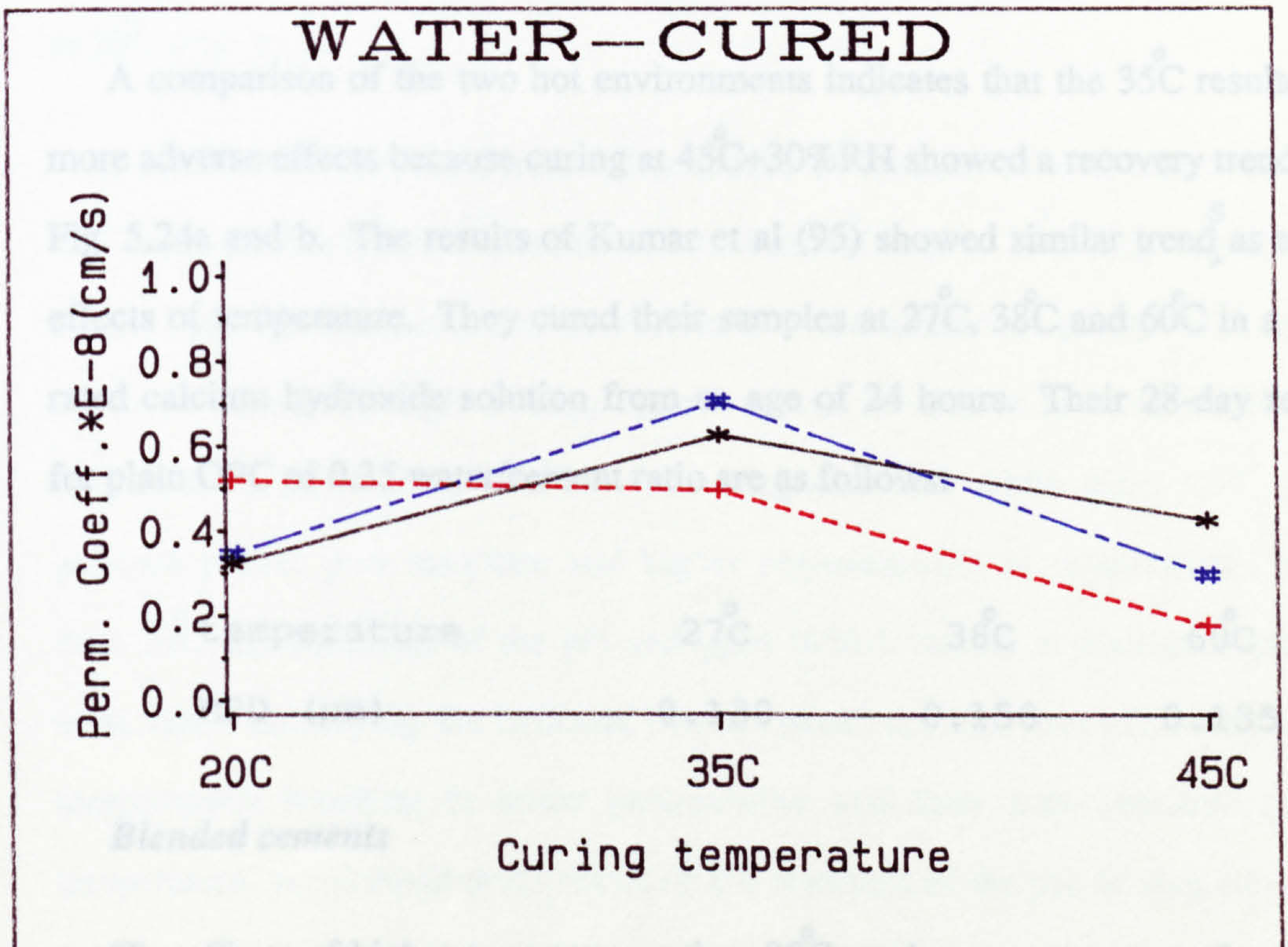
In the majority of cases, the pore structure results obtained from the MIP and permeability results indicated that there existed a critical curing period beyond which effects on the pore structure and permeability became insignificant, see Figs. 5.2, 5.3, and 5.11. This critical curing period seems to depend on the type of cement as well as the curing environment. For example, while plain OPC in all environments and OPC/pfa and OPC/ggbs in the first two environments (i.e. 20°C+70%RH and 35°C+70%RH) showed a critical curing period of approximately three days, the OPC/pfa and OPC/ggbs mixes showed a critical curing period of only one day at 45°C+30%RH. Nyame (52) has also shown that the pore surface area increased until a certain age, after which no significant increase was noticed. He nonetheless found that this age seemed to depend on the initial water/cement ratio.

The critical curing periods found by the author are seen to be in line with the minimum curing periods specified by BS8110 (133) as far as 20°C is concerned. The critical curing period at 20°C was found to be 3 days for all mixes whereas BS8110 specifies similar duration; i.e. 2.67 days as calculated from the equation specified by BS8110. The standard, however, does not specify minimum curing durations for ambient temperatures of over 25°C.

The existence of a critical curing period can be explained by the fact that the rates of hydration of the OPC, pfa or ggbs are known to reach a maximum beyond which they start to decrease. Hence, the changes in the pore structure (per unit time) taking place early in age are significantly bigger than those taking place at later ages. The reason that the OPC/pfa and OPC/ggbs samples kept at 45°C+30%RH exhibited lower critical curing periods than in the other two environments will be dealt with in the next few paragraphs when discussing the effects of curing environments.



(Fig. 5.24a) The effect of curing temperature on the pore surface area tested at 28 days of age



(Fig. 5.24b) The effect of curing temperature on the permeability coefficient, tested at 28 days of age

5.6.7 - The Effect of Curing Environment:

5.6.7.1 - Water Cured Samples:

Plain OPC

Higher temperatures than 20°C were shown by the author to have adverse effects on the pore structure and the permeability of cured plain OPC samples. The PSA results of continuously cured OPC samples at 35°C or 45°C were significantly lower than at 20°C (Fig. 5.24a and b). The results of Goto and Roy (46) confirm these trends. They found that mortar cured at 60°C contained a greater volume of larger pores than those cured at 27°C, a trend which was also confirmed by Roy and Parker (21) and Kumar, Roy and Higgins (95). An explanation of this was given by Neville (17) who stated that the rapid initial hydration appears to form products of a poor physical structure, probably more porous, so that a large proportion of them remain unfilled. A similar argument to this was also given by Bakker (41) in describing work done by Ladwig and Krogbeumker (96).

A comparison of the two hot environments indicates that the 35°C resulted in more adverse effects because curing at 45°C+30%RH showed a recovery trend, see Fig. 5.24a and b. The results of Kumar et al (95) showed similar trends as to the effects of temperature. They cured their samples at 27°C, 38°C and 60°C in a saturated calcium hydroxide solution from an age of 24 hours. Their 28-day results for plain OPC of 0.35 water/cement ratio are as follows:

temperature	27°C	38°C	60°C
MPD (µm)	0.130	0.150	0.135

Blended cements

The effects of higher temperatures than 20°C on the pore structure of continuously cured blended cements samples are seen to be the reverse of those found for plain OPC mixes, see Figs. 5.2, and 5.11. Fig. 5.24a shows that, with the exception of OPC/ggbs samples cured at 35°C, the PSA results of both the blended cement mixes in the two hot environments were significantly higher than those cured at 20°C. This trend is confirmed by Kumar et al (95), Bakker (41) and March (60). For example March (60) has shown that OPC/pfa mixes exhibited lower porosity early in age when cured at higher temperatures, compared with those cured at normal temperatures.

As to the effects on permeability, the precipitants of the additional reactions of the pfa at 35°C were seen to compensate for the more permeable OPC hydrate within, as a result of temperatures higher than 20°C. Therefore, OPC/pfa samples cured at 35°C showed similar permeability results to those achieved at 20°C (Fig. 5.24b). This however was not the case with OPC/ggbs. OPC/ggbs samples cured at 35°C exhibited higher permeability results than those cured at 20°C a trend similar to that of plain OPC. The reason for this may be explained by the results of the pore structure where slag samples showed higher MPD-V results at 35°C than at 20°C (Fig. 5.3).

In addition to this, the permeability results of blended cement mixes cured at 45°C were generally lower than those cured at 20°C and at 35°C (Fig. 5.24b). The reason for such behaviour can be attributed to the additional precipitants created by the reactions of the pfa or slag; these reactions are known to be slower than the hydration of plain OPC. Bakker (41) suggested that while plain OPC mixes produce poorer pore structure and higher permeabilities at temperatures higher than 20°C, the reactions of the pfa and ggbs (which results in additional precipitants hence densifying the hydrated cement paste) are also accelerated by higher temperatures resulting in lower permeability and finer pore structure. These temperature- accelerated precipitants of the reactions of the pfa or slag can therefore compensate for the physically poor hydrated OPC structures within the samples at higher temperatures. Diagrams of these reactions are shown in Fig. 2.17 in

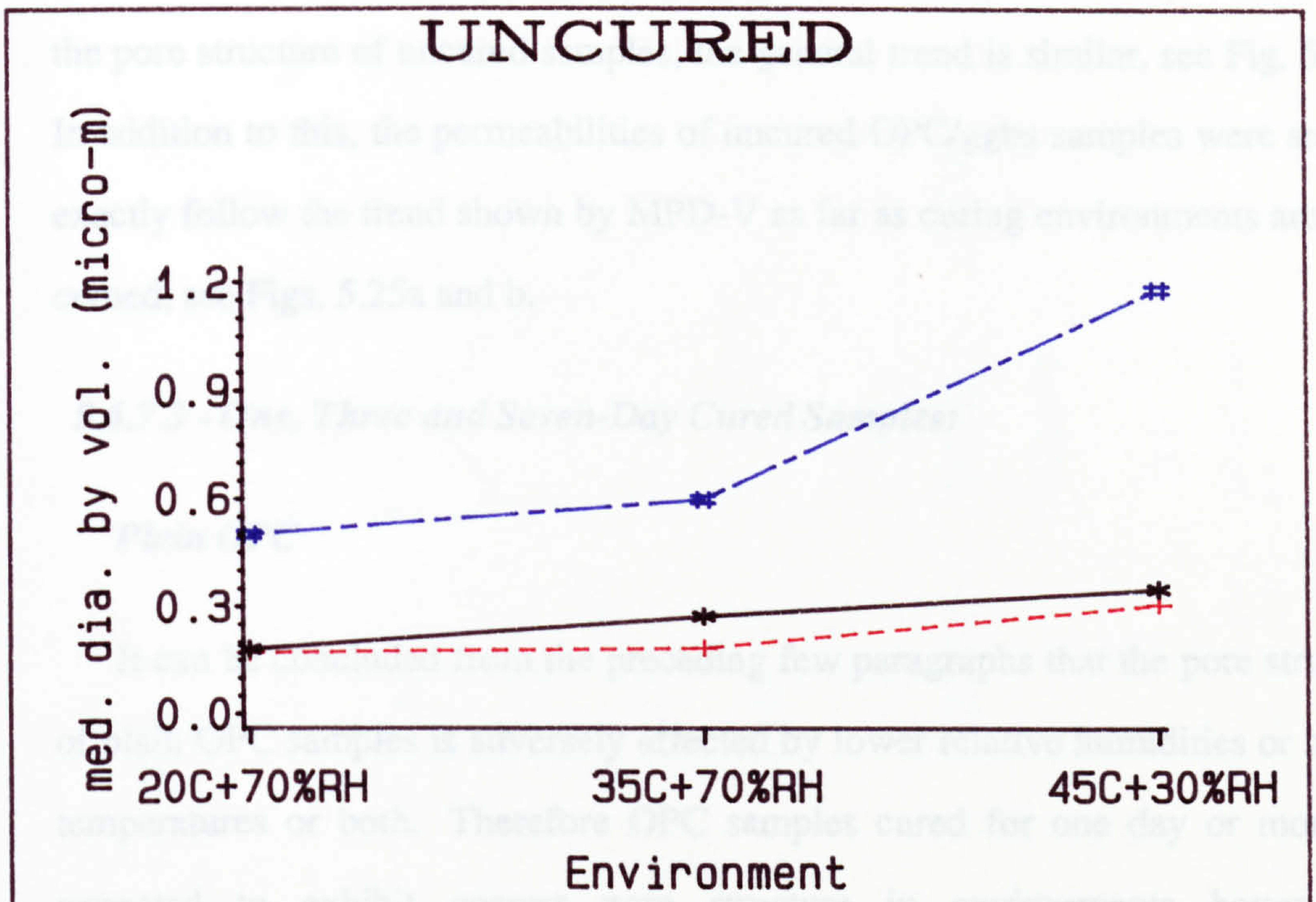
Chapter 2.

5.6.7.2 - Uncured Samples:

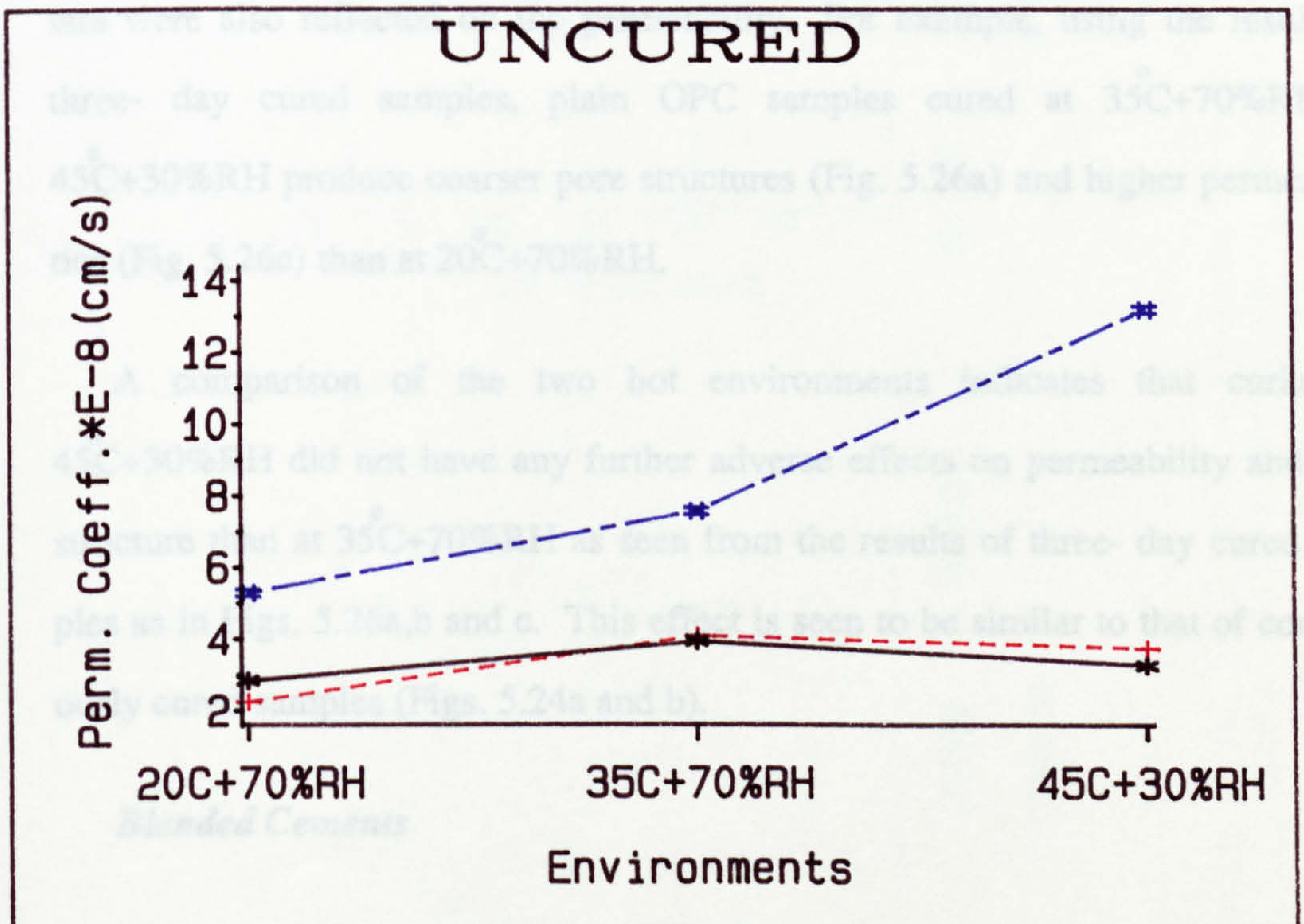
Higher temperatures and lower relative humidities are known to accelerate the evaporation rate of water from fresh and hardened cement mixes. In addition to this, higher temperatures are known to accelerate the hydration rate of OPC and slag (21) and the pozzolanic reaction of pfa (March(69)).

The pore structure of uncured samples of all mixes (plain OPC as well as blended cements) were seen to be adversely affected by the hotter environments compared with that of 20°C+70%RH, see Fig. 5.25a. Curing environments were seen to have the greatest influence on pores between 1 to 10 µm in diameter, the volume of pores in this range were increased significantly as environments became hotter or drier, see Fig. 5.5. This can be attributed to the fact that the evaporation rate of water is higher in the hotter environments than in cooler ones hence resulting a quicker cessation of the hydration process and in a coarser pore structure. The adverse effects of hotter environments on the pore structure of uncured samples were more noticeable with blended cements than with plain OPC and particularly so with ggbs which is used to replace 60% of the OPC, see Fig. 5.25a. The reason for such a trend could be attributed to the combined effects of the high evaporation rates of water from the samples as well as the relatively slow reaction rates of pfa and ggbs. Therefore the lack of moisture is seen to adversely affect the pore structure of all mixes and the greater the rate of early water loss, the greater the adverse effects, i.e. 45°C+30%RH resulted in more adverse effects on uncured samples of all mixes than 35°C+70%RH, see Fig. 5.25a.

Because of the adverse effects of environments hotter than 20°C+70%RH on the pore structure of uncured samples of all mixes, the permeability is expected to be higher in the hotter environments. Although the permeability results of the plain OPC and OPC/pfa mixes were not clearly seen to follow the trend shown by



(Fig. 5.25a) The effect of curing environment on the median pore diameter of uncured samples tested at 28 days of age



(Fig. 5.25b) The effect of curing environment on the permeability of uncured samples tested at 28 days of age the pore structure of uncured samples, the general trend is similar, see Fig. 5.25b. In addition to this, the permeabilities of uncured OPC/ggbs samples were seen to exactly follow the trend shown by MPD-V as far as curing environments are concerned, see Figs. 5.25a and b.

5.6.7.3 - One, Three and Seven-Day Cured Samples:

Plain OPC

It can be concluded from the preceding few paragraphs that the pore structure of plain OPC samples is adversely affected by lower relative humidities or higher temperatures or both. Therefore OPC samples cured for one day or more are expected to exhibit coarser pore structure in environments hotter than 20°C+70%RH. A confirmation of this is seen in Figs. 5.1 - 5.3 and 5.7 - 5.8 whereas Fig. 5.26a clearly illustrate this effect for three-day cured samples.

The adverse effects of hotter environments on the pore structure of OPC mortars were also reflected on the permeability. For example, using the results of three- day cured samples, plain OPC samples cured at 35°C+70%RH or 45°C+30%RH produce coarser pore structures (Fig. 5.26a) and higher permeabilities (Fig. 5.26c) than at 20°C+70%RH.

A comparison of the two hot environments indicates that curing at 45°C+30%RH did not have any further adverse effects on permeability and pore structure than at 35°C+70%RH as seen from the results of three- day cured samples as in Figs. 5.26a,b and c. This effect is seen to be similar to that of continuously cured samples (Figs. 5.24a and b).

Blended Cements

The permeability results of the OPC/pfa samples cured for one day or more at 35°C+70%RH were generally seen to be greater than those similarly cured at 20°C+70%RH despite the higher PSA results as can be seen in Figs. 5.26a and c

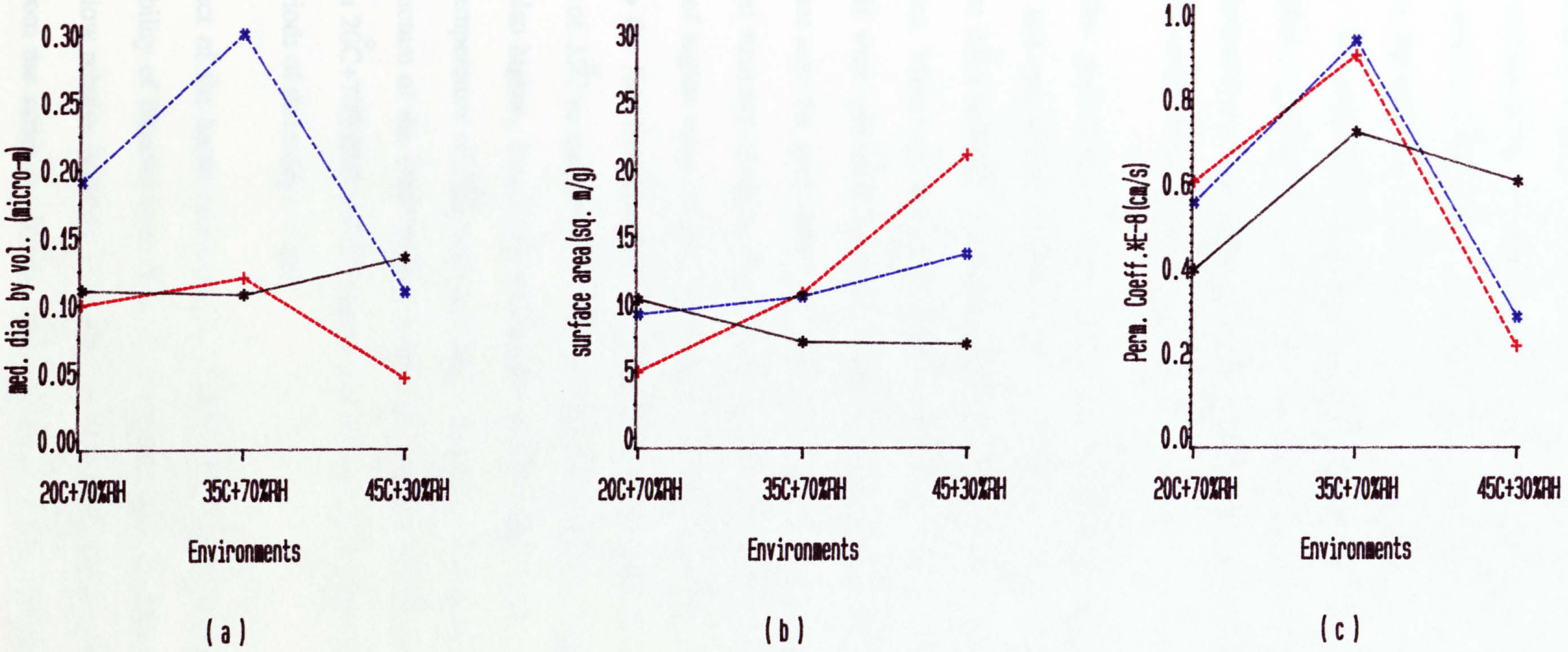


Fig. (5.26) The effects of curing environments on the median pore diameter, pore surface area and permeability of Three-day cured samples tested at 28 days of age

***=OPC +++=OPC/PFA ###=OPC/SLAG

using the results of three day cured samples. This could be attributed to the pore structure results seen earlier where the pfa samples cured at 35°C+70%RH exhibited greater volume of pores in the range of 0.5 to 1.0 μm in diameter compared with those cured at 20°C+70%RH, see Fig. 5.8b. Nonetheless, results from both environments showed closer agreement as the curing periods increased, see Fig. 5.3 and 5.11. The suggested reason for such a trend is that the rate of evaporation at 35°C+70%RH is greater than that at 20°C+70%RH resulting in a quicker cessation of the hydration process. However, when enough time is given for hydration to continue by longer curing periods, results became similar.

The median pore diameter results (Fig. 5.3) of OPC/ggbs samples cured for for one day and over at 35°C+70%RH were significantly higher than those similarly cured at 20°C+70%RH. Fig. 5.26b shows this using the results of three-day cured samples. Moreover, the permeability results of OPC/ggbs samples kept at 35°C+70%RH were generally higher than those stored at 20°C+70%RH, a trend similar to that seen for plain OPC, see Figs. 5.11 and 5.26c. In addition to the poor physical structure of the hydrated OPC within the blended cement samples (as a result of higher temperatures), the reason for such behaviour could also be attributed to the fact that although the reactions are accelerated by the higher temperature of 35°C as compared to 20°C, the evaporation rate of water from the samples is also higher. Hence, the increased reaction rates of pfa or ggbs due to the higher temperature of 35°C were not high enough to compensate for the poor physical structure of the OPC hydrate within the samples (when compared with those kept at 20°C+70%RH) and the higher rate of water loss from samples cured for short periods of three days or less.

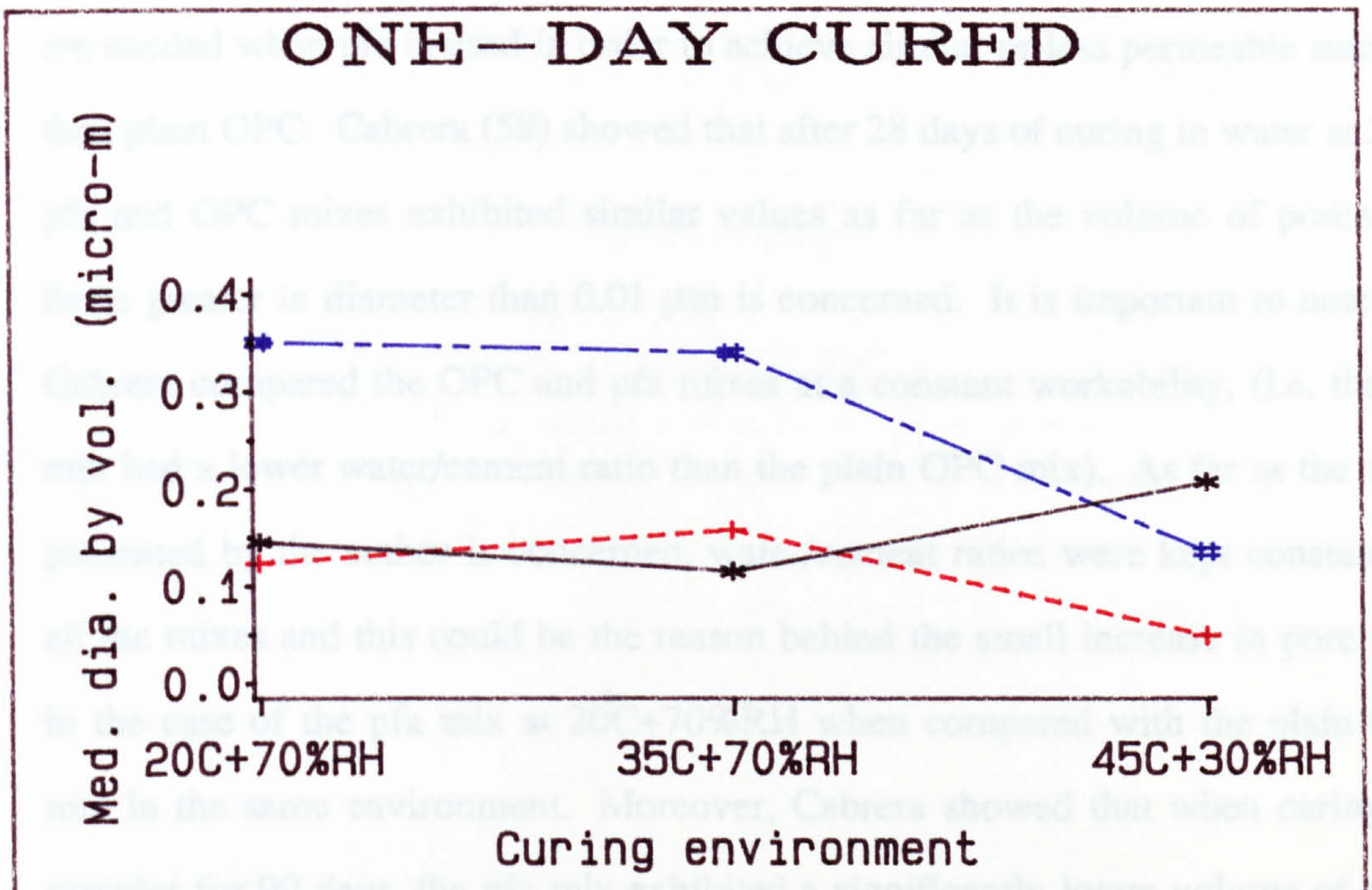
The effect of the hotter environment of 45°C+30%RH on the pore structure and permeability of blended cement was most interesting. In spite of the effects of the very low relative humidity, i.e. 30%, in increasing the evaporation rate of the water from the samples, the high temperature of 45°C resulted in finer pore structure and in more blocked pores hence resulting in lower permeability results from one day of curing when compared with those cured similarly in the other two environments, see Figs. 5.26a, b and c and 5.27a, and b. A possible explanation for this may be that the high temperature of 45°C increased the rate of the reaction of pfa and ggbs hence resulting in finer pore structure and lower permeabilities. This increase was sufficient to compensate for the poor physical structure of the OPC hydrate within these samples (when compared with those kept at 20°C+70%RH) and for the very high rate of water loss when samples were cured for period of at least one day. In addition to this, little change in the pore structure and the permeability results of blended cements were seen in samples cured for periods greater than one day. This suggests that curing for one day in the hot environment of 45°C+30%RH was sufficient to accelerate the initial hydration of the OPC and the additional reactions of pfa and ggbs to a level where no further significant changes in the pore structure can be expected when compared with those cured for 28 days.

5.6.8 - The Effect of Cement Type:

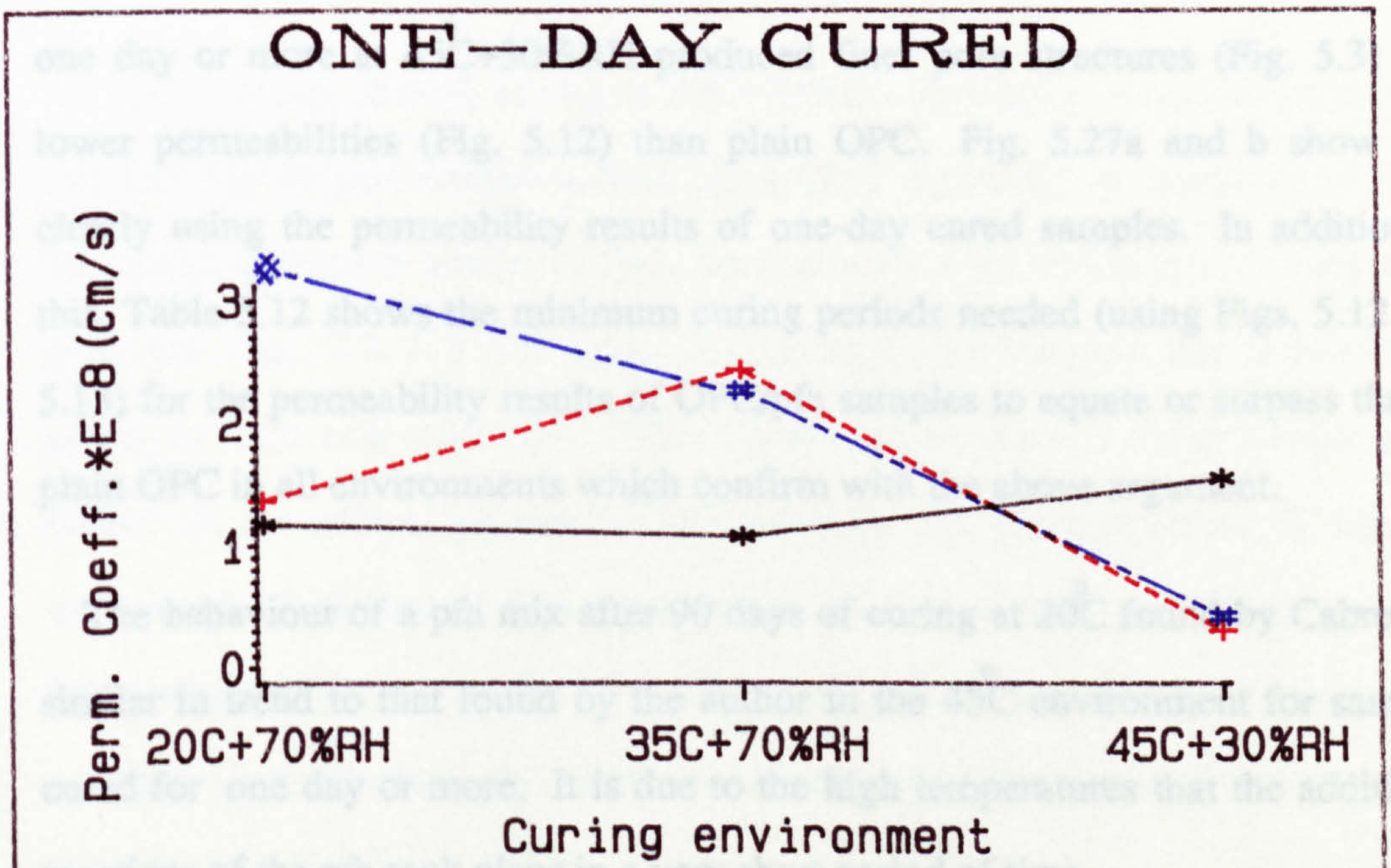
5.6.8.1- The Influence of Pfa:

Fig. 5.25a and b show that the permeability and MPD-V results of uncured OPC and OPC/pfa samples indicate a close agreement in all environments.

The inclusion of pfa at 20°C+70%RH resulted in sometimes similar but more often coarser pore structure and higher permeabilities than plain OPC for curing periods of one day and over, see Figs. 5.3, 5.24a and 5.26a. There is evidence in the literature that the use of pfa when cured at 20°C for long periods, i.e. longer than 28 days, does produce less permeable and finer pore structure mixes (58) than those of plain OPC. For example Lin and Fu (107) have shown that OPC/pfa samples were less permeable than the plain OPC samples after 90 days of curing at 20°C. This shows that at the normal temperatures of 20°C, longer curing periods



(Fig. 5.27a) The effect of curing environment on the median pore diameter of one-day cured samples Tested at 28 days of age



(Fig. 5.27b) The effect of curing environmrnt on the permeability coefficient of one day cured samples

Tested at 28 days of age

are needed when pfa is used in order to achieve similar or less permeable samples than plain OPC. Cabrera (58) showed that after 28 days of curing in water at 20°C, pfa and OPC mixes exhibited similar values as far as the volume of pores of those greater in diameter than 0.01 µm is concerned. It is important to note that Cabrera compared the OPC and pfa mixes at a constant workability, (i.e. the pfa mix had a lower water/cement ratio than the plain OPC mix). As far as the work presented by the author is concerned, water/cement ratios were kept constant for all the mixes and this could be the reason behind the small increase in pore sizes in the case of the pfa mix at 20°C+70%RH when compared with the plain OPC mix in the same environment. Moreover, Cabrera showed that when curing the samples for 90 days, the pfa mix exhibited a significantly lower volume of pores greater in diameter than 0.01 µm than plain OPC.

However, because of the argument given above about the effects of temperature on the hydration products of plain OPC and the additional reactions of pfa, OPC/pfa samples cured for seven days and over at 35°C+70%RH and those cured for one day or more at 45°C+30%RH produced finer pore structures (Fig. 5.3) and lower permeabilities (Fig. 5.12) than plain OPC. Fig. 5.27a and b show this clearly using the permeability results of one-day cured samples. In addition to this, Table 5.12 shows the minimum curing periods needed (using Figs. 5.12 and 5.13) for the permeability results of OPC/pfa samples to equate or surpass that of plain OPC in all environments which confirm with the above argument.

The behaviour of a pfa mix after 90 days of curing at 20°C found by Cabrera is similar in trend to that found by the author in the 45°C environment for samples cured for one day or more. It is due to the high temperatures that the additional reactions of the pfa took place in a very short period of time.

Table 5.12: The minimum curing periods (days) needed for OPC/pfa and OPC/ggbs mixes to equate or surpass the permeability results of plain OPC in the same environment.

cement type	environments		
	20°C+70%RH	35°C+70%RH	45°C+30%RH
OPC/pfa	28	7	less than 1
OPC/ggbs	7	28	less than 1

5.6.8.1 - The Influence of Ggbs:

Uncured OPC/ggbs samples were seen to exhibit a coarser pore structure and higher permeability than either plain OPC or OPC/pfa mixes in all environments, see Fig. 5.25a and b. This trend may be attributed to the high level of ggbs used compared with the percentage of pfa used.

The inclusion of 60% of slag at 20°C+70%RH resulted in a coarser pore structure and higher permeabilities than plain OPC especially in samples cured for three days or less but similar or finer pore structures for curing periods over three days, see Figs. 5.2, 5.3 and 5.13. This is expected because slag is inherently slower to react with water than OPC. Moreover, because of the argument given earlier on the effects of the 35°C+70%RH on the pore structure of blended cements, the inclusion of slag continued to produce coarser pore structures (Fig. 5.3) and higher permeabilities (Fig. 5.13) than plain OPC in this environment. An example which illustrates this trend can be seen using the results of one-day cured samples as in Fig. 5.27a and b.

In addition to this, the results also show that the OPC/ggbs samples cured for one day or more at 45°C+30%RH resulted in a finer pore structure (Fig. 5.3) and lower permeability (Fig. 5.13) results than plain OPC specimens. Figs. 5.26a, b and c and 5.27a and b show this trend using the permeability and pore structure results of one-day and three- day cured samples in all environments. This can be attributed to the observation stated earlier in this section that while OPC produces a poorer pore structure at temperatures higher than 20°C, the formation of additional precipitants from the hydration of the ggbs (which can compensate for this) was sharply accelerated by the high temperature of 45°C. These results of the pore structure were confirmed in trend by Roy and Parker (21) who found that 60/40 slag/OPC pastes exhibited a finer pore structure than plain OPC pastes when cured at 45C.

Table 5.12 indicates that longer curing time is needed at 35°C+70%RH than at 20°C+70%RH for the permeability of OPC/ggbs to equate or surpass that of plain OPC. Nontheless, much shorter curing time is required with OPC/ggbs when dealing with the 45°C+30%RH environment.

The trends of the results shown by the author indicates that to achieve the changes in pore structure that may take place after curing at 20°C for long periods may need much less curing time when the OPC/pfa or OPC/ggbs samples are cured at the high temperature of 45°C. While the permeability and MPD-V results of uncured ggbs samples were significantly higher than those of plain OPC in all environments, those OPC/pfa and OPC/ggbs specimens cured for one day or more and kept at 45°C+30%RH had improved permeabilities compared with the plain OPC mixes. These trends can be seen in Figs. 5.27a and b. This showed the superiority of the partial replacement of OPC by either pfa or slag in extreme hot environments from the point of view of permeability of one day and over cured samples, despite the lower relative humidity.

The results of the two cement replacement materials indicate that while OPC/ggbs samples produce similar or better results than OPC/pfa for samples cured for over three days at 20°C+70%RH (Figs. 5.2 and 5.14), the OPC/pfa mix exhibited better results for all curing durations in the two hot environments.

5.7 - Conclusions:

The following conclusions are based on the results found from the investigation of the effects of curing durations and curing environments (similar to those found in Middle Eastern countries) on the porosity and pore structure, permeability and water absorption of three mortar mixes (i.e. plain OPC, OPC/pfa and OPC/ggbs) of an equal water/cement ratio. The initial mix temperatures was controlled to be as close as possible to that of the environment in which they were placed and, in all cases, moisture loss was allowed to to take place only from the top-as-cast face of the sample. The duration of curing ranged from no curing at all to 28 days in all three environments and all tests were carried out at 28 days of age.

5.7.1 - The Relationships Between the Tests Results:

1 - The permeability results were seen to relate best with the median pore diameter by volume (MPD-V) results.

2 - The water absorption results are lowered (in the case of finer pore structures) only when the influences of more blocked pores and lower total porosity exceed that of the increase in capillary suction due to the increase in surface tension. Therefore, with the exception of the total porosity, the results of the pore structure found from the MIP can not be used to explain the changes in water absorption results.

3 - No significant statistical relationship was found between the water absorption and permeability results.

4 - Highly significant linear relationship was found between the oxygen permeability and the portable air permeability results.

5.7.2 - The Effect of Curing Duration:

1 - Longer curing periods resulted in lower porosity, finer pore structure, lower permeability and lower water absorption results for all mixes and in all environments.

2 - The tests of permeability and MIP indicated that there exists a critical curing period beyond which little changes, if any, occur for curing periods up to 28 days. This critical curing period was always seen to be less than or equal to three days.

3 - A critical curing period of about three days was seen for plain OPC mixes in all environments and OPC/pfa and OPC/ggbs samples at 20°C+70%RH and 35°C+70%RH.

4 - At 45°C+30%RH, a critical curing period of one day was seen for OPC/pfa and OPC/ggbs samples.

5.7.3 - The Effect of Curing Environment:

1 - Environments hotter than 20°C+70%RH were seen to adversely affect the pore size distribution and permeability results of uncured samples of all mixes and the hotter the environment, the greater the adverse effect.

2 - For the OPC mixes, the hot environments of 35°C+70%RH and 45°C+30%RH resulted in higher porosity, greater permeability and a higher number of large pores than those cured correspondingly at 20°C+70%RH.

3 - The hot environment of 35°C+70%RH resulted generally in similar pore size distributions and permeabilities for the OPC/pfa samples only when curing for seven days or longer when compared with those cured at 20°C+70%RH but higher permeabilities were seen for curing periods of three days and less.

4 - The hot environment of 35°C+70%RH was seen to adversely affect the pore structure and permeability of OPC/ggbs samples at all curing periods when

compared to similarly cured samples at 20°C+70%RH.

5 - Curing the OPC/pfa or OPC/ggbs samples for one day or more at 45°C+30%RH results in significantly better pore structure and permeability results when compared with the other two environments.

5.7.4 - The Effect of Cement Type:

1 - While OPC/pfa samples showed either worse, but more often similar, results at 20°C+70%RH to plain OPC, the OPC/pfa samples cured in the two hot environments produced better results as shown by all tests.

2 - The OPC/ggbs samples were seen to exhibit, in general, greater permeabilities and coarser pore structure than the plain OPC at 20°C+70%RH and 35°C+70%RH. However, the results of one day and over cured OPC/slag samples at 45°C+30%RH were generally better than those of the plain OPC when measured by all tests.

3 - With the exception of samples stored at 20°C+70%RH, the comparison between the two cement replacement materials indicated that the use of 30% pfa resulted in finer pore size distribution and lower permeabilities.

CHAPTER SIX

STRENGTH AND DURABILITY-RELATED PROPERTIES FOR OPC, OPC/PFA, AND OPC/GGBS CONCRETE MIXES

6.1 - Introduction:

The addition of pfa and slag together with curing periods and curing environments were shown to have effects on the durability properties of the mortar mixes as seen in the previous chapter. The effects of these variables on the pore structure of the cement mixes was explained directly by the results of the MIP and indirectly by the oxygen permeability and water absorption tests.

It was considered necessary to see whether or not the effects of the above parameters could also be reflected on concrete mixes measured using less sophisticated and in some cases standard durability and mechanical tests. In addition to this, a comparison will be made between the durability related tests to establish which if any is best suited for quality control on site to establish whether curing has been properly carried out. The widely used and accepted cube compressive strength test will also be carried out on all mixes and in all environments to investigate the applicability of such test for quality control. The cube test is invariably the only test used on site to check on the quality of cast-in-place concrete. The discussion will attempt to establish whether or not the strength test is a valid test for durability of in-situ concrete.

6.2 - Mix Proportions:

Five concrete mixes were chosen to study the effects of workability, cement content, and the addition of fly ash and ggbs on the parameters to be measured. The water/cement ratio for the control mix, mix two, was similar to that of the mortar mixes in the previous chapter. Details of the mix proportions are shown in Table 6.1.

The workability as measured by the slump test for the concrete mixes in all environments are shown in Table 6.2. The workability was seen not to be affected by the initial mix temperature if and only if the right amount of water is added at once. However, if the amount of water firstly added is less than that required to reach a certain slump, then the final water/cement ratio will be higher in the hotter environments because of the temperature- accelerated setting rate of cement and the higher evaporation rate of water from the mix.

Mixing was carried out as described in Chapter 3 and with each mix cast the following specimens were prepared:

1 - Ten 100mm cubes for the measurement of compressive strength and the total porosity.

2 - Five 350 mmX450 mm slabs, each containing four 150 mm diameter 100 mm deep cylindrical plastic moulds, see Plate 6.1, for the assessment of the initial surface absorption, water absorption and the relative air permeability using Figg method.

6.3 - Curing and Environmental Conditions:

The environments used in this part of the investigations were similar to those used in the mortar tests, see Table 5.2 (Chapter 5). The procedures for material storage and casting were identical to that of the mortar programme, see section 5.2. In an attempt to control the mix temperature as close as possible to that of the curing environments all materials were stored in the respective environments for one week before casting. Because of the size limitations of the environmental chamber, all casting were carried out in the laboratory at 20°C. The slabs were placed back in their respective environment immediately after casting. A loss of 5-10°C in the initial temperature of the mixes from that of the respective

Table 6.1: The mix proportions for the concrete mixes

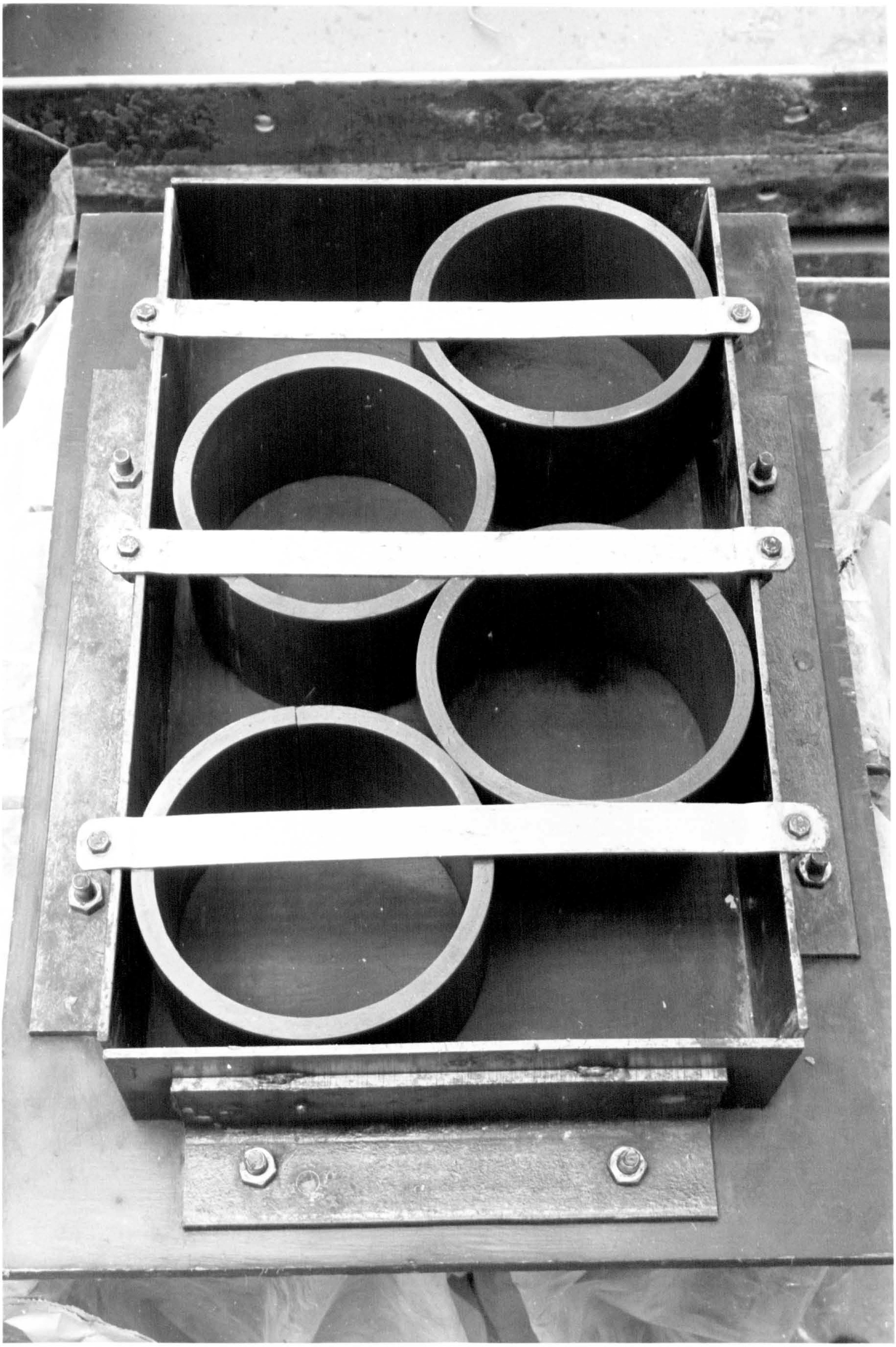
mix	OPC	pfa	slag	sand	gravel	water	remarks
1	1	0	0	2.1	4.2	0.64	low strength
2	1	0	0	1.5	3.0	0.44	high strength
3	1	0	0	1.5	3.0	0.48	as two but twice as workable
4	0.7	0.3	0	1.5	3.0	0.415	as two but 30%pfa
5	0.4	0	0.6	1.5	3.0	0.44	as two but 60%slag

* workability is 50-75mm of slump for all except mix three where the workability is between 100-150mm.

Table 6.2: The workability (slump-mm) for the concrete mixes

mix	Environments		
	20°C+70%RH	35°C+70%RH	45°C+30%RH
1	65	60-65	60
2	65-70	60	65
3	135	125-130	125-130
4	65	60	55-60
5	60	55-60	55-60

Plate 6.1: A typical slab and moulds used to cast the concrete specimens.



environment was seen in the two hot environments, see Table 6.3.

Table 6.3: The initial mix temperatures for the concrete mixes.

Mix	Environments	
	35°C+70%RH	45°C+30%RH
1	28°C	37°C
2	29°C	38°C
3	28°C	36°C
4	30°C	36°C
5	27°C	39°C

With the exception of uncured samples, the top-as-cast faces of all specimens were covered immediately after casting by means of polythene sheetings. Wet hession was applied at approximately six hours of age. The 100 mm cubes were demoulded at an age of one day and all sides except the top-as-cast face were covered by means of polythene sheetings and cellotape. The 150 mm diameter 100 mm deep discs were kept in thier moulds to the day of the start of the tests. The curing programme was similar to that of the mortar part (Chapter 5); it was divided into five categories: uncured, one-day, three-day, seven-day and continuous curing.

6.4 - Tests Carried out:

The five tests chosen to study the strength and some durability-related properties were as follows:

1 - Compressive strength;

2 - the test for water absorption;

3 - the initial surface absorption test (ISAT);
4 - the Figg relative air permeability test; and
5 - the total porosity.

The tests for water absorption and Figg were conducted on the same sample. All tests were carried out as described previously in Chapter 3 at 28 days of age.

6.5 - Results

6.5.1 - Compressive Strength:

The actual results of the test for compressive strength are shown in Figs. 6.1 and 6.2. The statistical analysis performed on the differences between the strengths of nominally identical samples indicates a test repeatability of 10% for 95% level of confidence. Results recorded are the average of two cubes.

- The Effect of Curing Period:

Figs. 6.1 and 6.2 illustrate the effects of curing periods on the strength of the five mixes stored in the three different environments. The results (Fig. 6.1) show that the compressive strength of one day and over cured specimens of all the OPC mixes were generally unaffected by the different curing periods. The effect of curing periods on the OPC/pfa mix showed similar trends to those of the OPC mixes although the difference between the cured and uncured specimens was statistically significant in all environments, see Fig. 6.2. With the exception of the OPC/ggbs samples stored at $45^{o}C$+30%RH, the sensitivity of the slag to curing period was greater than either the plain OPC or the OPC/pfa mixes.

- The Effect of Curing Environment:

As far as the first OPC mix (low strength) is concerned, the results in the different environments were all similar. On the other hand, the other two OPC mixes showed a reduction in compressive strength of samples stored at

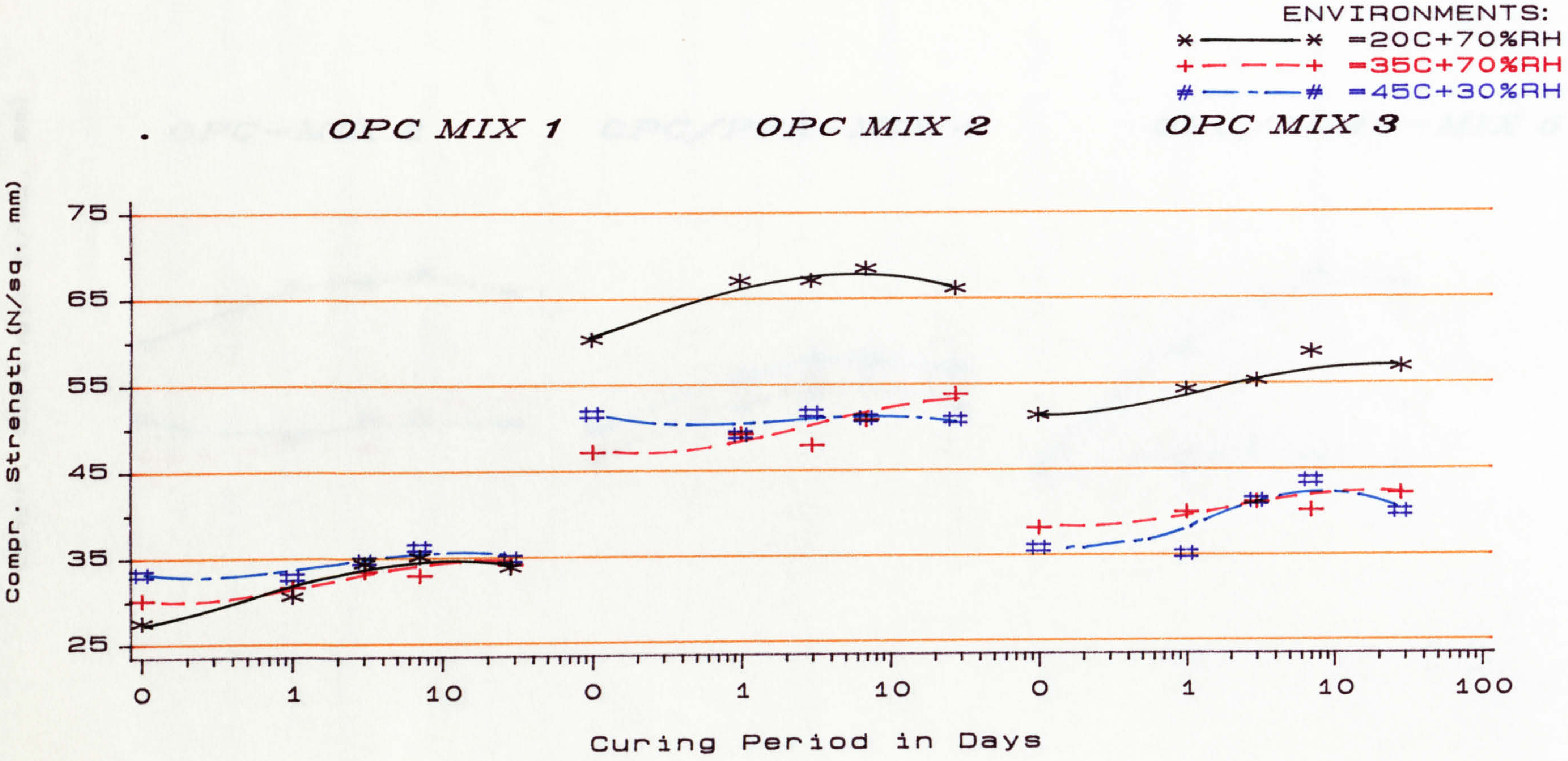


Fig. (6.1) The effects of curing period and environment on the compressive strength of concretes (Tests carried out at 28 days of age)

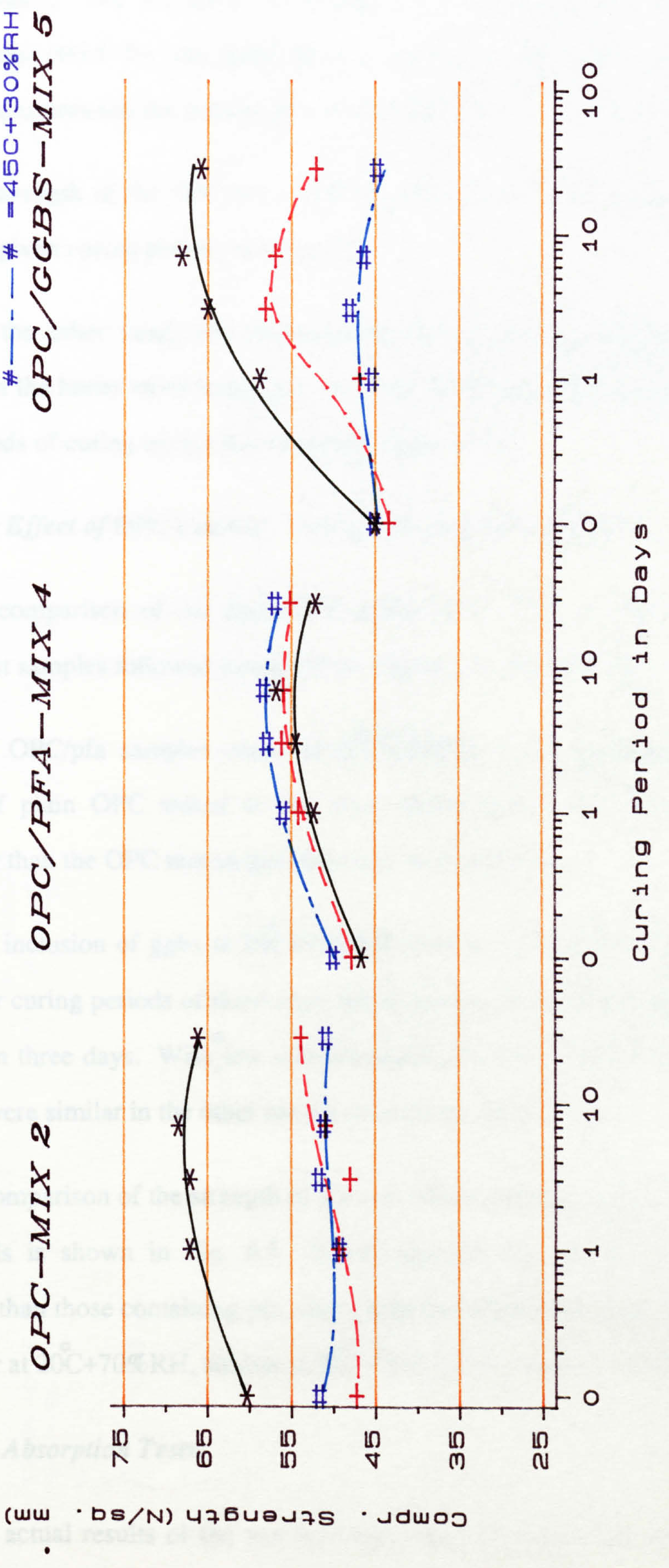


Fig. (6.2) The effects of curing period and environment on the compressive strength of concretes (Tests carried out at 28 days of age)

35°C+70%RH or 45°C+70%RH when compared to those kept in the 20°C environment. The reduction in strength was in some cases up to 20% for specimens cured for the same periods although there were no significance differences between the results obtained from the two hot environments.

The strength of the OPC/pfa samples were similar for all three environments for any given curing period, see Fig. 6.2.

On the other hand, the compressive strength of the OPC/ggbs specimens stored in the hotter environments were lower than those kept at 20°C (Fig. 6.2) for all periods of curing except the condition of no curing.

- The Effect of OPC Content, Workability and Cement Type:

A comparison of the three OPC mixes shows that mix two produced the strongest samples followed by mix three and mix one respectively.

The OPC/pfa samples cured at 20°C+70%RH were generally weaker than those of plain OPC stored in the same environment, see Fig. 6.3, but were stronger than the OPC mix in the other two environments.

The inclusion of ggbs at 20°C+70%RH resulted in similar results to the plain OPC for curing periods of three days and over but were weaker for curing periods less than three days. With a few exceptions,the strength of both the OPC and slag mixes were similar in the other two environments, see Fig. 6.4.

A comparison of the strength of the two mixes containing cement replacement materials is shown in Fig. 6.5. While uncured slag samples were generally weaker than those containing pfa, slag samples cured for one day and longer were stronger at 20°C+70%RH, similar at 35°C+70%RH but weaker at 45°C+30%RH.

6.5.2 - Absorption Tests:

The actual results of the test for total water absorption are shown Figs. 6.6

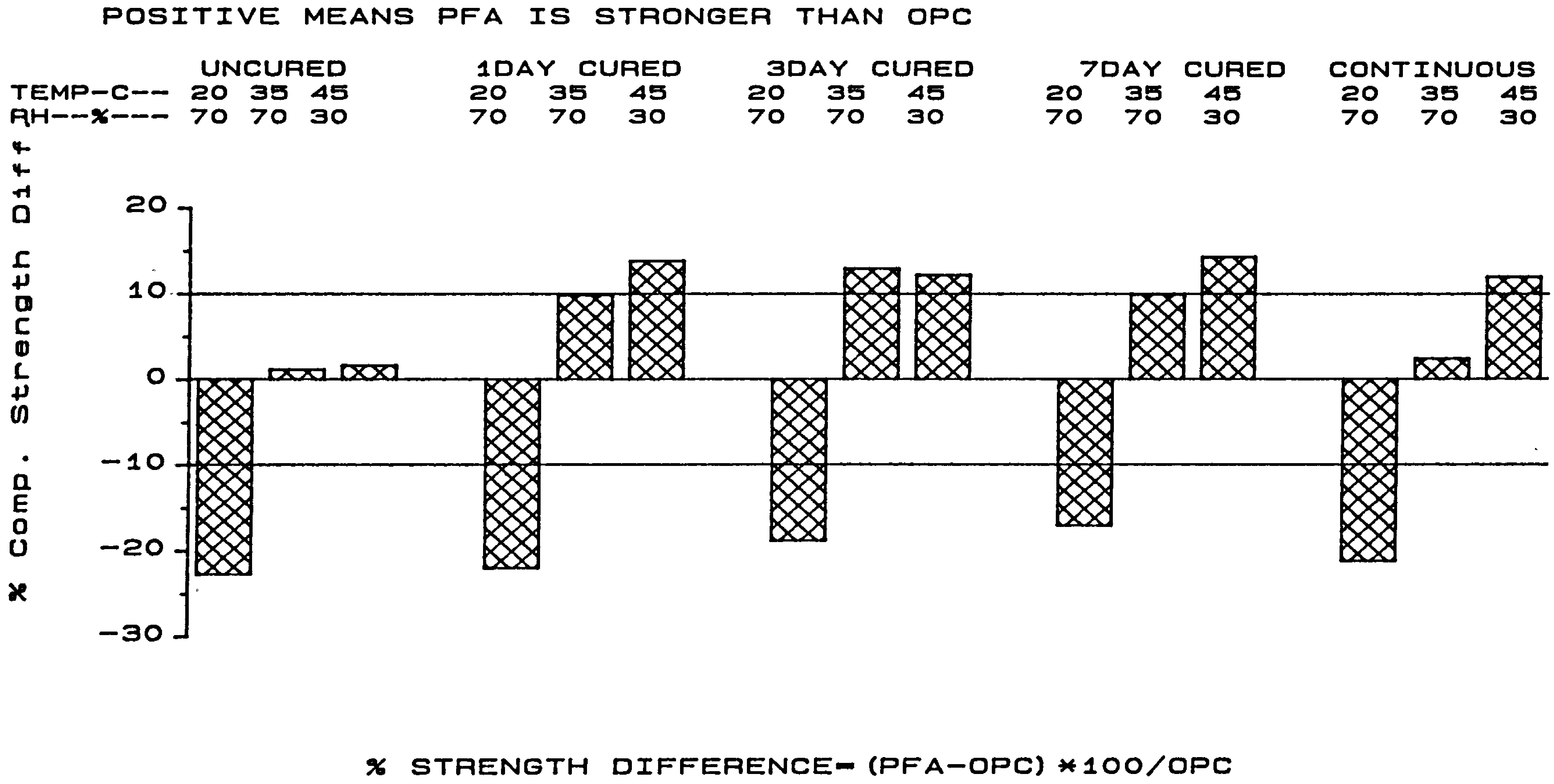


FIG. (6.3) The strength difference between pfa and OPC concretes in different environments and under various curing periods (Tests carried out at 28 days of age)

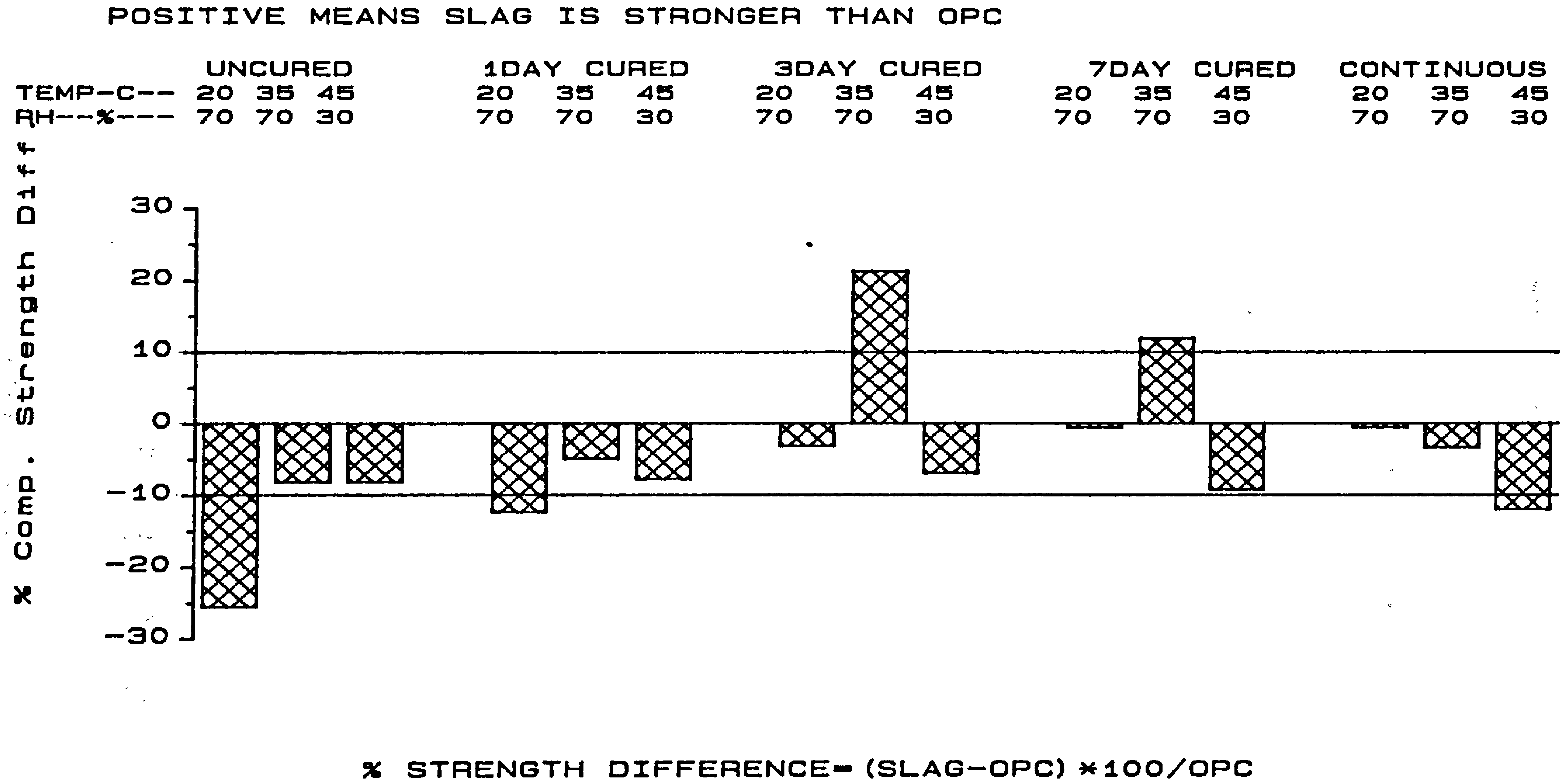


Fig. (6.4) The strength difference between slag and OPC concretes in different environments and under various curing period (Tests carried out at 28 days of age

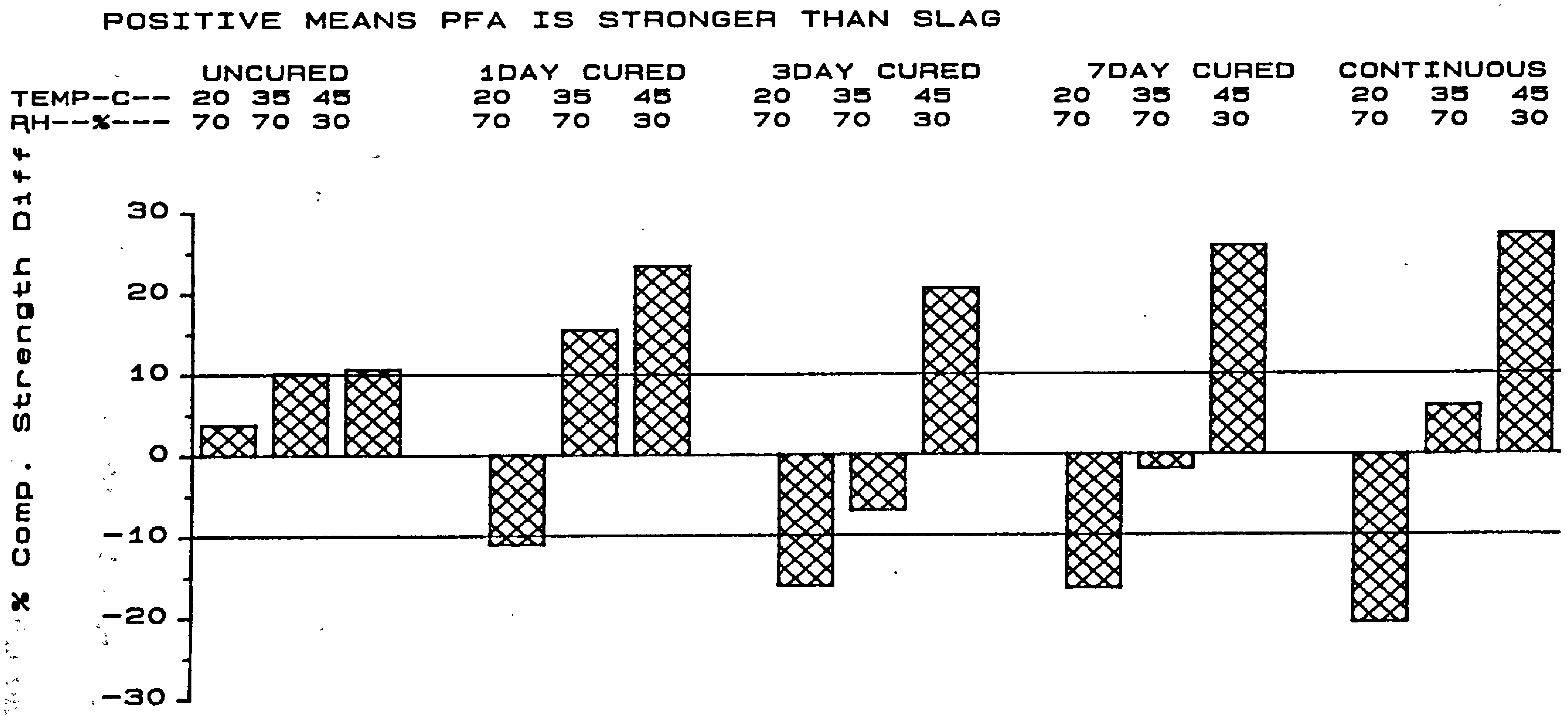


FIG. (6.5) The strength difference between pfa and slag concretes in different environments and under various curing periods (Tests carried out at 28 days of age and 6.7 and Figs. 6.8-6.9 illustrate the results for the initial surface absorption test (ISAT). The statistical analyses conducted on the differences between readings of nominally identical samples has shown a repeatability of 10% for a 90% level of confidence for both tests.

- *The Effect of Curing Period:*

Longer curing periods resulted, as expected, in lower absorption results for both total water absorption and ISAT for all mixes in all environments.

- *The Effect of Curing Environment:*

With the exception of those specimens of mix one that were stored at 35°C+70%RH, the total water absorption results of one day and over cured plain OPC samples in the two hot environments were slightly higher but not significantly different from those kept at 20°C+70%RH. The ISAT values on the other hand were statistically higher at both 35°C+70%RH and 45°C+30%RH than at 20°C+70%RH. In addition to this, the ISAT values of similarly cured OPC samples kept in both the two hot environments were generally similar.

The OPC/pfa samples stored at 35°C+70%RH exhibited generally similar results to those kept at 20°C+70%RH. Furthermore those samples stored at 45°C+30%RH showed lower total water absorption results but similar ISAT values when compared with those kept at 20°C+70%RH or at 35°C+70%RH.

The slag samples stored in either the 35°C or the 45°C environments exhibited higher water absorption results than those found at 20°C+70%RH for uncured, one-day and three-day cured samples whereas the ISAT results were generally similar.

- *The Effect of OPC Content, Workability and Cement Type:*

A comparison of the three OPC mixes indicate that with the exception of

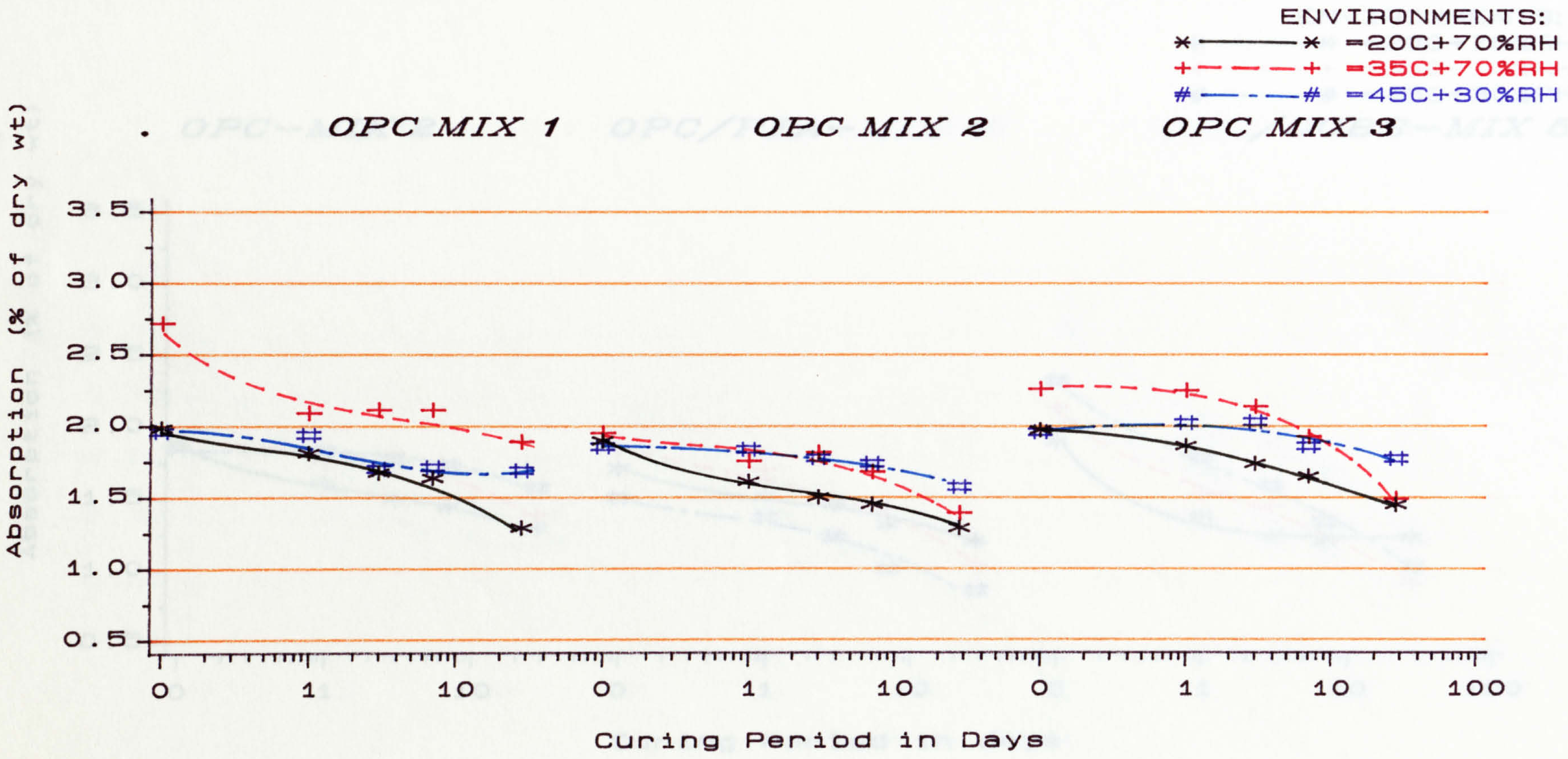


Fig. (6.6) The effects of curing period and environment on the total water absorption of concretes (Tests carried out at 28 days of age)

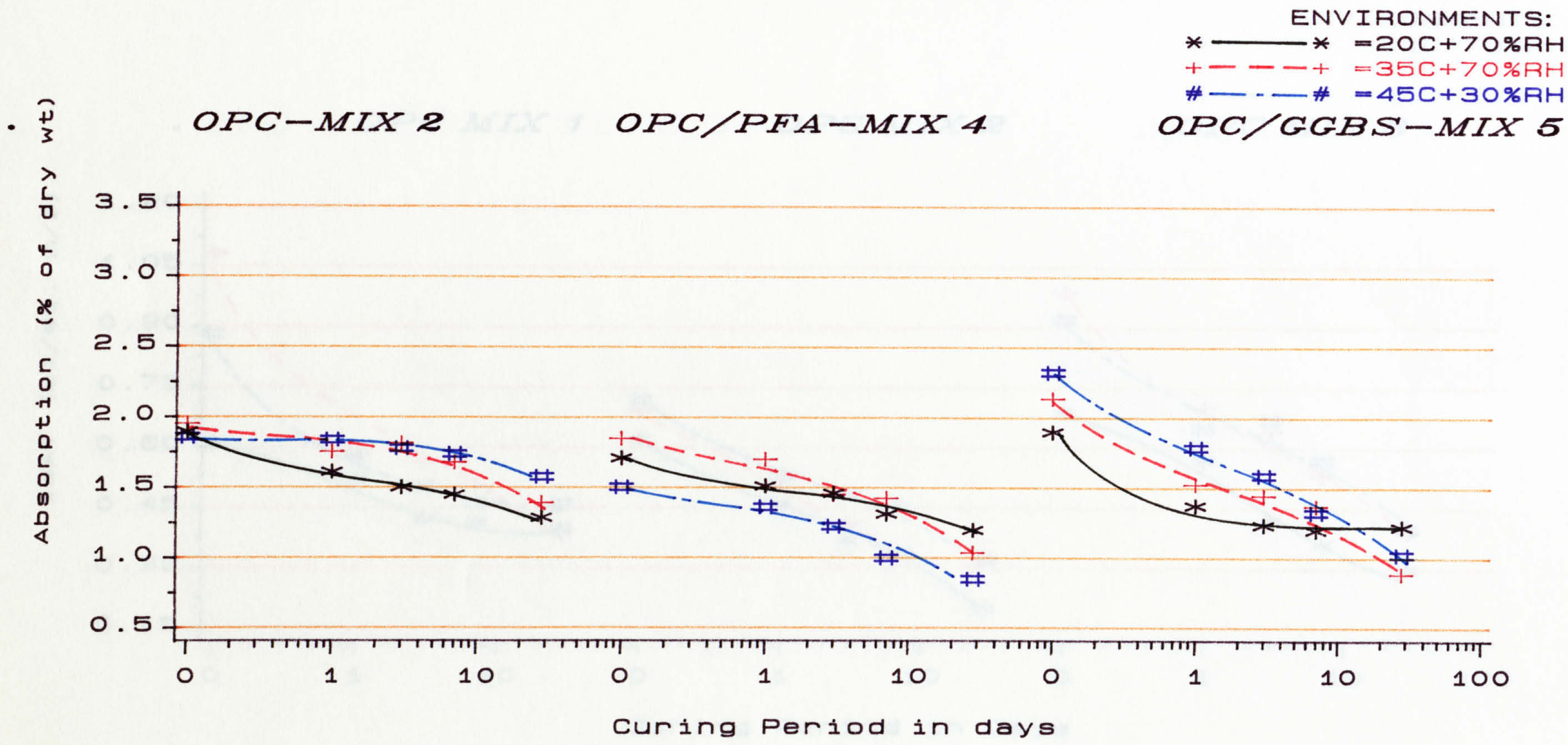


Fig. (6.7) The effects of curing period and environment on the total water absorption of concretes (Tests carried out at 28 days of age)

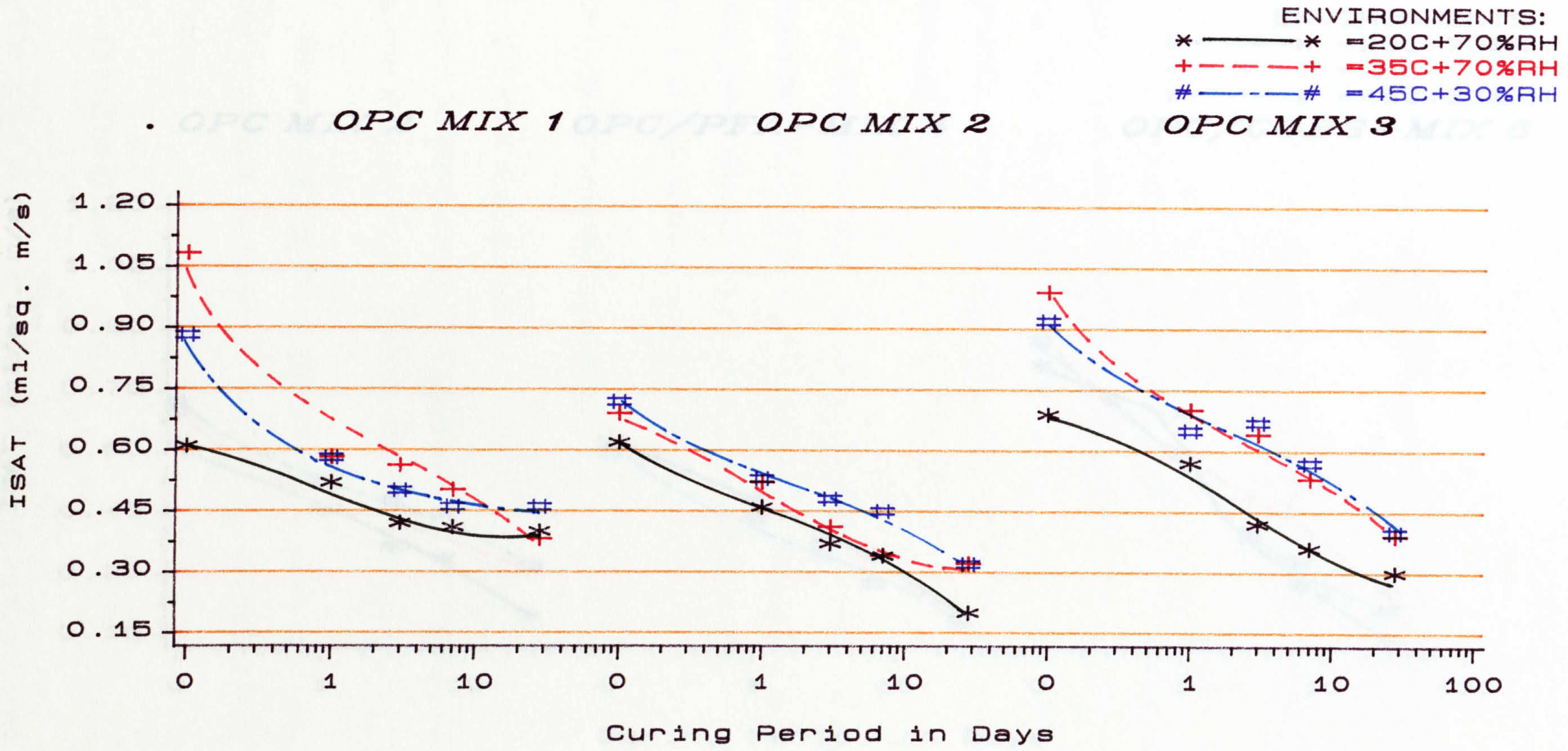


Fig. (6.8) The effects of curing period and environment on the initial surface absorption of concretes (Test carried out at 28 days of age)

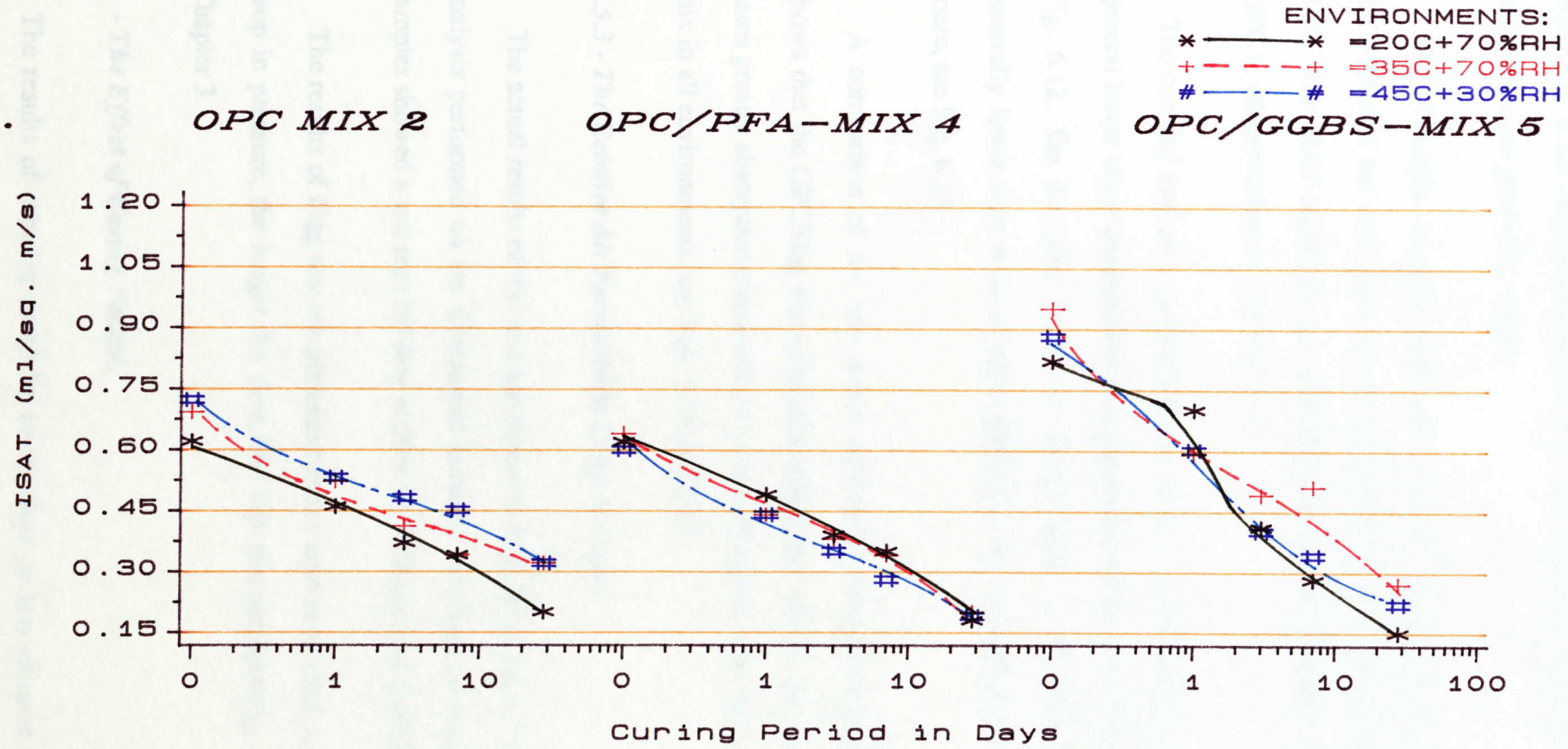


Fig. (6.9) The effects of curing period and environment on the initial surface absorption of concretes (Tests carried out at 28 days of age) uncured samples, mix two absorbed in general the lowest amount of water especially when considering the ISAT values. However, the results of mixes one and three were generally similar.

The OPC/pfa samples produced similar results to the plain OPC at 20°C+70%RH but were generally lower in the other two environments, see Fig. 6.10. The ISAT results of the OPC/pfa mixes were generally lower than plain OPC in all environments, see Fig. 6.11.

The one day and over cured OPC/slag samples in all environments showed in general lower water absorption results than those of the plain OPC (mix two), see Fig. 6.12. On the other hand, the ISAT values of the OPC/ggbs mix were generally lower than those of plain OPC only for curing periods of 7 days and more, see Fig. 6.13.

A comparison of the two mixes containing cement replacement materials shows that the OPC/slag mix exhibited sometimes similar but in the majority of cases greater absorption characteristics when compared with those of the OPC/pfa mix in all environments, see Figs. 6.14 and 6.15.

6.5.3 - The Relative Air Permeability (Figg Method):

The actual results of this test are shown in Figs. 6.16 and 6.17. The statistical analysis performed on the differences between readings of nominally identical samples showed a test repeatability of 20% for 90% level of confidence.

The results of Figg test are presented as the time in seconds needed per 1 kPa drop in pressure, the longer the time, the less the permeability, see Fig. 3.9 in Chapter 3.

- The Effect of Curing Period:

The results of samples cured for seven days or less showed that there is an

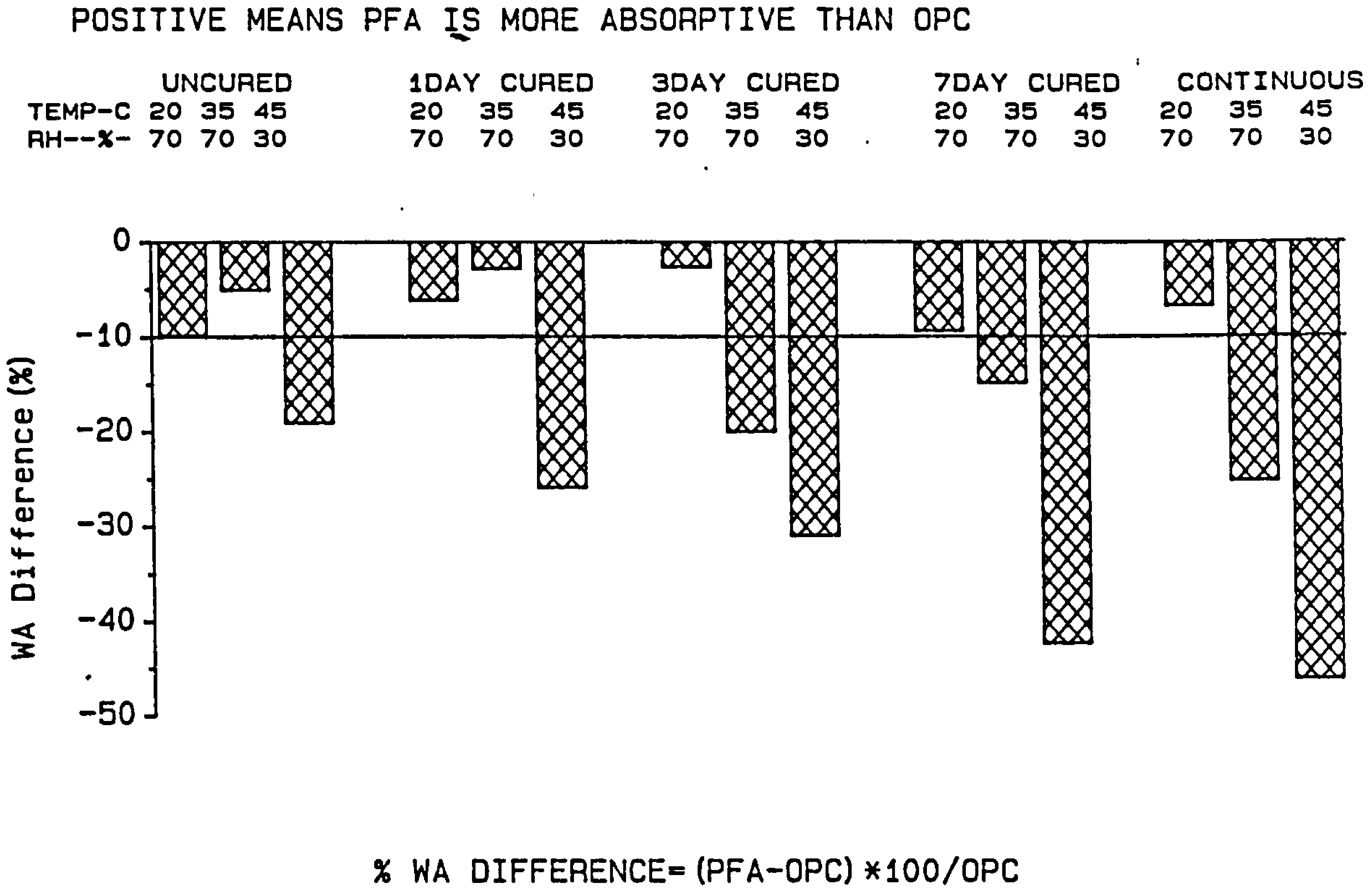


Fig. (6.10)
The water absorption difference between pfa and OPC concretes in different environments and under various curing periods (Tests carried out at 28 days of age

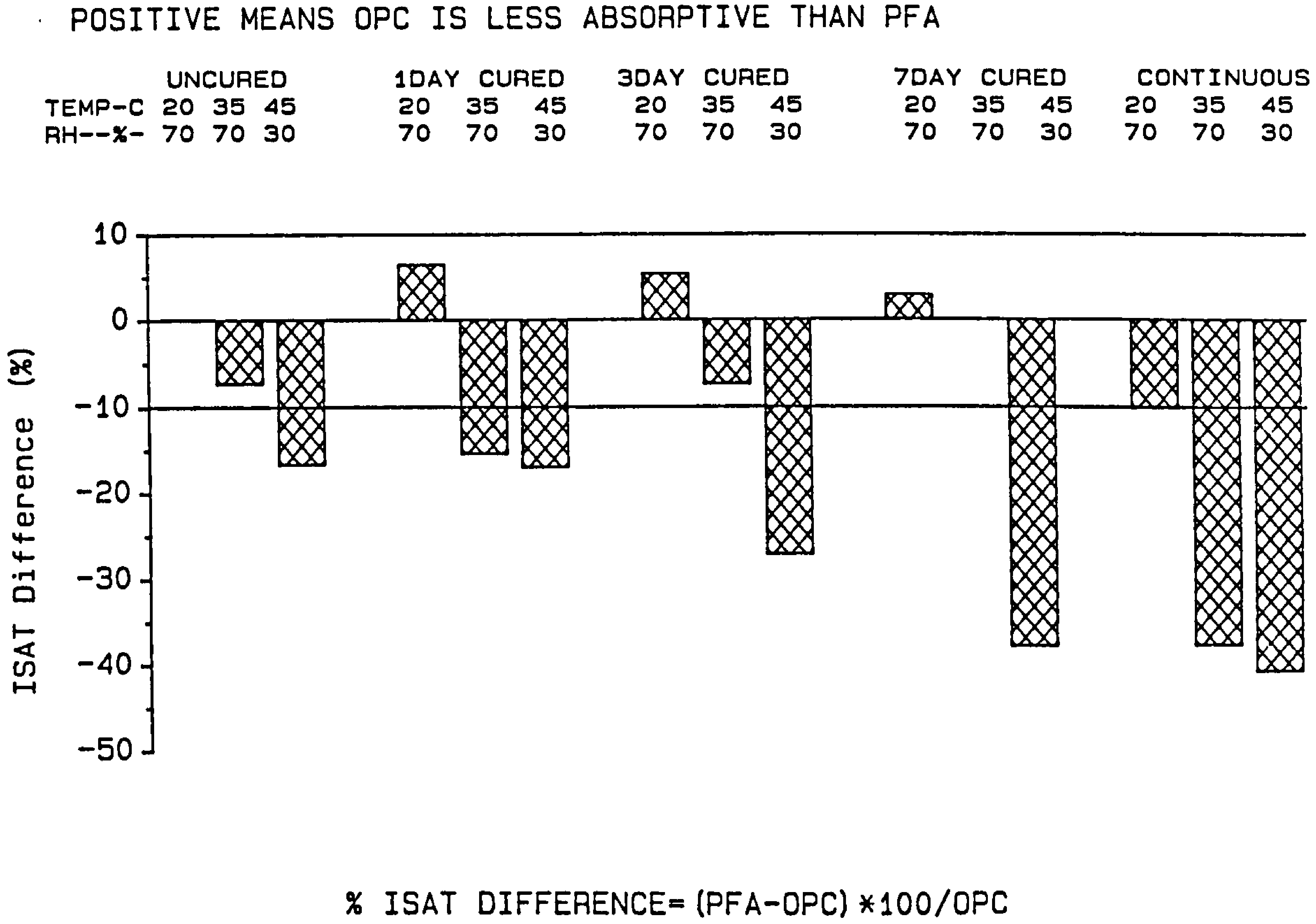


Fig. (6.11) The ISAT difference between pfa and OPC concretes in different environments and under various curing periods (Tests carried out at 28 days of age

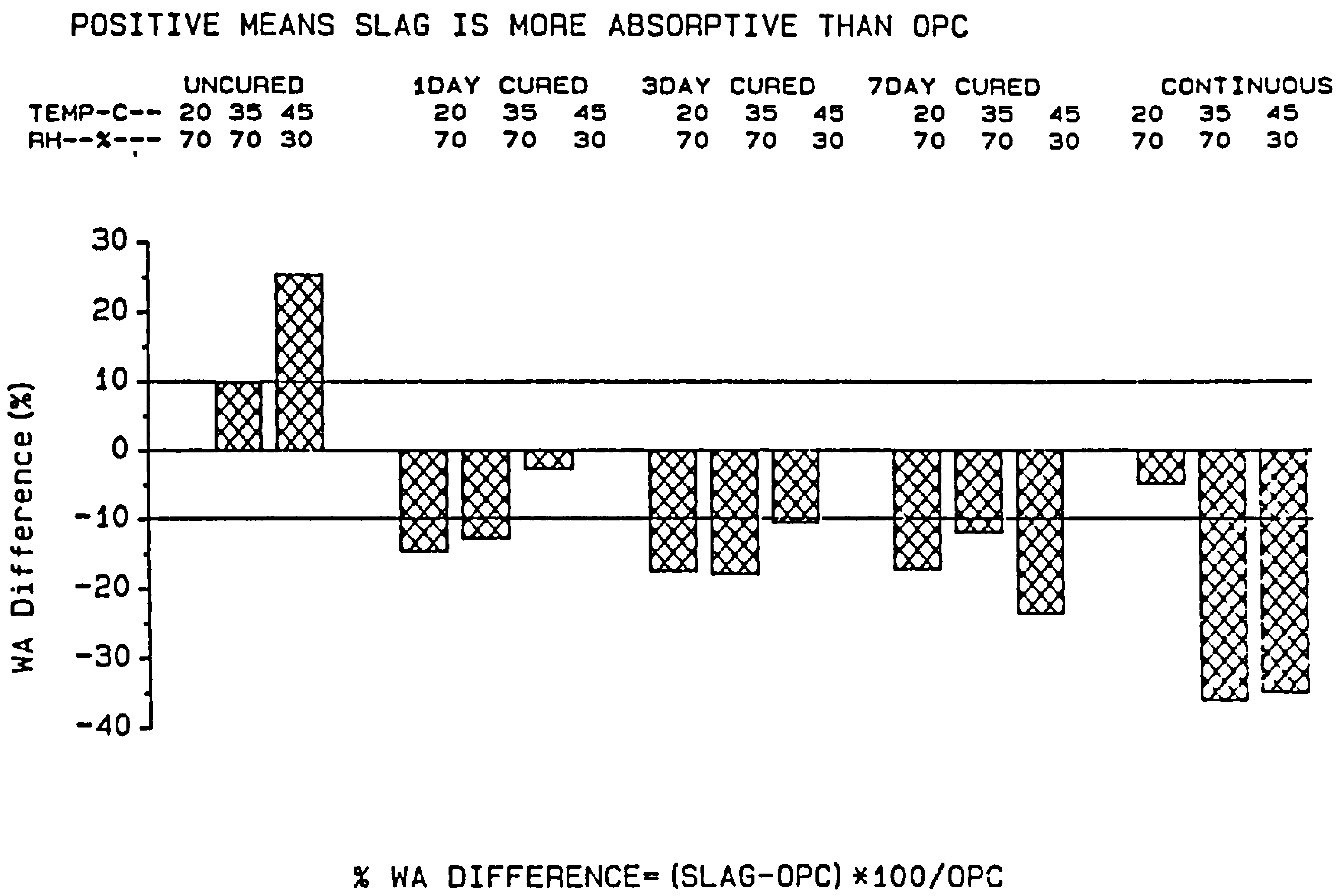


Fig. (6.12)
The water absorption difference between slag and OPC concretes in different environments and under various curing periods (Tests carried out at 28 days of age

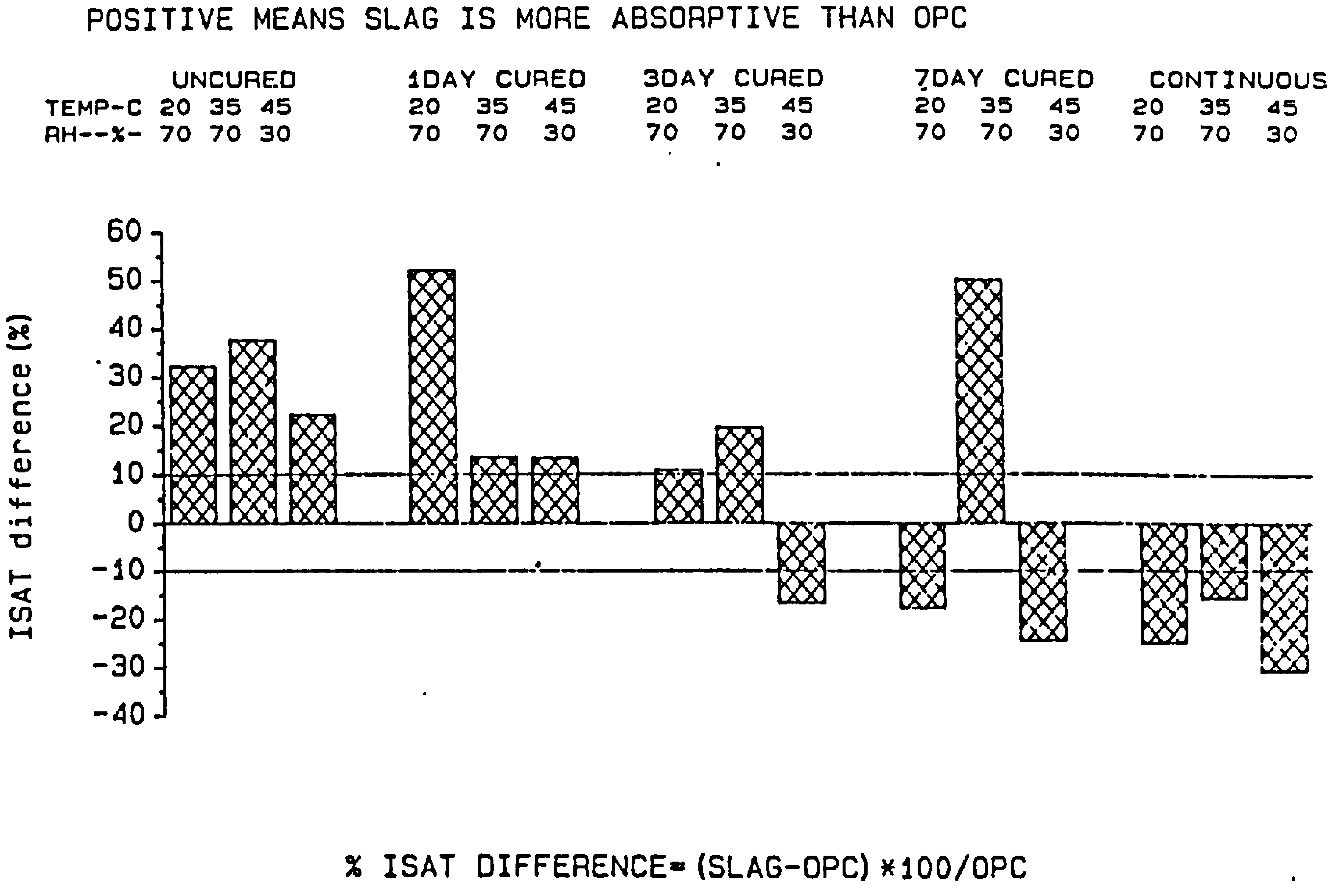
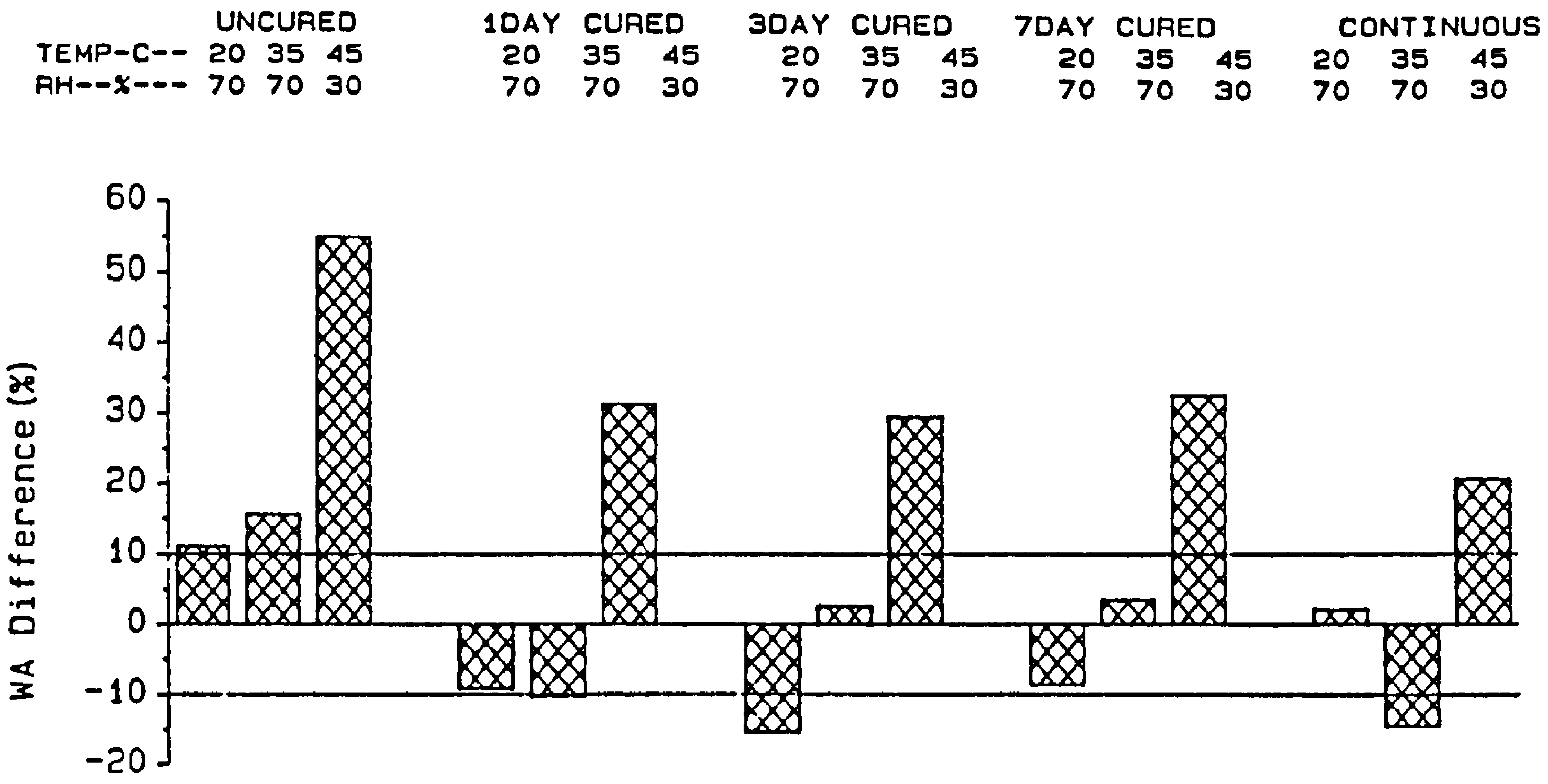


Fig. (6.13) The ISAT difference between slag and OPC concretes in different environments and under various curing periods (Tests carried out at 28 days of age

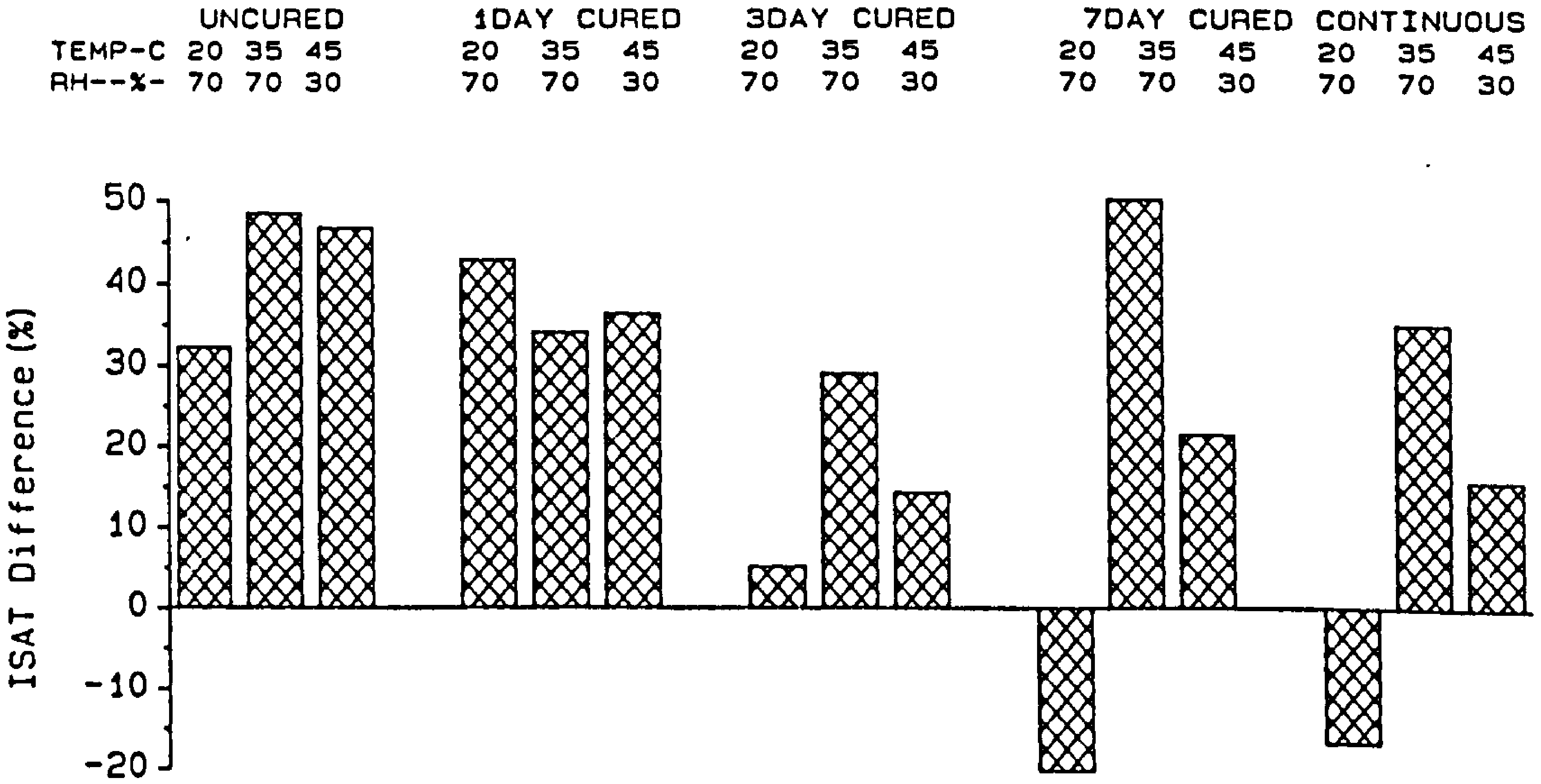
POSITIVE MEANS SLAG IS MORE ABSORPTIVE THAN PFA



% WA DIFFERENCE= (SLAG-PFA) *100/PFA

FIG. (6.14)
The water absorption difference between slag and pfa concretes in different environments and under various curing periods (Tests carried out at 28 days of age

POSITIVE MEANS SLAG IS MORE ABSORPTIVE THAN PFA



% ISAT DIFFERENCE= (SLAG-PFA) *100/PFA

Fig. (6.15) The ISAT difference between pfa and slag concretes in different environments and under various curing periods (Tests carried out at 28 days of age

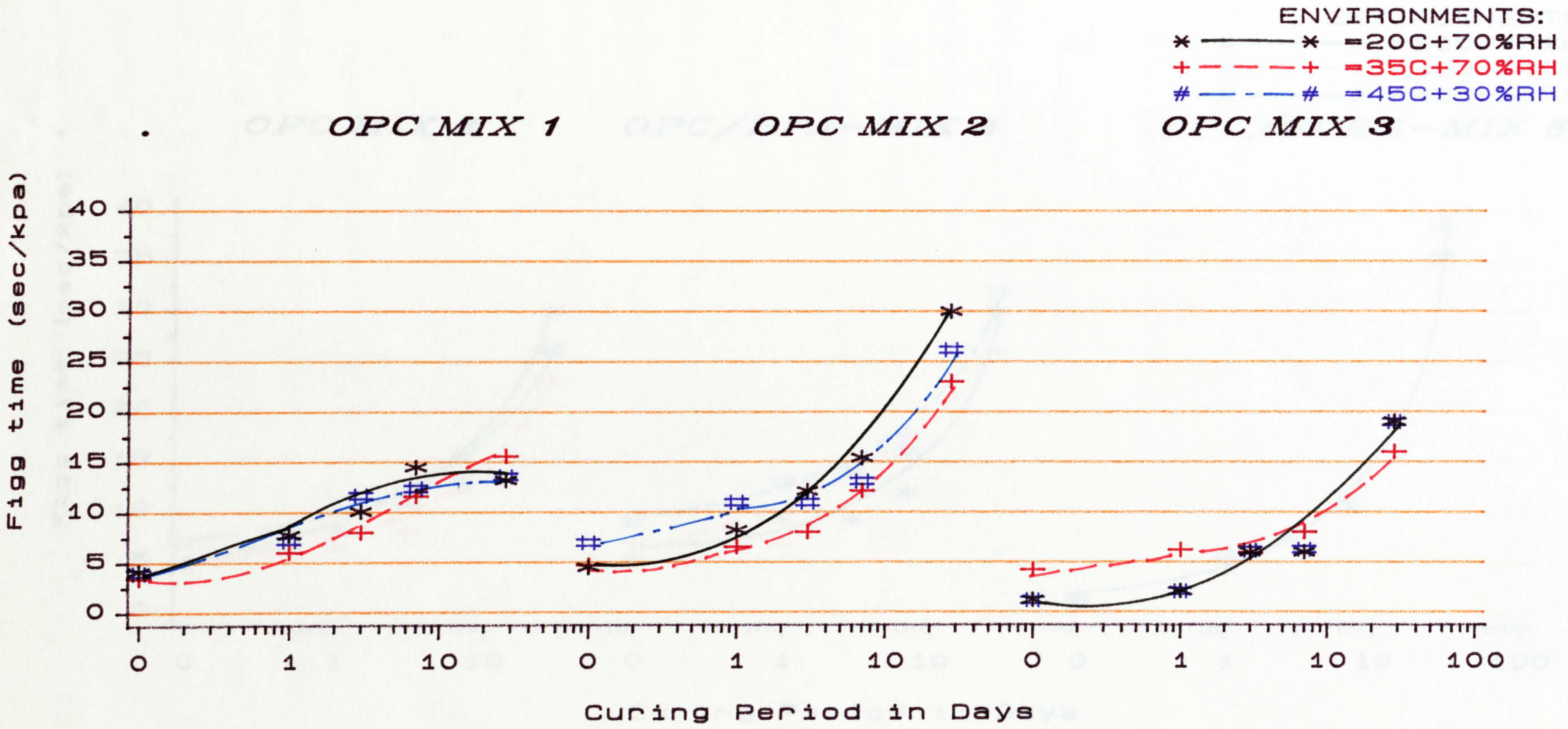


Fig. (6.16) The effects of curing period and environment on the relative air permeability by Figg method --the longer the time, the less permeable the sample-- (Tests carried out at 28 days of age)

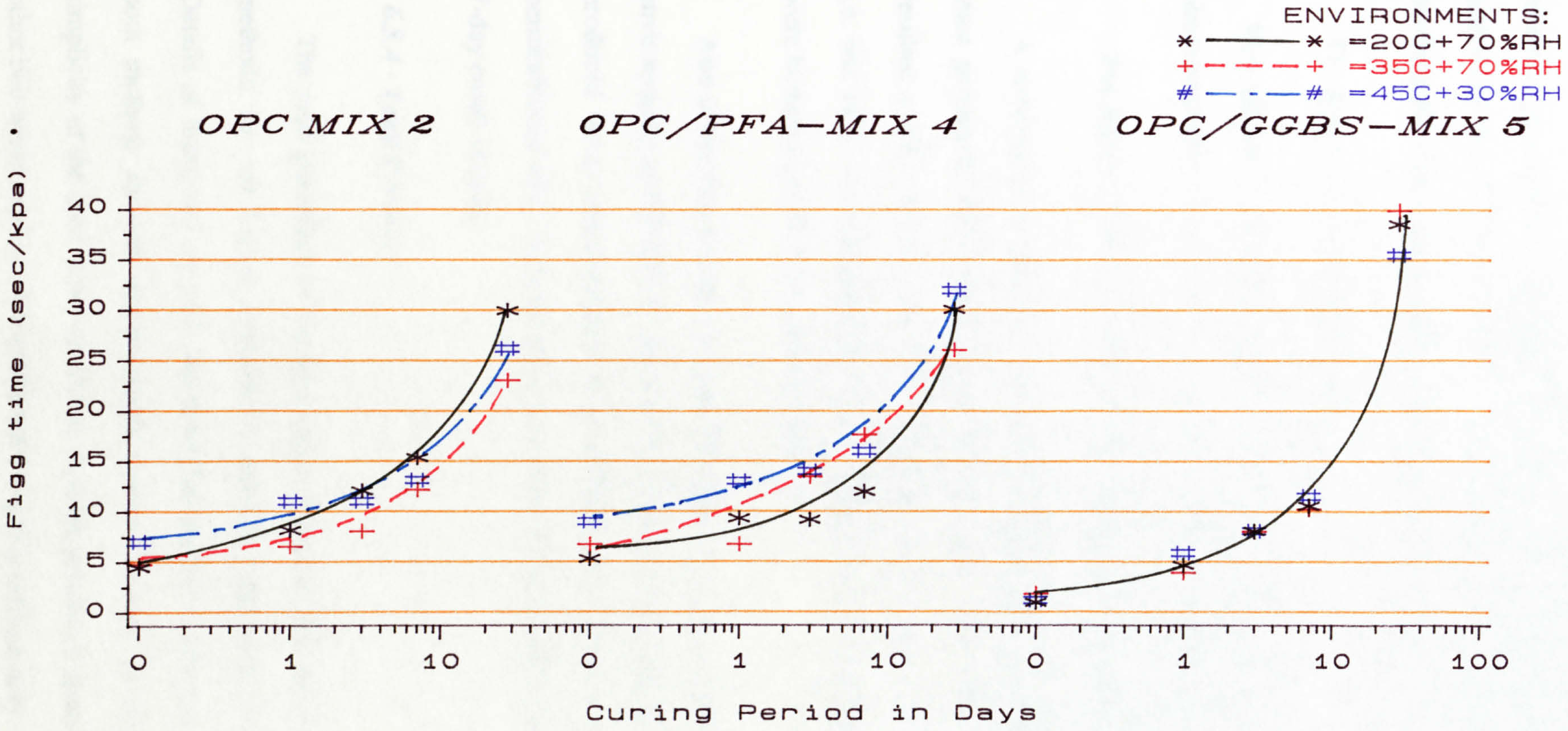


Fig. (6.17) The effects of curing period and environment on the relative air permeability by Figg method
--the longer the time, the less permeable the sample--
(Tests carried out at 28 days of age)

increasing trend in the results as curing periods increased although the differences between consecutive curing periods were sometimes insignificant. However, the difference between seven-day and continuously cured samples was bigger than the difference between any other two consecutive curing periods.

- The Effect of Curing Environment:

With all mixes and for any given curing period the relative permeability results obtained in each of the three environments were not significantly different.

- The Effect of OPC Content, Workability and Cement Type:

A comparison between the three OPC mixes indicates that mix two was the least permeable followed by mix one then mix three. The inclusion of pfa resulted at 20°C+70%RH and 35°C+70%RH in similar results to that of plain OPC, i.e. mix two. The permeability of the OPC/pfa samples stored at 45°C+30%RH were however generally lower than plain OPC.

Also comparing the results of the OPC/ggbs to those of either plain OPC in all environments or OPC/pfa in the first two environments indicates that the slag mix produced lower permeabilities when samples were continuously cured, higher permeabilities when samples were uncured and similar permeabilities for 1, 3 and 7-day cured samples.

6.5.4 - Total Porosity:

The total porosities of the five mixes stored at 45°C were measured by two methods, i.e. the helium pycnometry and the total water saturation methods. Details of these two methods are described earlier in Chapter 3. The results of both methods showed similar trends, hence, because of this and due to the simplicity of the total water saturation method, results of specimens stored in the other two environments were evaluated using this method only.

Actual results of the porosity test are shown in Table 6.4 whereas Table 6.5 expresses them in a percentage form relative to the control, i.e. continuously cured samples of mix two at 20°C. The statistical analysis performed on the differences between the porosity results of nominally identical samples indicates a repeatability of about 5% for 95% level of confidence.

Increasing curing periods were seen to have only a slight effect if any on the porosity of all mixes. A decreasing trend in the porosity results was observed as curing duration increased. Nonetheless, this trend is not as clear as that seen with mortar (Fig. 5.1 in Chapter 5) which may be attributed to the volume of cement paste present, i.e. mortar samples contain more cement gel per unit volume than concrete, making the effects of curing durations more apparent on mortar than on concrete.

The hotter environments of 35°C+70%RH and 45°C+30%RH resulted in the total porosities of the OPC and OPC/ggbs mixes being, with few exceptions, greater than those obtained at 20°C+70%RH. However, the results in both of the hot environments were similar to each other. The total porosities of the OPC/pfa mixes were generally unaffected by curing environments.

The total porosities of mix two were generally higher than those of mix one; mix two has a higher cement content and lower water/cement ratio. Also comparing mixes two and three shows that the latter obtained higher porosities with the exception of samples kept at 20°C+70%RH.

The inclusion of 30%pfa was seen to produce similar results at 20°C+70%RH but lower porosities in the other two environments when compared to plain OPC. The inclusion of slag on the other hand produced at 20°C+70%RH lower results than plain OPC, however, the results were similar in the other two environments.

A comparison of the two mixes containing cement replacement materials shows that slag produced lower porosities at 20°C+70%RH but higher results in the other

Table 6.4: The actual results of the total porosities (% of volume) of the five concrete mixes used using the total water saturation method.

environment	curing period (days)	mixes				
		1	2	3	4	5
20°C+70%RH	0	11.67	13.88	13.10	12.95	11.84
	1	11.00	12.80	12.57	12.35	11.12
	3	11.00	12.60	12.46	12.76	10.34
	7	9.72	11.82	12.16	11.22	10.70
	28	10.26	11.92	12.46	11.26	10.00
35°C+70%RH	0	12.56	13.22	13.90	11.91	14.27
	1	12.04	13.28	13.69	11.86	13.27
	3	12.03	13.21	13.42	11.79	13.02
	7	11.85	13.35	13.61	11.90	13.50
	28	11.91	13.02	13.21	11.50	13.09
45°C+30%RH	0	12.30	13.10	13.78	12.40	14.40
	1	12.24	12.56	13.41	11.96	13.60
	3	12.11	12.60	13.26	12.01	13.78
	7	11.92	12.50	13.44	11.81	13.40
	28	11.54	12.2	13.13	11.12	13.20

Table 6.5: Total porosities of the five concrete mixes in percentage form relative to the control, i.e. continuously cured mix two samples.

environment	curing period (days)	mixes				
		1	2	3	4	5
20°C+70%RH	0	98.0	116.5	109.9	108.6	99.4
	1	92.4	108.1	105.5	103.6	93.4
	3	92.4	105.7	104.6	98.7	86.7
	7	81.6	99.2	102.1	94.1	89.9
	28	86.1	100.0	104.6	94.4	83.6
35°C+70%RH	0	105.4	110.9	116.7	100.0	119.8
	1	101.0	110.9	114.8	99.6	111.4
	3	101.1	108.5	112.7	99.8	109.3
	7	100.0	112.1	114.3	100.0	113.3
	28	99.5	109.3	110.9	96.6	109.9
45°C+30%RH	0	103.3	109.9	113.2	104.0	120.8
	1	102.8	105.5	112.6	100.3	114.1
	3	101.7	105.8	113.2	100.8	115.7
	7	100.1	105.6	111.4	99.1	112.4
	28	96.9	102.3	110.2	93.3	110.7

two environments.

6.6 - Discussion:

6.6.1 - Variability of Test Results:

The repeatabilities of the water absorption and ISAT results were within 10% for 90% level of confidence whereas the repeatability of porosity results was within 5% for 90% level of confidence. The variability, on the other hand, of the relative air permeability results as measured by the Figg Method were greater (20% for 90% level of confidence) than those of the other tests referred to in this chapter. This was so despite the modification made by prefabricating the holes (instead of drilling) using bolts that were 10 mm in diameter by 40 mm in depth embedded in the top-as-cast face of the push-out discs. The variability in the results may be attributed to many factors including: 1) the inaccuracy in controlling the depth of the sealed part of the hole. 2) the small thickness of concrete from the surface to the hollow part of the hole, i.e. 20 mm, in which one big continuous pore could influence the results significantly. An important observation seen with this test is that results become more repeatable and consistent when samples were continuously cured. A statistical analyses was performed on the limited data of the continuously cured samples to find the repeatability of this test. It was found that the results of continuously cured sample were repeatable to within 12% for 90% level of confidence.

6.6.2 - Relationships Between Strength and Absorption, Permeability and Porosity:

Figs. 6.18, 6.19 and 6.20 show graphically the relationships between strength and: ISAT, water absorption and relative permeability respectively. In all three graphs, an inverse relationship can clearly be seen for the results of each of the mixes separately but there was no unique relationship for all the mixes collectively. These figures also show that different mixes with significantly

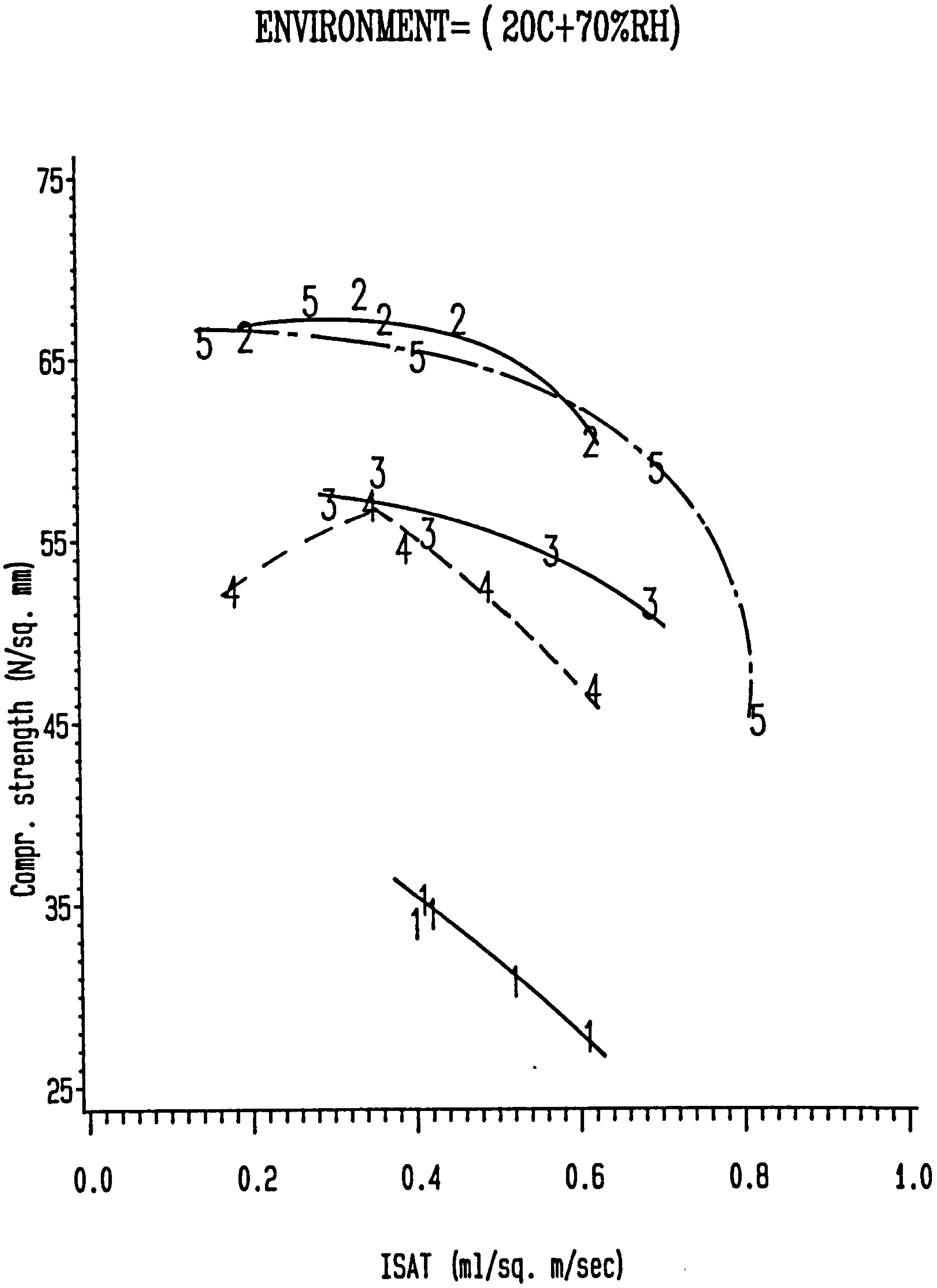


Fig. (6.18) The relationship between ISAT and compressive strength of different mixes, slump=50-75mm for all but mix 3 1=opc (c.c.=275kg/cu.m), 2=opc (c.c.=400kg/cu.m), 3=as 2 but twice as workable, 4=as 2 but 30%pfa, 5=as 2 but 60%ggbs

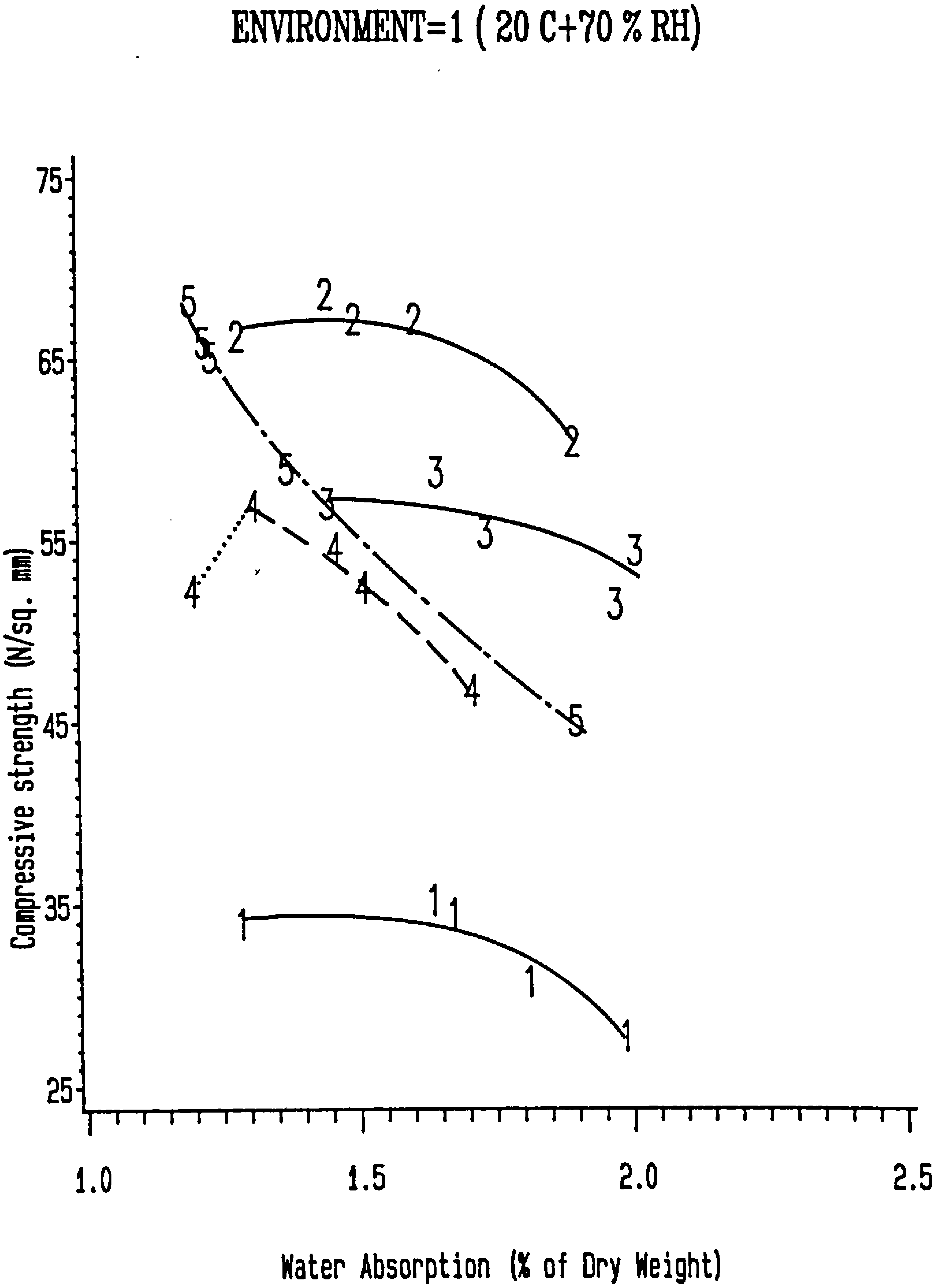


Fig. (6.19) The relationship between water absorption and strength of different mixes, slump=50-75mm for all but mix 3 1=opc (c.c.=275kg/cu.m), 2=opc (c.c.=400kg/cu.m), 3=as 2 but twice as workable, 4=as 2 but 30%pfa, 5=as 2 but 60%ggbs

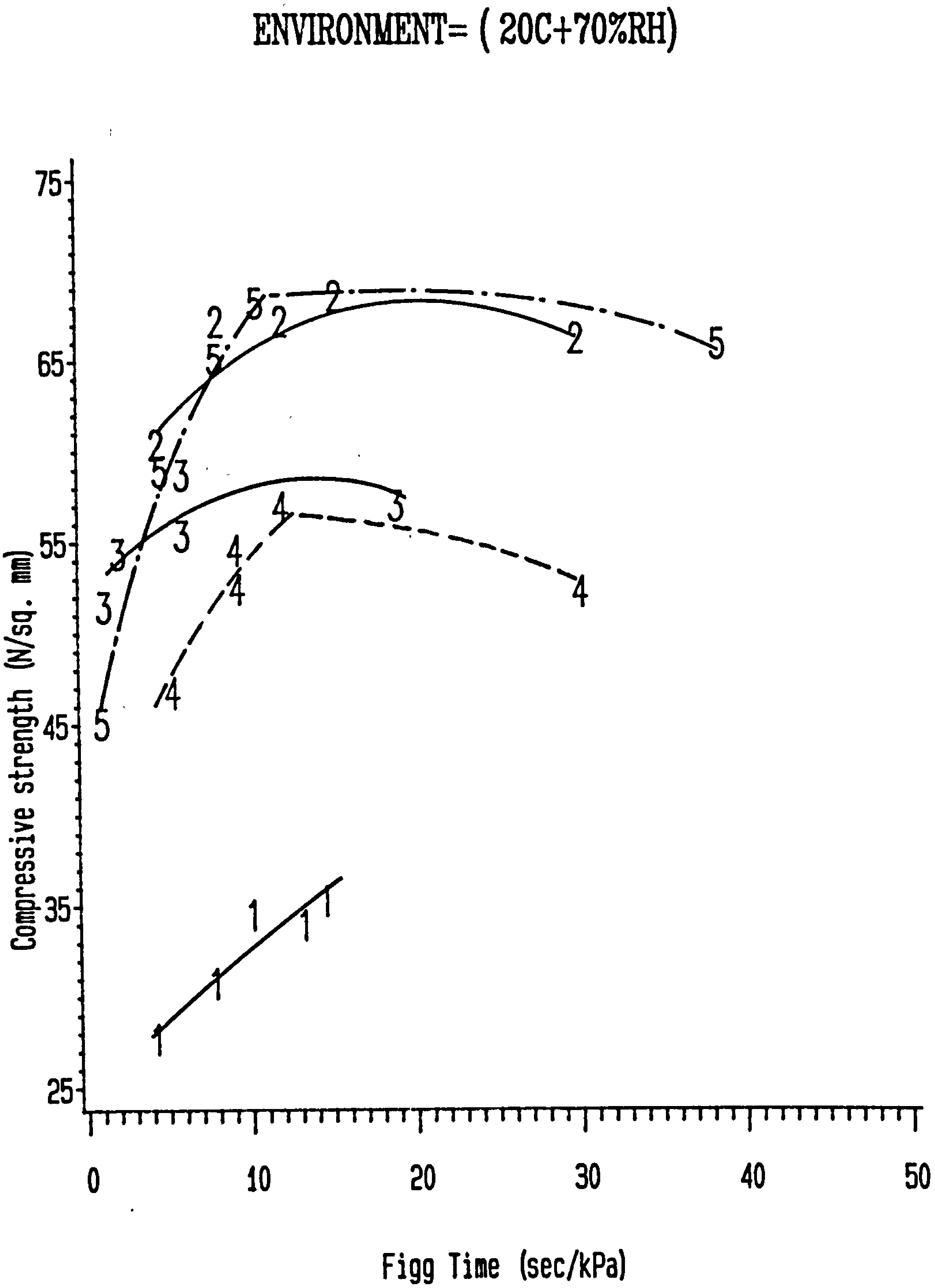
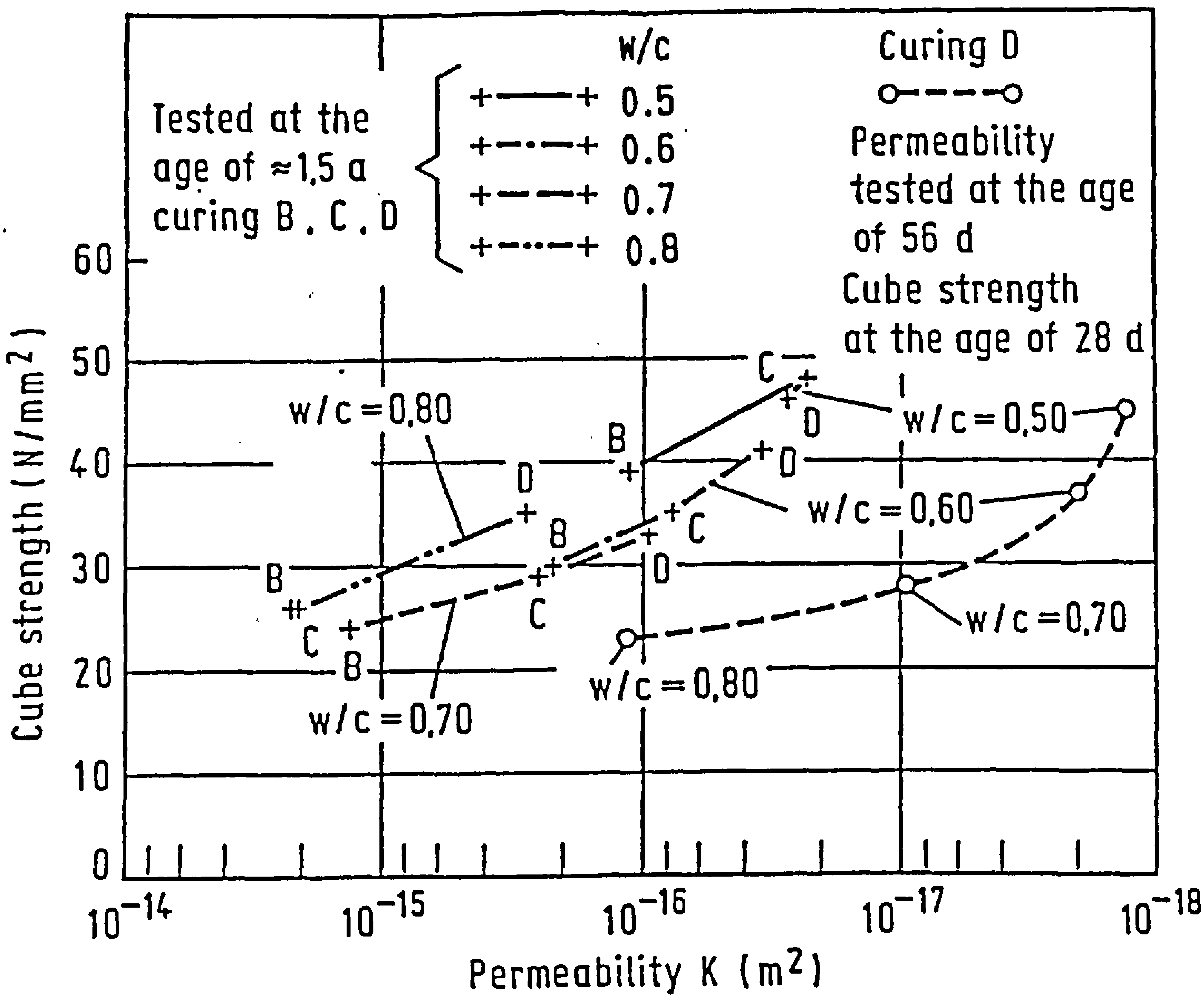


Fig. (6.20) The relationship between Figg test and compressive strength of different mixes, slump=50-75mm for all but mix 3 1=opc (c.c.=275kg/cu.m), 2=opc (c.c.=400kg/cu.m), 3=as 2 but twice as workable, 4=as 2 but 30%pfa, 5=as 2 but 60%ggbs different compressive strengths can exhibit similar ISAT, water absorption or permeability results. In addition to this, it was observed that in some cases stronger samples could absorb more water than weaker ones, see Table 6.6. The most obvious example seen to substantiate this trend is when comparing the results of mixes one and two. The reason for such a trend can be explained by the fact that although mix two had significantly lower water/cement ratio, the volume of cement paste present, which is known to be more porous and more absorptive than the aggregates, was higher than mix one. Grube (44) has also published similar trends on the relationship between strength and oxygen permeability, see Fig. 6.21. He showed that mixes with various water/cement ratios and different strengths had similar permeabilities.

Table 6.6: Strength and ISAT results of OPC, pfa and slag samples under different curing durations at 20C+70%RH.

curing duration	Mixes					
	OPC		OPC/pfa		OPC/ggbs	
	strength	ISAT	strength	ISAT	strength	ISAT
Uncured	60.3	0.62	46.6	0.52	44.9	0.82
3-day	67.1	0.37	54.5	0.39	65.0	0.41
28-day	66.2	0.20	52.1	0.18	68.1	0.15

Furthermore, the statistical analyses performed on the results showed that for all the mixes collectively there is no significant relationship between strength and either the water absorption or the permeability tests, see Table 6.6. Hence, it can be concluded from the graphical representations (Figs. 6.18-6.20), Table 6.6 and the statistical analysis (Table 6.6) that there is no clear overall relationship between strength and either absorption or permeability. Therefore if it is assumed



Curing: B = 1 day in mould then drying at 20C+65%RH
C = 3 days in mould then drying at 20C+65%RH
D = 28 days in mould then drying at 20C+65%RH

Fig. (6.21): Correlation between compressive strength and permeability (44).

that durability is related to either ISAT, permeability or water absorption, then the measurement of strength alone is unlikely to give a measure of durability.

Fig. 6.22 shows the relationship between strength and porosity using the results of all mixes cured at 20°C+70%RH. The results of each mix separately show that there is an inverse relationship; i.e. the lower the porosity the higher the strength but as with ISAT, Figg test and water absorption, there is no overall relationship between both tests for all results as a whole. Samples of an equal porosity can have significantly different compressive strength results.

6.6.3 - Comparisons Between Water Absorption,
ISAT, Figg Test and Porosity:

In this section an attempt will be made to find out the most suitable test for explaining the effects of the different factors on the durability- related properties of the concretes under test.

The statistical analyses conducted on the results of the water absorption and ISAT tests (Table 6.7) show that there is generally a good linear relationship between them for all mixes and in all environments. An example of this is shown in Fig. 6.23 using the results of all five mixes at 20°C+70%RH. In addition to this, the statistical analyses (Table 6.7) indicates that the relationships between the relative air permeability (i.e. Figg test) and either one of the two absorption tests are better represented by a square root function than by a linear function. This is confirmed by the graphical representation shown in Figs. 6.24 and 6.25 which indicates a nonlinear relationship a trend which is found to be similar to that found in Chapter 5(see Figs. 5.20- 5.22)

The sensitivity of the ISAT results to both curing periods and curing environments is greater than that seen with the total water absorption test. This is what one would expect since ISAT measures the property of only one face; i.e. that one exposed to the ambient conditions, whereas water absorption measures the

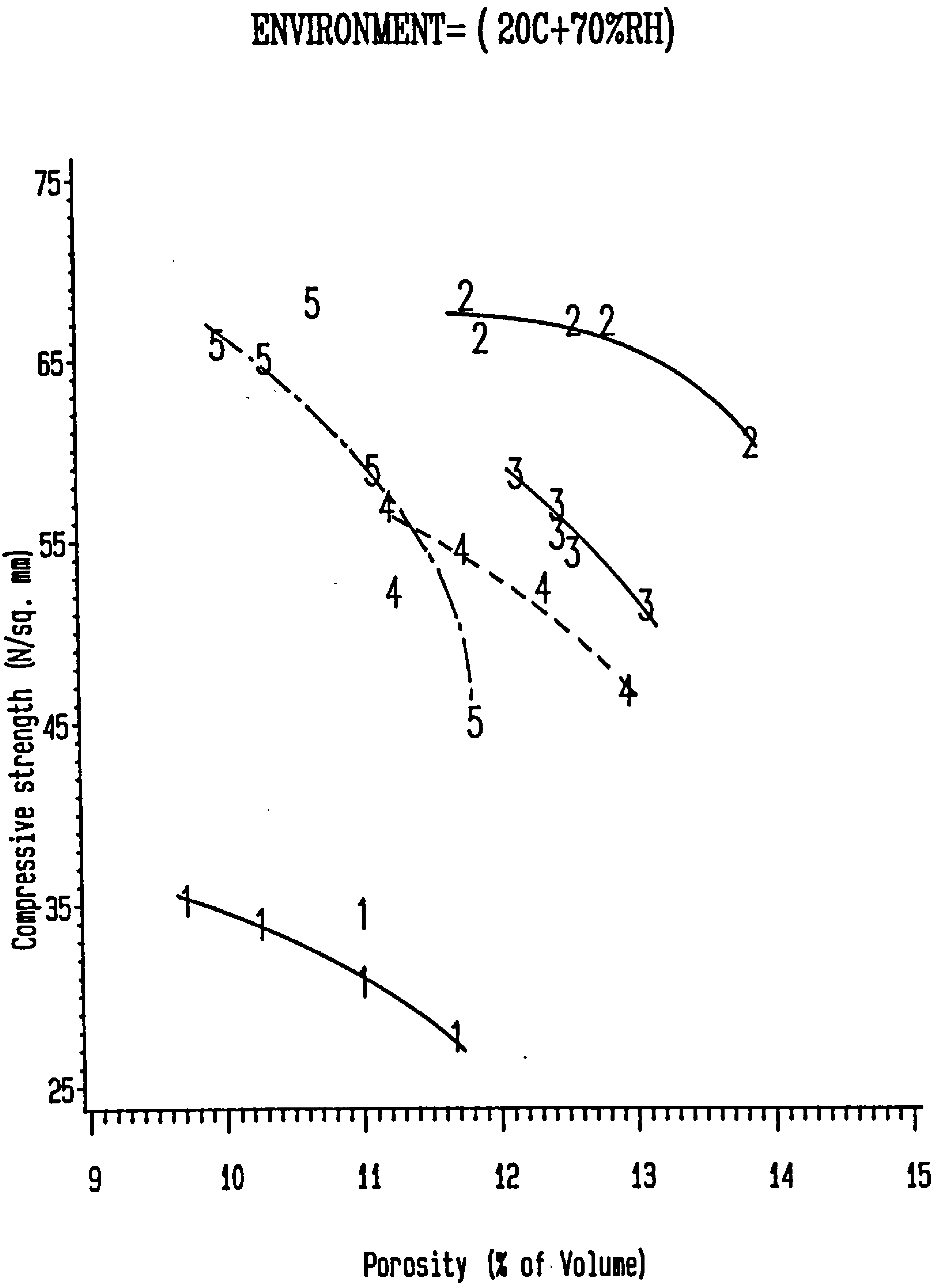


Fig. (6.22) The relationship between porosity and compressive strength of different mixes, slump=50-75mm for all but mix 3 1=opc (c.c.=275kg/cu.m), 2=opc (c.c.=400kg/cu.m), 3=as 2 but twice as workable, 4=as 2 but 30%pfa, 5=as 2 but 60%ggbs

Table 6.7 : Correlation coefficients and level of significance of linear relation between the tests used on the concrete mixes.

	Mix					environment		
	1	2	3	4	5	1	2	3
# of points	15	15	15	15	15	25	25	25
w. absorp. vs. ISAT	.774 .0007	.878 .0001	.744 .0015	.86 .0001	.857 .0001	.7173 .0001	.8398 .0001	.7965 .0001
ISAT vs Figg Test	-.760 .0010	-.803 .0003	-.678 .0055	-.870 .0001	-.774 .0007	-.8259 .0001	-.6918 .0001	.8162 .0001
w.absorpt. vs Figg Test	-.649 .0080	-.825 .0001	.559 .0302	-.830 .0001	-.7283 .0021	-.6811 .0001	-.7663 .0001	-.7408 .0001
strength vs ISAT	-.411 .1180	-.388 .1535	-.596 .0190	-.665 .0069	-.4493 .0929	-.3221 .1152	-.5517 .0043	-.5060 .0098
strength vs Figg Test	.754 .001	.2588 .3517	.1187 .6735	.4185 .1207	.2273 .4152	.2748 .1838	.3748 .0649	.3904 .0537
ISAT VS square root (Figg)	- .846 .0001	- .8436 .0001	- .6902 .0044	- .8973 .0001	- .8656 .0001	- .8945 .0001	- .8028 .0001	- .8921 .0001
water absor vs square root (Figg)	- .6714 .0061	- .8422 .0001	- .5181 .0479	- .8614 .0001	- .8180 .0001	- .7546 .0001	- .7778 .0001	- .7543 .0001
porosity vs strength	- .2473 .3739	- .4206 .1185	- .9176 .0001	- .5846 .0221	- .8176 .0002	- .2532 .2219	- .0060 .9774	- .2142 .0001
porosity vs ISAT	.5857 .0218	.6060 .0166	.7561 .0011	.7950 .0004	.4211 .1180	.3917 .0528	.4321 .0310	.5062 .0654

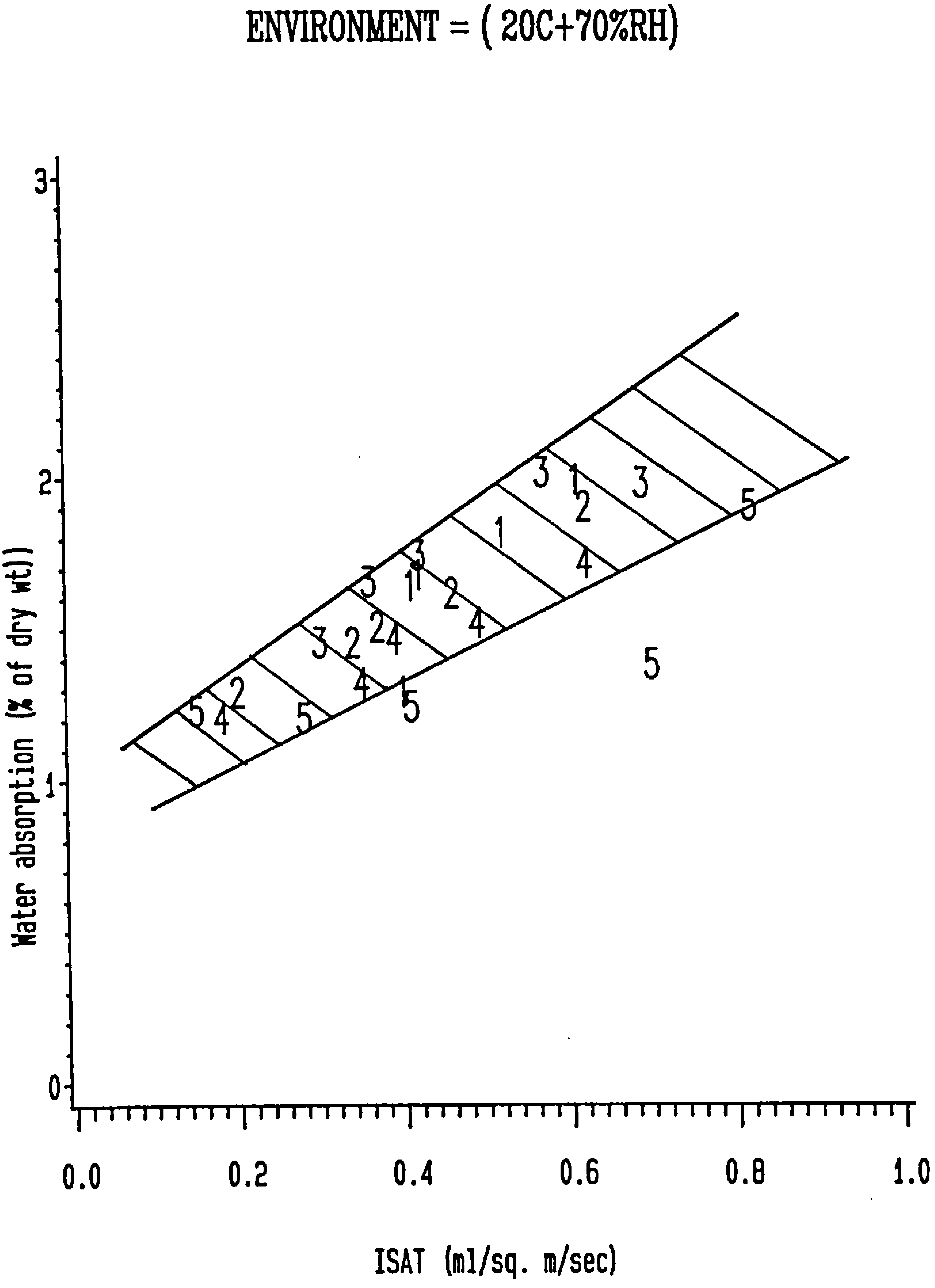


Fig. (6.23) The relationship between ISAT and water absorption of different mixes, slump=50-75mm for all but mix 3
1=opc (c.c.=275kg/cu.m), 2=opc (c.c.=400kg/cu.m), 3=as 2 but twice as workable, 4=as 2 but 30%pfa, 5=as 2 but 60%ggbs

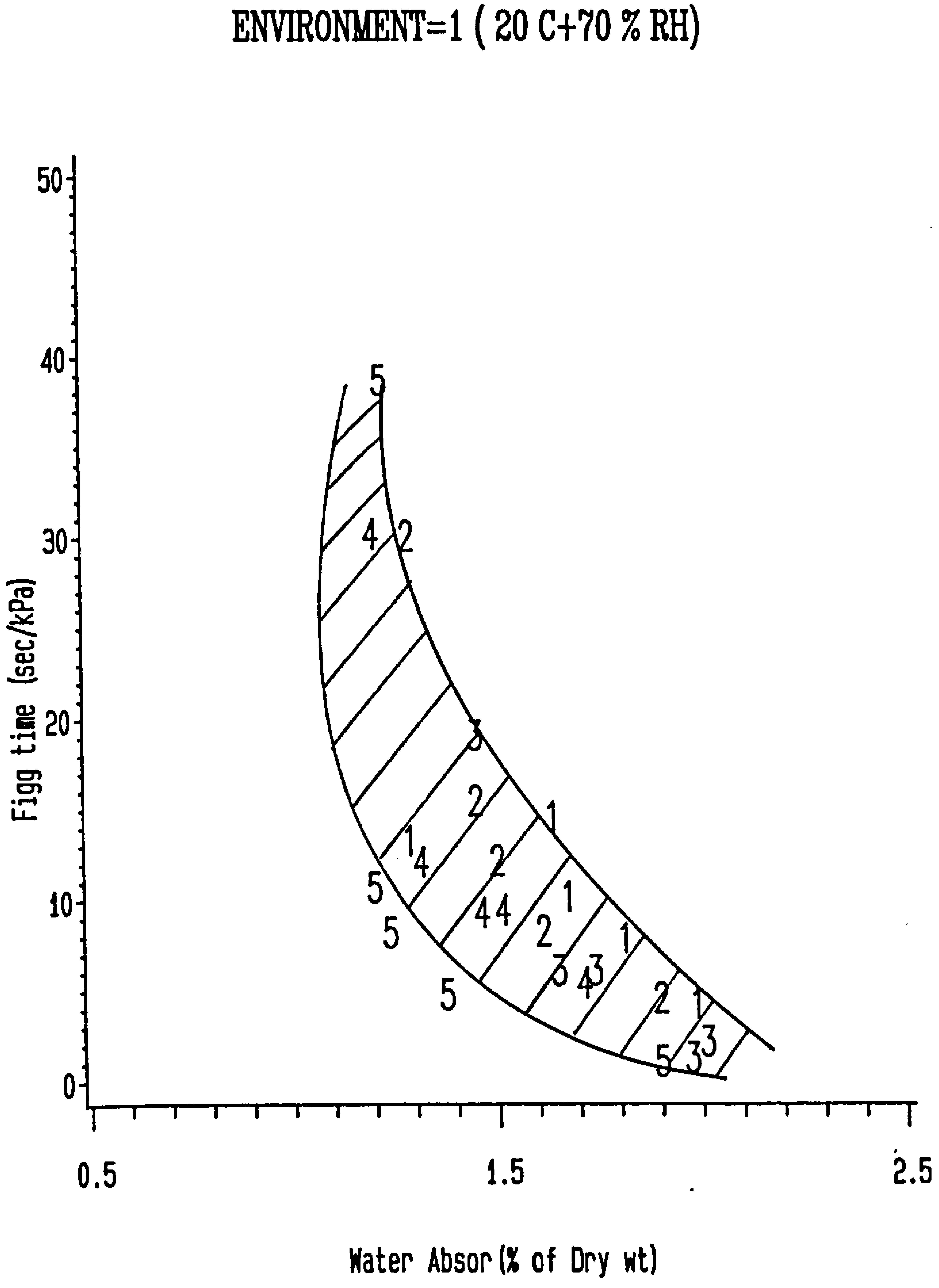


Fig. (6.24) The relationship between water absorption and Figg test results of different mixes, slump=50-75mm for all but mix 3 1=opc (c.c.=275kg/cu.m), 2=opc (c.c.=400kg/cu.m), 3=as 2 but twice as workable, 4=as 2 but 30%pfa, 5=as 2 but 60%ggbs

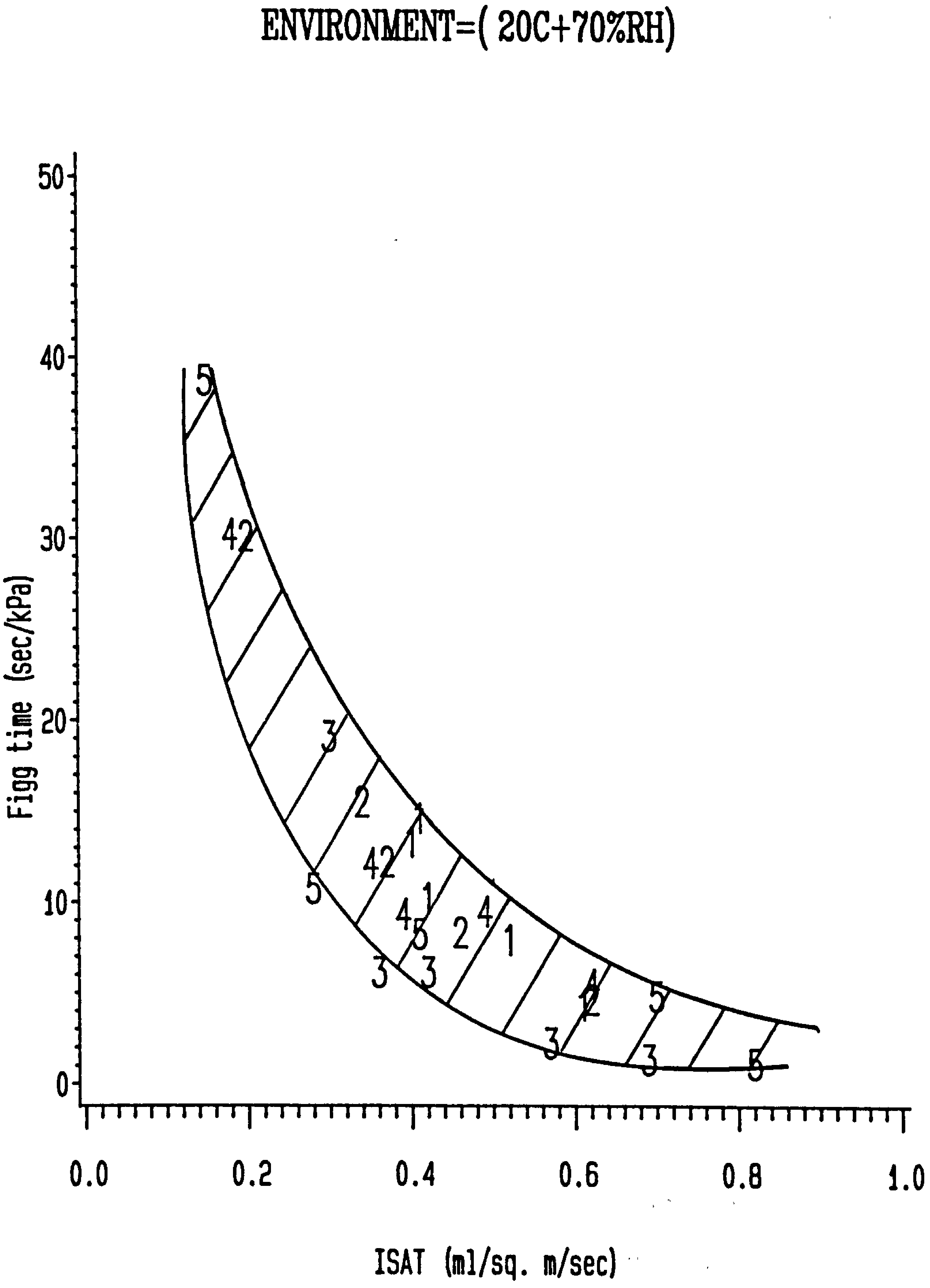


Fig. (6.25) The relationship between ISAT and Figg test results of different mixes, slump=50-75mm for all but mix 3 1=opc (c.c.=275kg/cu.m), 2=opc (c.c.=400kg/cu.m), 3=as 2 but twice as workable, 4=as 2 but 30%pfa, 5=as 2 but 60%ggbs properties of all faces including those covered to the day of testing. While the extreme ambient conditions, i.e. high temperatures and lower relative humidities, will largely affect only that face exposed to them, the other sides are not similarly affected because they are covered to the day of testing making these effects on the total water absorption less apparent than on ISAT. Therefore, because of the above argument, ISAT results are considered to be better than those of the water absorption test in discussing the effects of the different factors on the properties of concrete.

While both ISAT and Figg results gave in general a similar picture, a comparison of both sets of test results indicates that the ISAT is in general a better test for studying the effects of curing periods, curing environments and cement type. The reason for choosing ISAT over Figg can be summarized as follows:

1 - Test repeatability; ISAT was seen to be more repeatable than the Figg test as shown earlier, see section 6.6.1.

2 - With the exception of the continuously cured samples, ISAT was more sensitive to the effects of curing durations than Figg.

3 - ISAT was also able to detect the effects of curing environments whereas the Figg test was not.

It is nonetheless relevant to mention that as a site test, the Figg test is in many cases easier to perform than ISAT.

In contrast to both Figg and ISAT, the total porosity results showed little or no sensitivity to either curing periods or curing environments, see Table 6.4. Therefore, the results of ISAT are considered to be better than the porosity results in helping to explain the effects of the different parameters on the durability-related properties of concrete. For this reason, the ISAT results will be the only ones used later in the discussion on the effects of curing on durability.

6.6.4 - Compressive Strength:

6.6.4.1 - The Effect of Curing Period:

The study presented in Chapter 5 on the effect of initial moist curing periods on the pore structure of OPC, OPC/pfa and OPC/ggbs mixes indicated that longer curing periods resulted in significantly finer pore structure in all environments. The results also indicated that there existed a critical curing period beyond which the influence on the pore size distribution became either relatively small or insignificant; three days in the case of OPC in all environments and OPC/pfa and OPC/ggbs in the first two environments but one day for OPC/pfa and OPC/ggbs at 45°C+30%RH. Hence, it was expected by the author that strength would be, to some extent, similarly affected. The compressive strength results presented here are not in agreement with those of the pore structure especially when dealing with curing periods up to three days. This suggests that some changes occur in the pore structure that may appear to lower the permeability but have little influence on strength.

Plain OPC

With regard to the influence of curing periods on the strength of OPC concrete, the results presented here appear to be in disagreement with those of Popovics (77). He showed that different initial moist curing periods at 20°C before storing at 20°C+60%RH had significant effects on the strength of OPC concretes, see Fig. 6.26. Uncured and three-day cured (50 mm) cubes were about 20% and 45% weaker than the continuously cured samples when tested at 28 days of age. A similar thing to Popovics has also been found by Price as reported by Neville (17). The difference in the trends shown by Popovics and Price to those of the author may be attributed to the rate of evaporation of water from the sample. It is believed that the samples of Popovics and Price when uncured, were allowed to dry from all sides whereas in the work reported here all sides except the top-as-

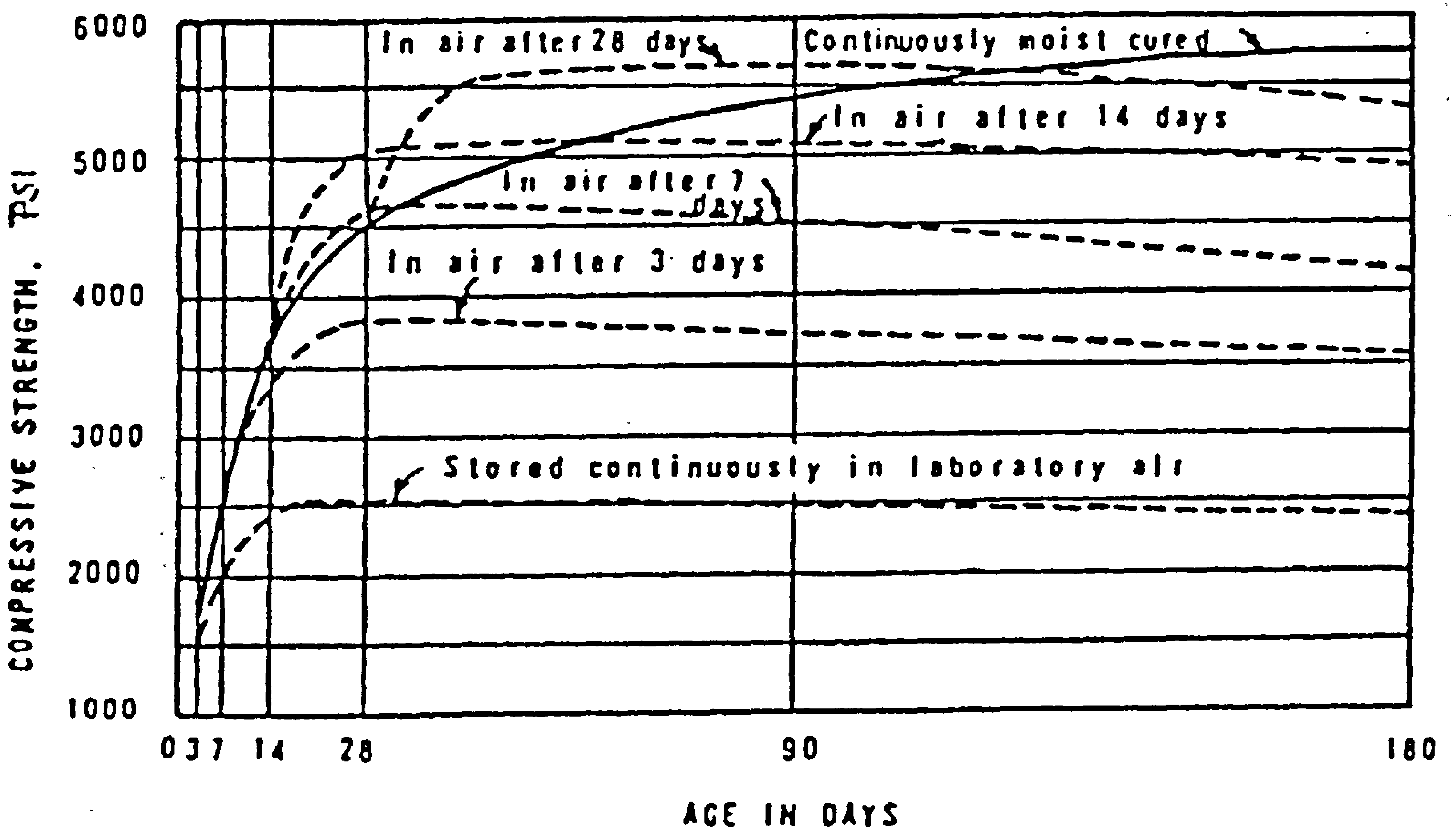


Fig. (6.26) Compressive strength of concrete dried in laboratory air after previous moist curing. water/cement ratio=.50. cement content=330 Kg/m . slump=87mm (77) cast face of the samples were covered to the day of testing. This suggests that covering all sides except the top-as-cast face may have reduced the rate of moisture loss resulting in such a behaviour.

Popovics did show however that when testing at 28 days, the seven-day cured and continuously cured samples were similar in strength a trend confirmed by the author's results. The explanation suggested by Popovics for this was based on the observation that drying decreases the volume of hardened cement paste. These volume reductions are caused by the increased surface tension in water-filled small pores during drying which reduces the distances between surfaces in hydrated cement gel (77). The strength is then increased due to the increased bond between these surfaces (77). In addition to this, Popovics reported that fully saturated concretes are expected to be lower in strength than dry samples due to internal water pressure exerted on the surfaces of cement gel when an external pressure is applied. This explanation reported by Popovics is valid when comparing continuously cured samples to those cured by for seven days and less, however, this does not explain why one, three, and seven days cured samples had similar strengths.

Blended Cements:

The general trend of the effects of curing periods on the compressive strength of OPC/pfa samples is seen to be similar to that seen on plain OPC (i.e. curing duration had little effect on the strength results). Hence, the argument given earlier as to the effects of sealing all sides except the top-as-cast face is considered to be valid here.

The greater sensitivity of OPC/ggbs samples to curing periods than either plain OPC or OPC/pfa mixes (at 20°C+70%RH or 35°C+70%RH) may be expected to some extent since this mix has a higher percentage of cement replacement material (compared to pfa), which is inherently slower to react with water than

OPC, and hence longer curing periods are therefore needed.

Nonetheless and similarly to the plain OPC mixes, the strength of the OPC/slag samples cured at 45°C+30%RH were unaffected by curing periods. This trend may be attributed to the influence of the higher temperature of 45°C in accelerating the hydration reaction of the slag to a level where the strength was not affected by further curing periods.

6.6.4.2 - The Effect of Curing Environment:

Plain OPC

The effects of hot environments on the compressive strength of OPC concretes indicate that hotter curing environments lead to a reduction in strength compared with that achieved at 20°C+70%RH for all curing periods (uncured as well as continuously cured samples), see Table 6.8. Such a trend has been observed before by many researchers, see Chapter 2. For example, Klieger (76) showed that OPC concretes cured for seven days at 45°C before curing at 20°C+100%RH to an age of 28 days were about 15% weaker than similar samples cured for 28 days at 20°C+100%RH. Other researchers such as Ridley (113) and Shalon and Ravina (38) have also reported similar trends as shown in the literature review chapter.

Table 6.8 : Compressive strength (N/mm^2) of OPC concrete under different curing periods and curing environments. (mix 2: c.c.=400kg/m3, w/c=0.44)

Curing period	environments		
	20°C+70%RH	35°C+70%RH	45°C+30%RH
uncured	60.3	47.2	51.7
Three-day	67.1	47.9	51.6
Continuous	66.2	53.8	50.9

A possible explanation of this was suggested by Neville (17) and Bakker (41) (as discussed in Chapter 5). They said that high temperatures produce a physically poorer structure in the hydrated OPC pastes, see Fig. 2.17a. According to Neville (17), Verbeck and Helmuth suggested that the temperature- accelerated initial hydration rate retards the subsequent hydration and produces a non- uniform distribution of the hydration products within the sample. The reason for this is, according to Neville, that the high initial rate of hydration does not provide sufficient time for the diffusion of the hydration products away from the cement grain as in the case of lower temperatures. Hence a high concentration of these products are precipitated in the vicinity of the hydrating grain thus retarding the subsequent hydration. A confirmation of this has already been seen by the pore structure results of Chapter 5.

It is however interesting to see that although both the lack of curing and the hotter environments produce coarser pore structures in the OPC mortar mixes, the strength of OPC concrete was not similarly affected by both; the strength was lower at 35°C+70%RH and 45°C+30%RH than at 20°C+70%RH but the effects of curing periods were generally insignificant. This suggests that the strength of plain OPC mixes is influenced by temperature accelerated rates of initial hydration reactions more than by the lack of curing time.

Price (112) provided data on the effects of temperature during the first two hours after mixing on the strength of concrete with a water/cement ratio of 0.53. The range of temperatures investigated by Price was 4 to 49°C. Beyond the age of two hours, all specimens were cured at 20°C and were sealed to prevent moisture loss. The results (Fig. 6.27) showed that specimens cured at temperatures below 18°C were about 10% stronger than similar samples cured at over 18°C.

In conclusion, the 28-day compressive strength of plain OPC concretes (when compared to concretes cast and/or cured at normal temperatures; approximately

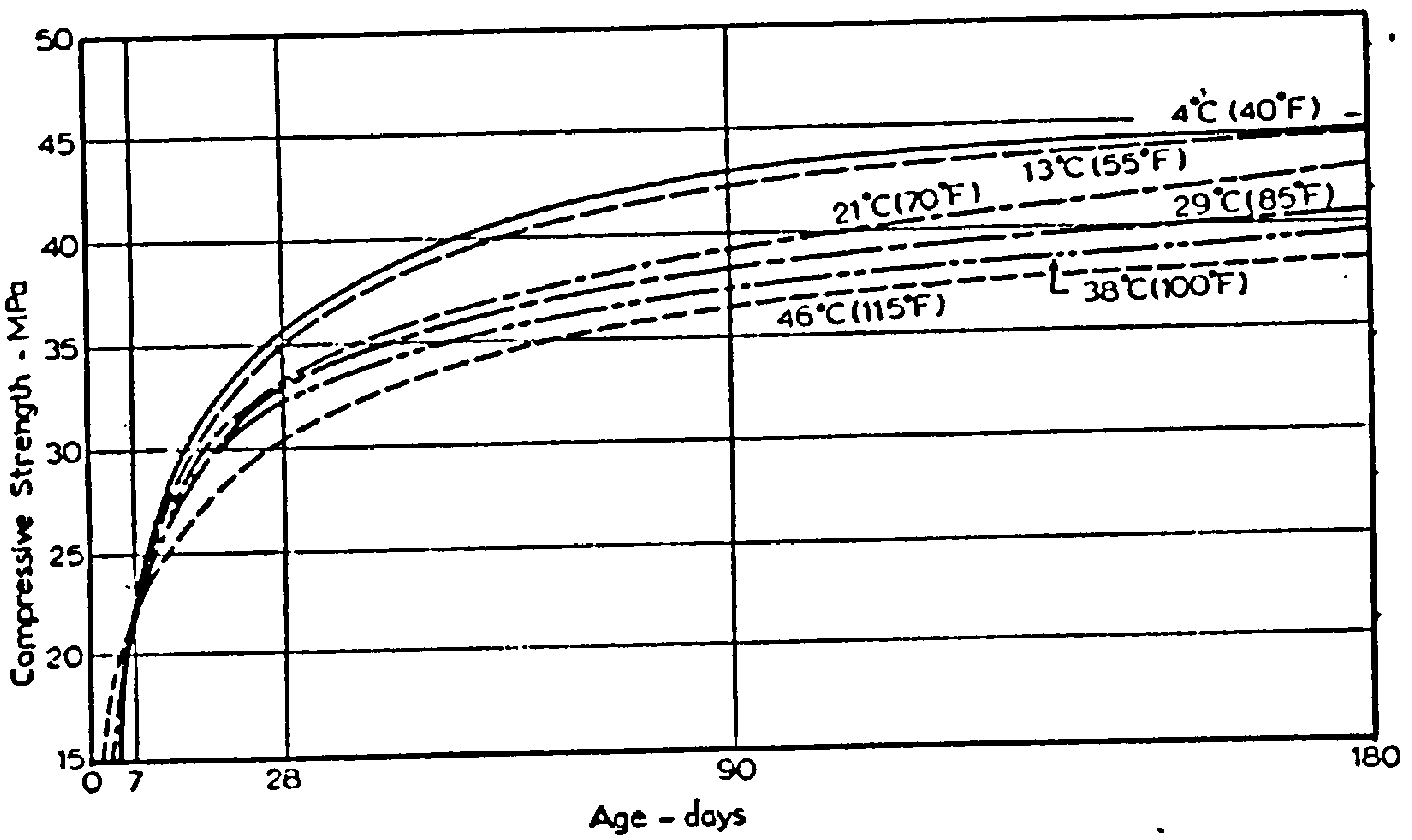


Fig. (6.27) Effect of temperature during the first two hours after casting on the development of strength (all specimens sealed after the age of 2 hours at 21C (112)

20°C) is seen to be lowered by both initially high temperatures of fresh concretes (as shown by Price) as well as by high curing temperatures (as shown from the results reported by the author as well as those of other researchers).

In addition to this, the results reported by the author showed that the strength reductions observed at 35°C+70%RH and 45°C+30%RH (when compared to those at 20°C+70%RH) were statistically similar. This is in line with the finding of Shalon and Ravina (38) who concluded a similar trend as shown previously in the literature review (Chapter 2). They reported that:

> "... there exists a critical temperature of the concrete at which strength is minimum. At lower temperatures, down to a certain limit, the strength is higher, while at higher temperatures the strength is either no longer affected or shows a tendency toward recovering. The value of the critical temperature depends upon characterestics of the concrete and the specific conditions, particularly upon evaporation."

Furthermore, hotter environments were seen to have more of a detrimental effect on those mixes with the higher cement content (mixes 2 and 3) than on mix 1 with the lower cement content. A trend of this type is expected because the environment affects the cement paste within the mixes and the greater the volume of cement paste, the greater the influences will be.

OPC/pfa

The discussion on the pore structure of OPC/pfa mortars in Chapter 5 indicated that the additional temperature-accelerated reactions of the pfa compensated for the adverse effects of the high temperatures on the hydrated OPC paste within the samples. Unlike the plain OPC concrete mixes, the OPC/pfa samples cured at either 35°C+70%RH or 45°C+30%RH had a slightly higher strength than those at 20°C+70%RH but were not significantly different from each other, see Table 6.9.

This indicates that the additional precipitants of the reaction of the pfa with the lime (Fig. 2.17b) were able to compensate for the physically weak OPC paste produced within the hotter environments. These results seem to be confirmed in trend by those reported by March et al (69). They cast 70/30 OPC/pfa paste samples (water/cement ratio = 0.47) under laboratory conditions and at an age of 24 hours, they cured the samples in water at different temperatures. Their results showed that the OPC/pfa pastes stored at 35°C and 50°C in water were stronger than those kept under water at 20°C after 28 days of age, see Fig. 6.28.

OPC/ggbs

Hot environments were seen to lower the strength of OPC/ggbs samples cured for one day and over, see Table 6.10. As far as the 35°C+70%RH environment is concerned a trend of this type may be explained, to some extent, by the pore structure results presented in Chapter 5 (see Fig. 5.3). The median pore diameter by volume was significantly higher at 35°C+70%RH than that obtained at 20°C+70%RH for all curing periods, see Fig. 5.3.

It is interesting however to see a trend of this type at 45°C+30%RH because the high temperature of 45°C was seen in Chapter 5 to accelerate the reactions of the ggbs resulting in a finer pore structure and lower permeabilities from one day of curing when compared with similarly cured samples in the other two environments. This is not however reflected in the strength results as seen in Table 6.10. The suggested explanation of this may be attributed to either one of these two points or both: 1) since the principal oxides in slag are the same to those in OPC, the hydration products of the ggbs are also adversely affected by higher temperatures due to the increased rate of initial hydration resulting in physically weak structures as explained earlier. 2) while the formation of the additional precipitants (Fig. 2.17c) was sufficient to compensate for the more permeable OPC hydrate within as a result of high temperatures (Chapter 5), it was

Table 6.9 : Compressive strength (N/mm^2) of OPC/pfa concrete under different curing periods and curing environments.

Curing period	environments		
	20°C+70%RH	35°C+70%RH	45°C+30%RH
uncured	46.6	47.7	50.0
Three-day	54.5	56.1	58.0
Continuous	52.1	55.1	56.9

Table 6.10: Compressive strength (N/mm^2) of OPC/ggbs concretes under different curing periods and curing environments.

Curing period	environments		
	20°C+70%RH	35°C+70%RH	45°C+30%RH
uncured	44.9	43.3	45.0
Three-day	65.0	58.1	48.1
Continuous	68.1	52.0	44.8

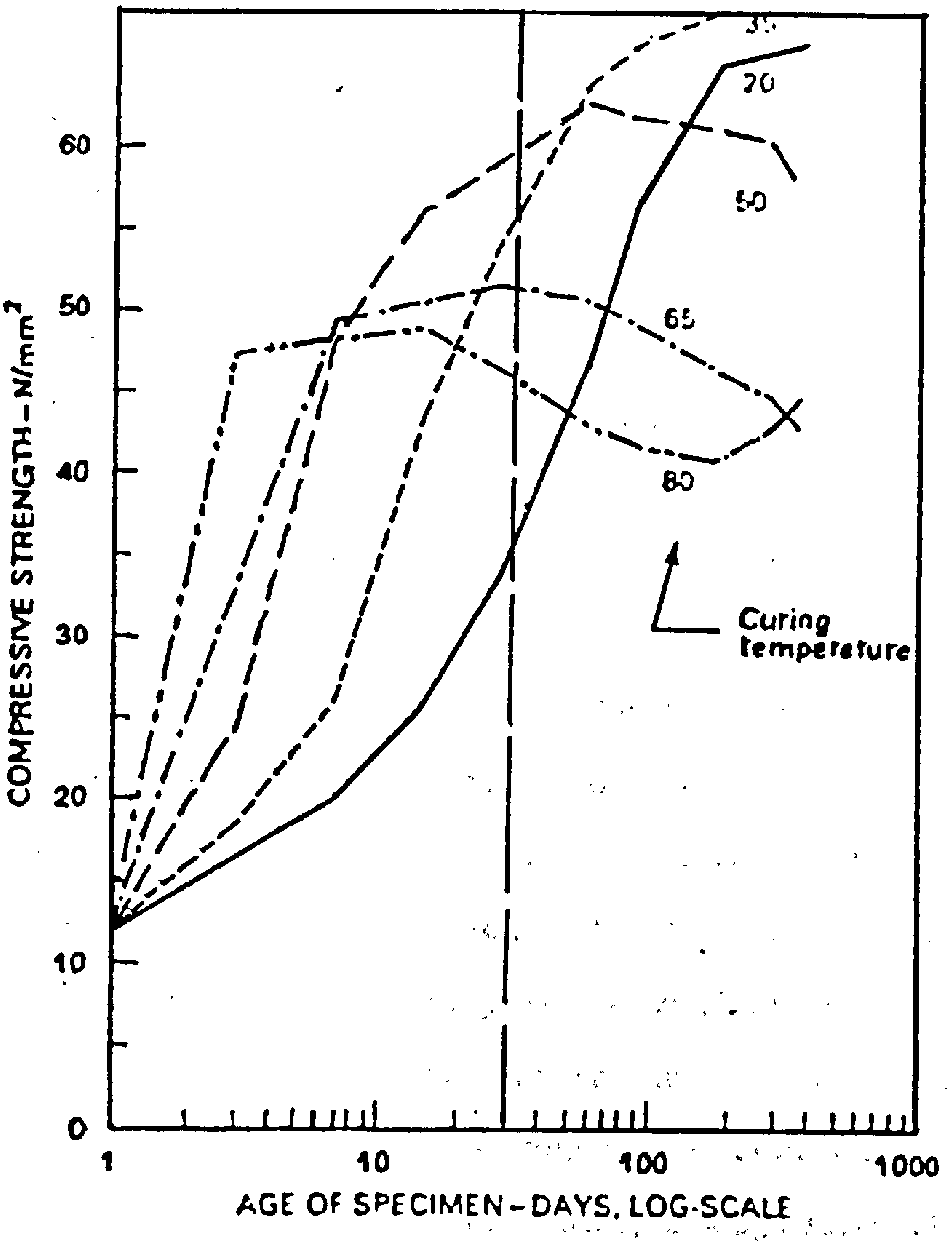


Fig. (6.28) Strength development in OPC/pfa pastes with time and curing temperature (69) not significant enough to compensate for the physically weak pore structures produced by the OPC and ggbs within the samples.

Wainwright (80) has reported results of a work done by Pratas showing the effects of three curing temperature (5°C, 20°C and 30°C) on the strength of plain OPC and 50/50 OPC/ggbs concretes. While plain OPC was shown to produce slightly lower strength at 30°C than at 20°C or 5°C, OPC/slag showed the opposite, see Fig. 6.29. Moreover, Hwang and Lin (101) investigated the effects of three curing temperatures (20°C, 50°C and 80°C) on the strength of concretes made with and without ggbs. Their results (Fig. 6.30) show that curing 40/60 OPC/ggbs at 80°C resulted in the weakest samples whereas curing at 50°C showed the opposite when specimens were tested at 28 days of age. With regard to the effects of 50°C on the strength of 40/60 OPC/ggbs concrete as oppose to that cured at 20°C, the results reported by Lin and Hwang are not in line with those reported by the author. The reason for such behaviour may be attributed to the initial concrete temperature of the mixes. It is understood that in the works described above, samples were cast and/or cured at normal temperatures for a period of time before transferring to the environment of concern. For example Hwang and Lin subjected their samples to the different curing temperatures about 60 hours after mixing, a procedure different from that carried out by the author. The initial chemical reactions within Hwang and Lin samples took place at normal ambient temperatures for about 60 hours, whereas the initial mix temperatures as well as the ambient temperature were high from the time of mixing in the case of samples tested by the author. On the other hand, although Pratas (107) samples were immersed in water immediately after casting, the reason for the difference in trend may be attributed to the following: 1) The initial mix temperature which has been shown earlier to influence the strength of concrete. Pratas cast his samples at normal temperatures, a procedure different from that used by the author. 2) Curing temperatures investigated by Pratas were up to 30°C only whereas those used in the current investigation deals with 35°C and 45°C. It is relevant,

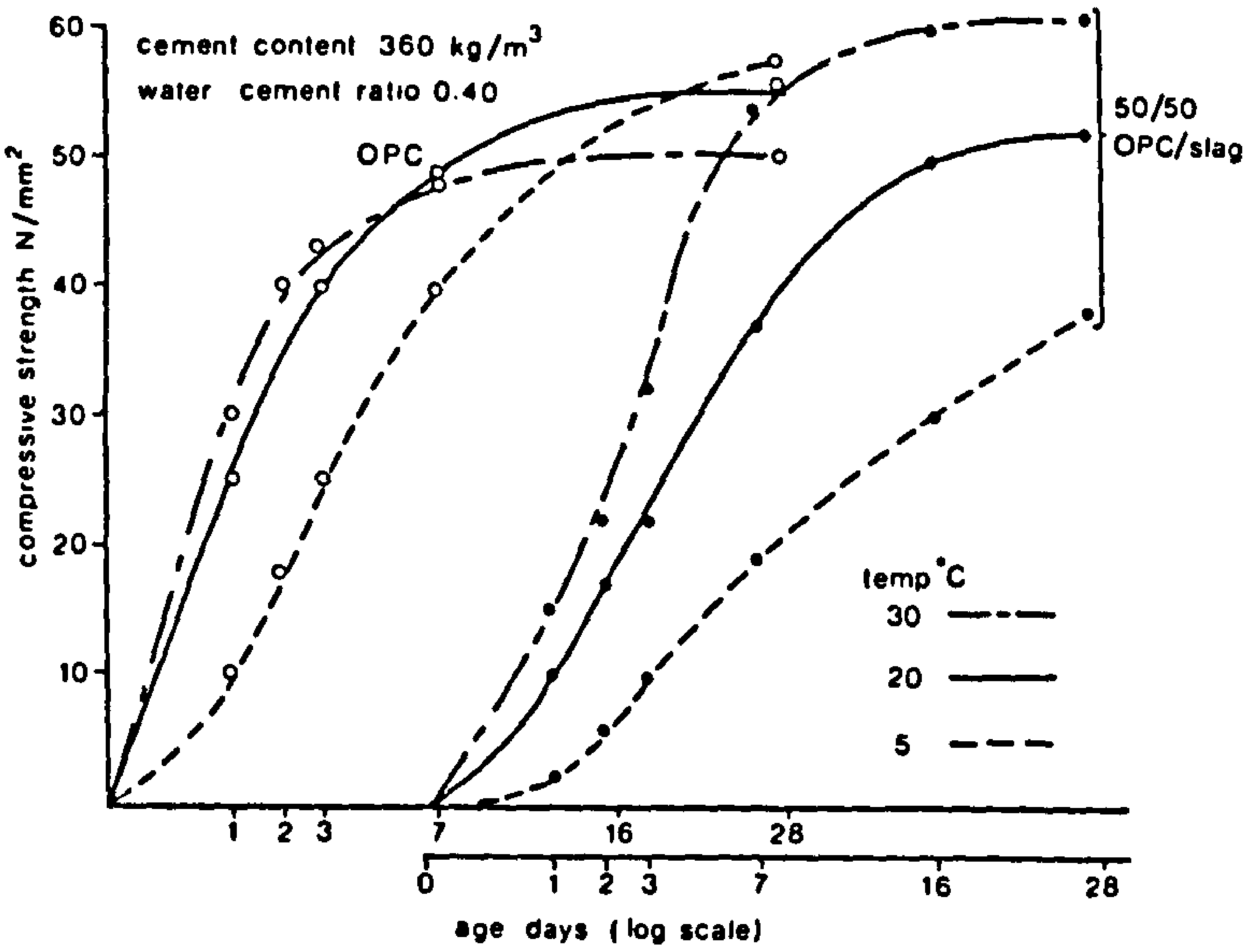


Fig. (6.29) The effect of temperaure on strength of water cured concretes with and without slag (107

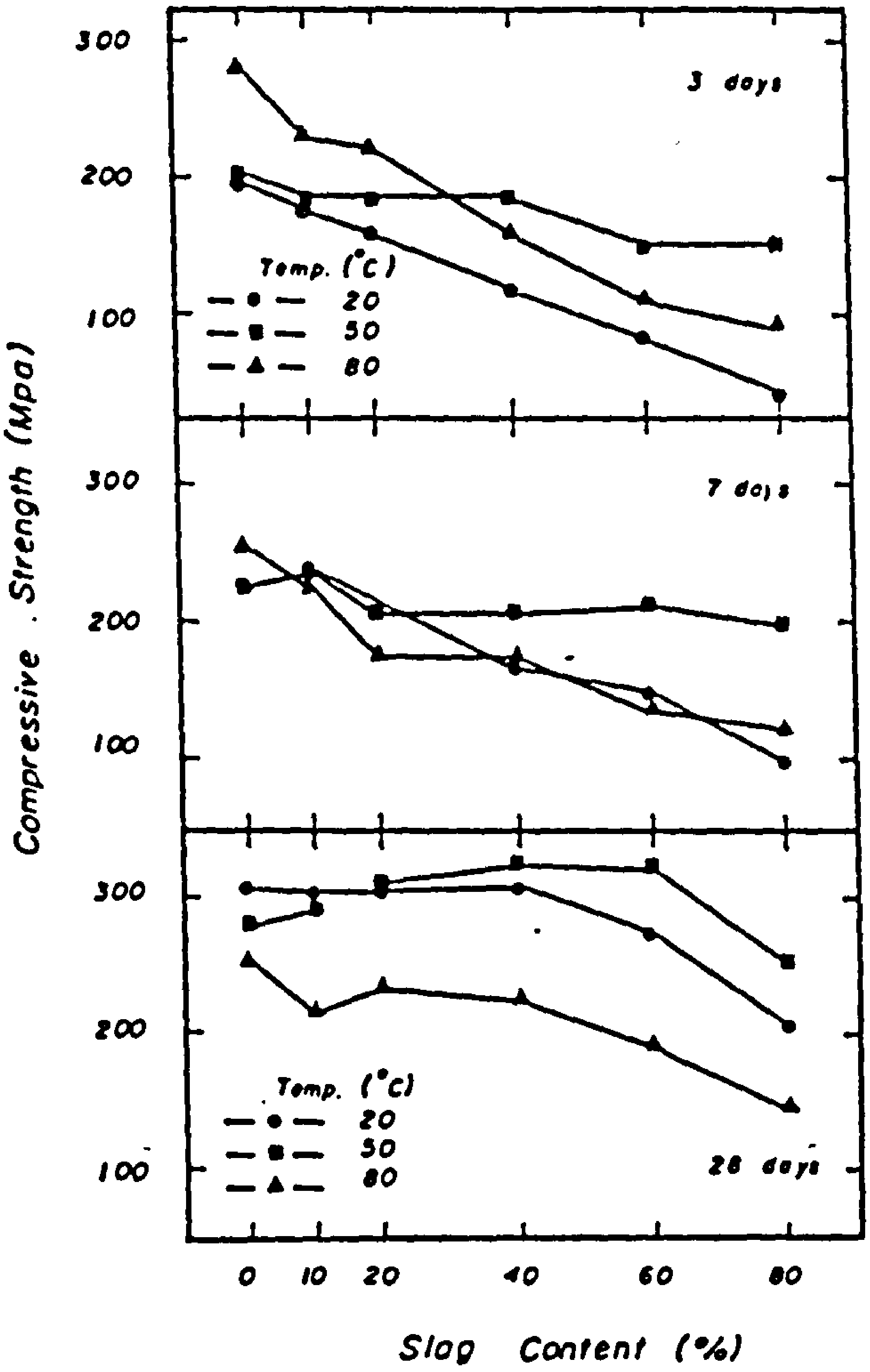


Fig. (6.30) The effect of curing temperaure on the strength development of mortar with various slag contentes with w/c ratio=0.47 (101) nonetheless, to report that at 20°C, the trend of the results found by Pratas is seen to be similar to that found by the author. This illustrates the importance of initial hydration rates of OPC or ggbs as affected by temperature. This unusual trend reported by the author was rechecked by additional casting of a similar mix in both the two hot environments and similar results were obtained. Further study is therefore needed to explain these trends in more details.

6.6.4.3 - The Effect of Cement Content:

As expected a reduction in strength of up to 50% was seen when the water/cement ratio was increased by one third in order to maintain a constant slump with the lower cement content mix , i.e. mix one compared to mix two in all environments.

6.6.4.4 - The Effect of Workability:

The strength results of the OPC concretes reported here appear to be in disagreement with those of Burg (5) who suggested that the addition of about 8-10% more water to compensate for slump loss does not have any significant adverse effects on the strength of concrete. Burg carried out his tests on concrete samples mixed for 5 minutes in a truck mixer at the truck's rated mixing speed. At the job site, 8 to 10% of the total unit weight of water was added to compensate for slump loss, an example of Burg's results are given in Table 6.11.

The results reported by the author showed that the addition of 11% more water did have an adverse effects on the strength of OPC samples for all curing periods. The reason for this disagreement between the results of both series of tests could be attributed to the fact that Burg's samples were compacted long after the initial mixing. This may have resulted in the water/cement ratio at compaction being lower than that at mixing because of the evaporation of water from the mix. The mix tested by the author were compacted immediatly after mixing as described in Chapter 3.

Table 6.11: Compressive strength (MPa) of concrete mixes before and after retempering with 8-10% of the total unit weight of water.(tested at 28 days of age) (Burg 1983)(5).

	at the plant	at site as received	at job after retempering
average	33.9	36.2	35.0
max value	38.8	42.7	42.2
min value	23.4	33.0	30.1

6.6.4.5 - The Effect of Cement Type:

The Influence of Pfa

Fig. 6.31a shows that uncured OPC/pfa samples were weaker than uncured plain OPC specimens at 20°C+70%RH but were statistically similar in the other two environments.

Replacing 30% of the OPC by pfa at 20°C+70%RH reduced the strength for curing periods of one day and over compared with plain OPC (Fig. 6.3 and 6.31b and c) even though the water/cement ratio was lower. This trend is confirmed by March et al (69) who carried out their tests on plain OPC and 70/30 OPC/pfa pastes of an equal water/cement ratio (i.e. 0.47). They found that when curing at 20°C the strength of OPC/pfa pastes surpassed that of plain OPC at 180 days of age, see Fig. 6.32, a trend confirmed by others such as Gopalan et al (74). However, because of the ability of the OPC/pfa mix to maintain its strength in hotter environments while at the same time , the strength of plain OPC samples became

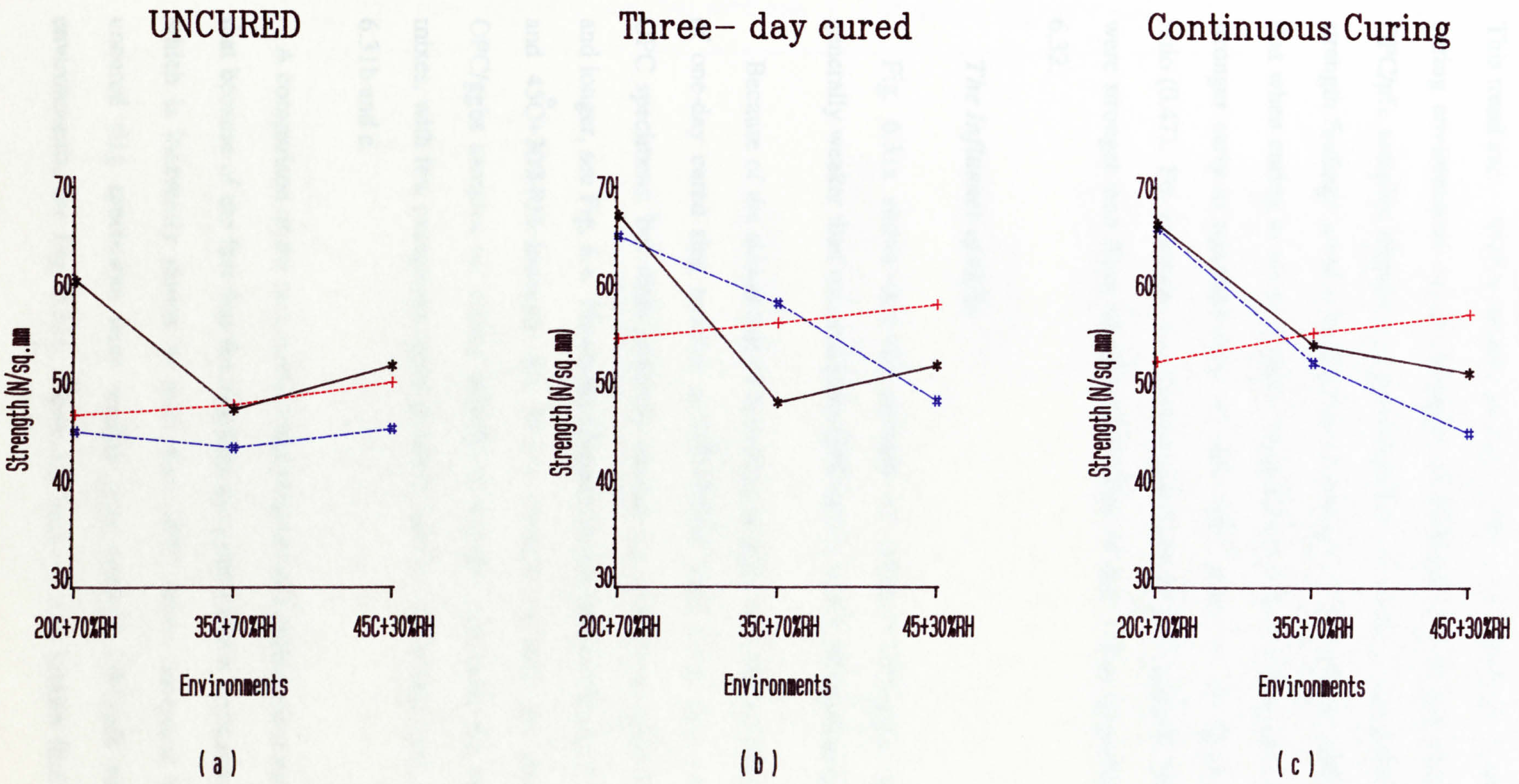


Fig. (6.31) The effects of curing environments on the 28-day strength results of uncured, 3-day and continuously cured samples

***=OPC +++=OPC/PFA ###=OPC/SLAG

lower, Fig. 6.3 shows that the one day and over cured OPC/pfa samples were generally stronger than the plain OPC specimens in the two hot environments. This trend can clearly be seen in Figs. 6.31b and c which show the influence of curing environments on the strength of three-day cured and continuous cured OPC/pfa samples respectively in comparison to those of the plain OPC. These strength findings are also compatible with those of March et al (69). They found that when curing in water at high temperatures, the OPC/pfa paste samples were stronger early in age than those of plain OPC pastes of an equal water/cement ratio (0.47). For example, at curing temperatures of 35°C and 50°C OPC/pfa pastes were stronger than those of plain OPC after 28 and 7 days respectively, see Fig. 6.32.

The Influence of Ggbs

Fig. 6.31a shows that the strength of uncured OPC/ggbs samples were generally weaker than uncured plain OPC specimens in all environments.

Because of the slower rate of hydration of ggbs than that of OPC, the strength of one-day cured slag samples at 20°C+70RH were lower than similarly cured OPC specimens, but were generally similar for specimens cured for three days and longer, see Fig. 6.4. However, because the hot environments of 35°C+70%RH and 45°C+30%RH lowered the 28-day strength of both the plain OPC and OPC/ggbs samples for curing periods of one day and over, the results of both mixes, with few exceptions, were generally similar, i.e. within 10%, see Figs. 6.4, 6.31b and c.

A comparison of the two mixes containing cement replacement materials shows that because of the fact that the slag mix has more cement replacement material (which is inherently slower to react than OPC) when compared with 30%pfa, uncured slag specimens were weaker than uncured OPC/pfa samples in all environments, see Fig. 6.31a. However, because it is known that slag is more

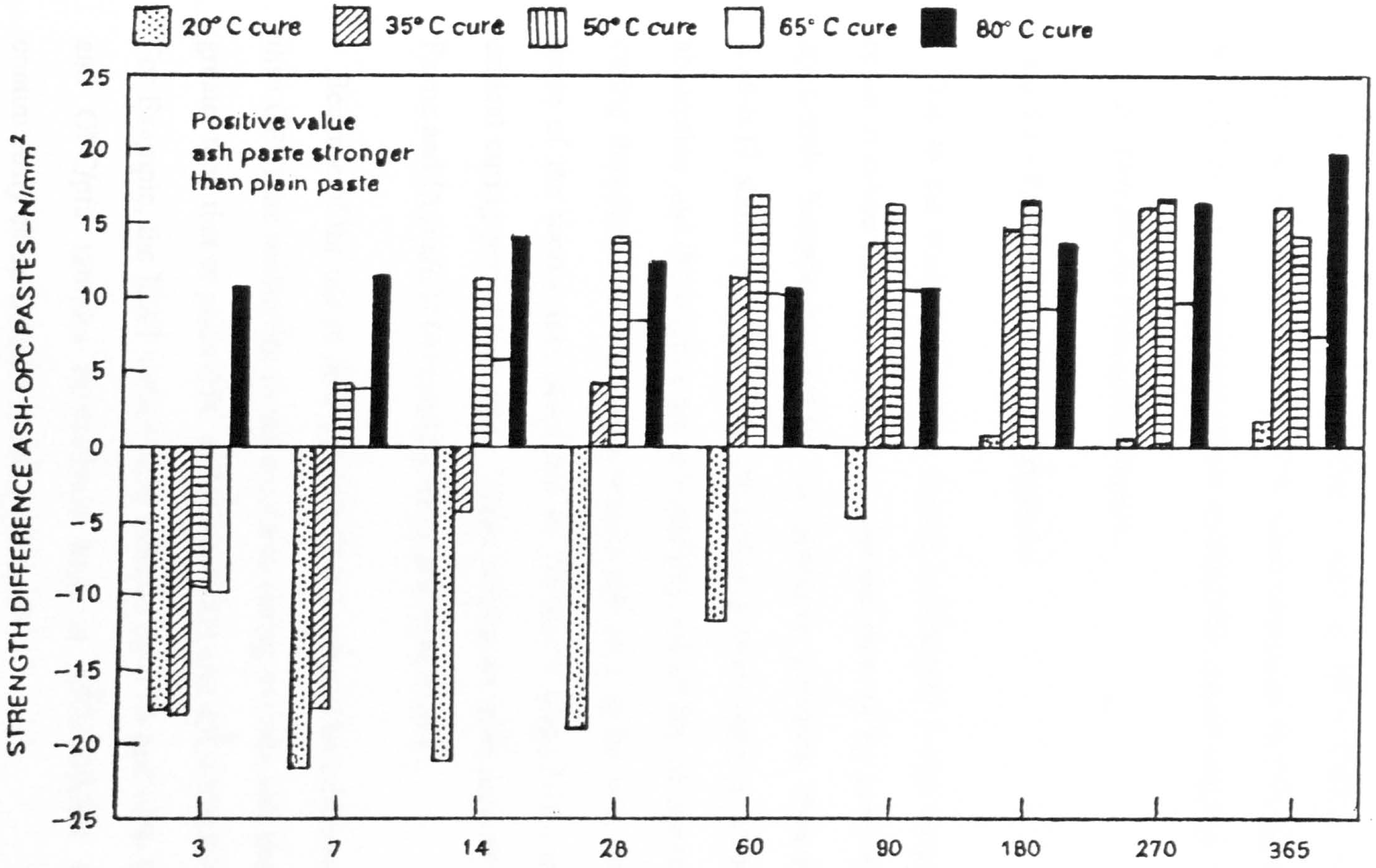


Fig. (6.32) Strength difference between OPC and OPC/pfa pastes (69) reactive with water than pfa at normal temperatures (pfa does not react with water on it's own), slag specimens cured for one day or over at 20°C+70%RH were stronger than similarly cured OPC/pfa (Figs. 6.5 and 6.31b and c). Furthermore and due to the effects of hot environments on the strength of both mixes, the pfa samples showed generally similar results at 35°C+70%RH but were stronger samples at 45°C+30%RH (Fig. 6.5) when compared to OPC/ggbs samples. Figs. 6.31b clearly illustrate these effects on three-day cured samples of all mixes.

6.6.5 - Durability-Related Properties:

6.6.5.1 - The Effect of Curing Periods:

Due to the observation given earlier in Chapter 5 that longer curing periods result in denser and finer pore structures and more of the pores near to the surface apparently become blocked by the hydration products, then Fig. 6.6- 6.9 and 6.16-6.17 show that increasing the curing periods resulted in a reduction in the absorption and the relative air permeability values for all mixes. With regard to curing durations, the absorption results are seen to be very similar in trend to those of the mortar mix presented in Chapter 5 (Fig. 5.16), in which no clear critical curing period was seen. These results are also seen to be confirmed by Payne and Dransfield (44) and Senbetta and Scholer (22).

Because of the use of 30% pfa (which is known to be inherently slower to react than OPC) the sensitivity of the results to curing periods was generally seen to be greater than that of plain OPC at 35°C+70%RH and 45°C+30%RH, see Table 6.12. For Example, the ISAT values were reduced by 55% and 68% for the plain OPC and OPC/pfa samples respectively kept at 45°C+30%RH when comparing continuously cured samples to those uncured.

The presence of a higher level of ggbs (compared with 30%pfa), which is also inherently slower to react than OPC, resulted in more sensitive behaviour than either the OPC or OPC/pfa mixes, see Table 6.12.

6.6.5.2 - The Effect of Curing Environment:

Plain OPC

Bakker (41) reported that temperature influences the rate of precipitation as well as the locality of the hydrate products. He reported that plain OPC cured at normal temperatures produces hydration products that are well dispersed thus closing off better the capillary pores than at higher temperatures. Because of this, for any given curing period, the ISAT values reported by the author were seen to be higher at 35°C+70%RH and 45°C+30%RH than at 20°C+70%RH, see Table 6.13 and Fig. 6.33 a, b and c a trend compatible with the oxygen permeability results in Chapter 5.

Blended cements:

To the contrary of the general trend of the plain OPC mixes, the different ambient conditions had generally insignificant effects on the ISAT results of OPC/pfa samples at any given curing period, see Fig. 6.33. In addition to this, the general trend of the OPC/slag mix results (with the exception of samples cured at 35°C+70%RH and uncured samples in all environments) was similar to those of the OPC/pfa mix, see Fig. 6.33. This can be attributed to the observation seen earlier in Chapter 5 that while the hotter environment of 45°C+30%RH produced coarser pore structures for plain OPC mixes, the temperature- accelerated additional reactions at 45°C of the pfa and ggbs resulted in finer pore structure and hence more pores became blocked. In addition to this, these results indicate that the reduction in ISAT values which may have been expected due to the presence of more blocked pores (when comparing blended cement samples cured in hotter environments with those cure at 20°C+70%RH) was compensated for by the increase in capillary suction due to the presence of finer pores which may lead to an increase in ISAT.

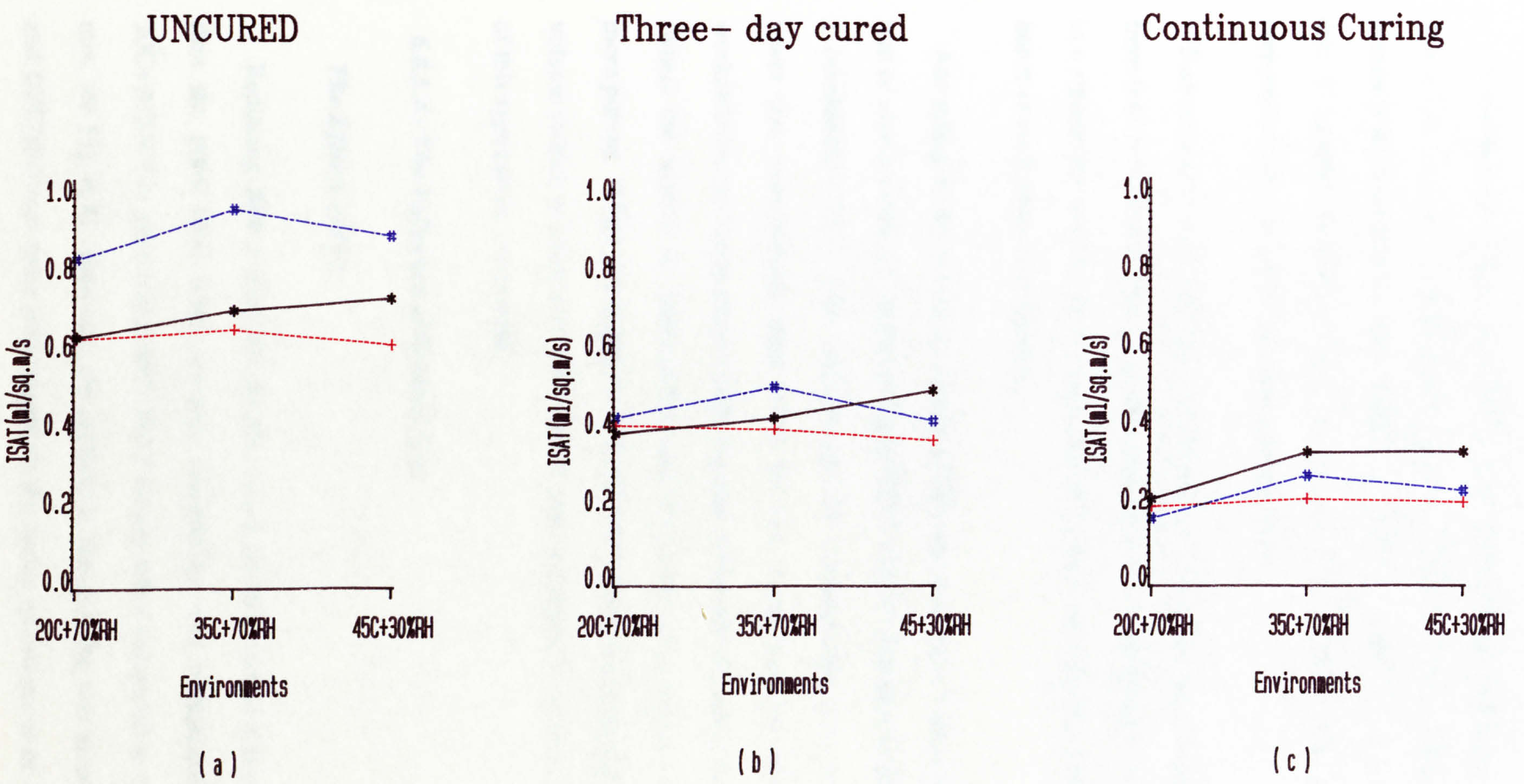


Fig. (6.33) The effects of curing environments on the ISAT results of uncured, 3-day and continuously cured samples

***=OPC +++=OPC/PFA ###=OPC/SLAG

6.6.5.3 - The Effect of OPC Content and Workability:

A comparison of the three OPC mixes indicates that, because of the fact that mix 2 had the lowest water/cement ratio, it achieved in general the lowest ISAT results in all environments, see Table 6.14. Although the volume of cement gel in mix 2 samples is greater than that in mix 1 specimens, this is more than compensated for by the lower water/cement ratio.

Furthermore, increasing the workability by increasing the water/cement ratio from 0.43 to 0.48 at a constant cement content (mix 3 compared to mix 2) resulted in a significant increase in the ISAT values for all curing periods especially in the hotter environments, see Table 6.14.

According to the laboratory results of this research, mix 3 with about 120-150 mm of slump exhibited similar or higher ISAT values compared with those of mix 1 (workability 50-75 mm) even though the water/cement ratio is significantly lower (i.e. water/cement ratio =0.48 for mix 3 but 0.64 for mix 1). Higher workabilities can cause greater bleeding and settlement resulting in the top layer (where the relative air permeability and ISAT tests were carried out) becoming more porous. When this is added to the fact that mix 3 has a greater cement paste volume (which is inherently more porous than the aggregates) than mix 1, a trend of this type can be understood.

6.6.5.4 - The Influence of Cement Type

The Effects of Pfa

Replacing 30% of the OPC by pfa (which yielded a lower water/cement ratio than the plain OPC when constant workability was maintained) resulted at 20°C+70%RH in generally similar ISAT results when compared to the plain OPC mix, see Fig. 6.33. However, the difference between the two mixes (plain OPC and OPC/pfa) was more pronounced in the hotter environment of 45°C+30%RH

Table 6.12: Percentage ISAT difference between uncured and continuously cured samples in all environments ((uncured-continuously cured)/uncured)*100%

cement type	curing environment		
	20°C+70%RH	35°C+70%RH	45°C+30%RH
plain OPC	68	54	55
OPC/pfa	70	70	68
OPC/ggbs	81	71	75

Table 6.13: ISAT results ($ml/m^2/s$) of plain OPC concrete under different curing periods and environments. (c.c=400kg/m^3, w/c=.48, slump=120-150mm, i.e. mix 3).

Curing period	environments		
	20°C+70%RH	35°C+70%RH	45°C+30%RH
uncured	0.69	0.99	0.92
Three-day	0.42	0.64	0.66
Continuous	0.30	0.39	0.40

Table 6.14: ISAT results ($ml/m^2/s$) of plain OPC concretes under different curing periods and environments.

Curing period	environment	mixes		
		mix 1	mix 2	mix 3
Uncured	20°C+70%RH	0.61	0.62	0.96
Three-day	20°C+70%RH	0.42	0.37	0.42
Continuous	20C+70%RH	0.40	0.20	0.30
Uncured	45°C+30%RH	0.88	0.72	0.92
Three-day	45°C+30%RH	0.50	0.48	0.66
Continuous	45C+30%RH	0.43	0.32	0.40

than at 20°C+70%RH or at 35°C+70%RH (pfa exhibited lower results). Dhir (80) carried out tests on plain OPC and OPC/pfa samples that were cured at 20°C, his results indicated that when a simple partial replacement of OPC by pfa was adopted, i.e. water/cement ratio was kept constant, higher ISAT results were obtained with pfa than with OPC at an age of 28 days. He, nonetheless, mentioned that this trend may be reversed at later ages. However, he found that when concrete was designed for a constant workability, as is the case in this research, the 28-day results of both the plain OPC and OPC/pfa were similar, a similar trend was also reported by the author as shown in Fig. 6.11. Other results reported in the third draft report on in-situ permeability published by the Concrete Society (98) showed that the 56-day ISAT results of OPC/pfa concretes were similar to those of plain OPC (nominal cement contents were 200 and 300 Kg/m^3). These results were obtained from Levitt by a private communication. It was also reported from the same source in the same draft report that higher curing temperatures (40°C and 60°C as opposed to 20°C) reduce the ISAT results of the OPC/pfa samples when compared to the plain OPC ones, a trend which also confirms the results reported by the author in this research.

Table 6.15 shows the minimum curing periods required for the ISAT results of OPC/pfa to equate or surpass those of plain OPC. Figs. 6.11 and 6.13 were used to obtain these values. It is seen from the Table 6.15 that at 20°C+70%RH and 35°C+70%RH, OPC/pfa samples produced in general similar or lower ISAT values than plain OPC. On the other hand, lower ISAT results were seen for OPC/pfa than for plain OPC for all curing durations at 45°C+30%RH. Also comparing the results in Table 6.15 to those in Table 5.12, shorter curing periods were indicated by ISAT (in the case of concrete designed at a constant slump) than by oxygen permeability measured on mortar (Chapter 5). One of the reasons for this trend may be attributed to the fact that while the water/cement ratios of both plain OPC and OPC/pfa mortar mixes were similar, the OPC/pfa concrete had a lower water/cement ratio than the plain OPC mix.

Table 6.16 illustrates on the other hand the curing time needed for all three mixes in all environments to reach a certain a target ISAT value. This target value was assumed to be that of the three-day cured plain OPC samples at 20°C+70%RH. The reasons for choosing this particular value are: 1) This curing duration was seen in Chapter 5 to be the maximum critical curing period after which no significant changes in the pore structure were observed 2) In an environment of 20°C+70%RH, BS8110 recommends a curing duration of about three days for concretes made with OPC. It can be seen that while plain OPC samples required longer curing times to reach the target ISAT value at 35°C+70%RH and at 45°C+30%RH than at 20°C+70%RH, the times required for the OPC/pfa samples were not affected.

The Effects of Ggbs:

The inclusion of ggbs to replace 60% of the OPC at 20°C+70%RH resulted in generally lower ISAT results compared with OPC only for samples cured for seven days and longer; the uncured and one-day cured samples exhibited higher ISAT values. However, the high temperatures of 45°C produced, as shown in Chapter 5, a finer pore structure and more blocked pores in the hydrated OPC/slag paste than in the plain OPC for curing periods of one day and over and hence smaller ISAT values were observed for periods of curing of three days and over, see Fig. 6.33.

Table 6.15 shows the minimum curing periods required for ISAT values of OPC/ggbs to equate or surpass those of plain OPC. These results are seen to be similar (although not identical) in trend to those found in Chapter 5, i.e. Table 5.12. Furthermore, curing at 45°C+30%RH was seen to require the shortest curing period followed by curing at 20°C+70%RH then curing at 35°C+70%RH a trend identical to that seen in Table 5.12. Table 6.16, on the other hand, shows that at 35°C+70%RH, a longer curing time is needed for OPC/ggbs samples to reach the

Table 6.15 : The minimum curing period (days) required for the ISAT value of OPC/pfa and OPC/ggbs concretes to equate or surpass that of plain OPC

cement type	environment		
	20°C+70%RH	35°C+70%RH	45°C+30%RH
OPC/pfa	S	S or L	L
OPC/ggbs	between 3 and 7	between 7 and 28 (approx 21)	between 1 and 3

S= similar ISAT results to OPC for all curing durations
L= lower ISAT results to OPC for all curing durations

Table 6.16: Curing period (days) required for OPC, pfa and slag samples to reach a target value. Target is assumed to be 3-day cured OPC samples at 20C+70%RH.

cement type	environment		
	20°C+70%RH	35°C+70%RH	45°C+30%RH
Plain OPC	3	7	between 7 and 28 (approx. 20)
OPC/pfa	3	3	3
OPC/ggbs	3	between 7 and 28 (approx. 18)	3

target value than at either 20°C+70%RH or 45°C+30%RH.

A comparison of the two mixes containing cement replacement materials indicates that uncured OPC/pfa samples exhibited better results than the uncured OPC/ggbs specimens in all environments (Fig. 6.33a) a trend identical to that seen in Chapter 5 using permeability and pore structure results. As was the case in Chapter 5, while the inclusion of 60% ggbs at 20°C+70%RH ggbs resulted in better or similar results for samples cured for one day or more compared with OPC/pfa samples, the opposite is true in the other two environments (Figs. 6.33b and c). It is important to recall here that the water/cement ratio for the OPC/pfa mix was lower than that for the OPC/ggbs mix.

6.6.6- Quality control programme:

The results and the above discussion show that while the test for compressive strength was best in differentiating between the mix proportions but not between the various curing periods, the results from ISAT showed the opposite trend. Hence in order to verify both the mix proportions and curing programmes, a durability- related test such as permeability or ISAT together with the cube strength should be carried out.

A comparison of the simple techniques used in the work presented in this chapter showed that ISAT is the most suitable test for the verification of curing regimes, see section 6.6.3.

The idea presented in Fig. 6.34 may be used for verification of both the mix proportions and the curing programme carried out on site. The strength and thus mix proportions can be evaluated as usual using standard cubes cured at 20°C. To verify whether curing has been carried out as specified, concrete cubes (inside moulds) may be placed along side the structure and distributed in such a way that they will be cured simultaneously with the structure. These samples can then be tested by ISAT (as specified by the standard) and then Fig. 6.34 can be utilized.

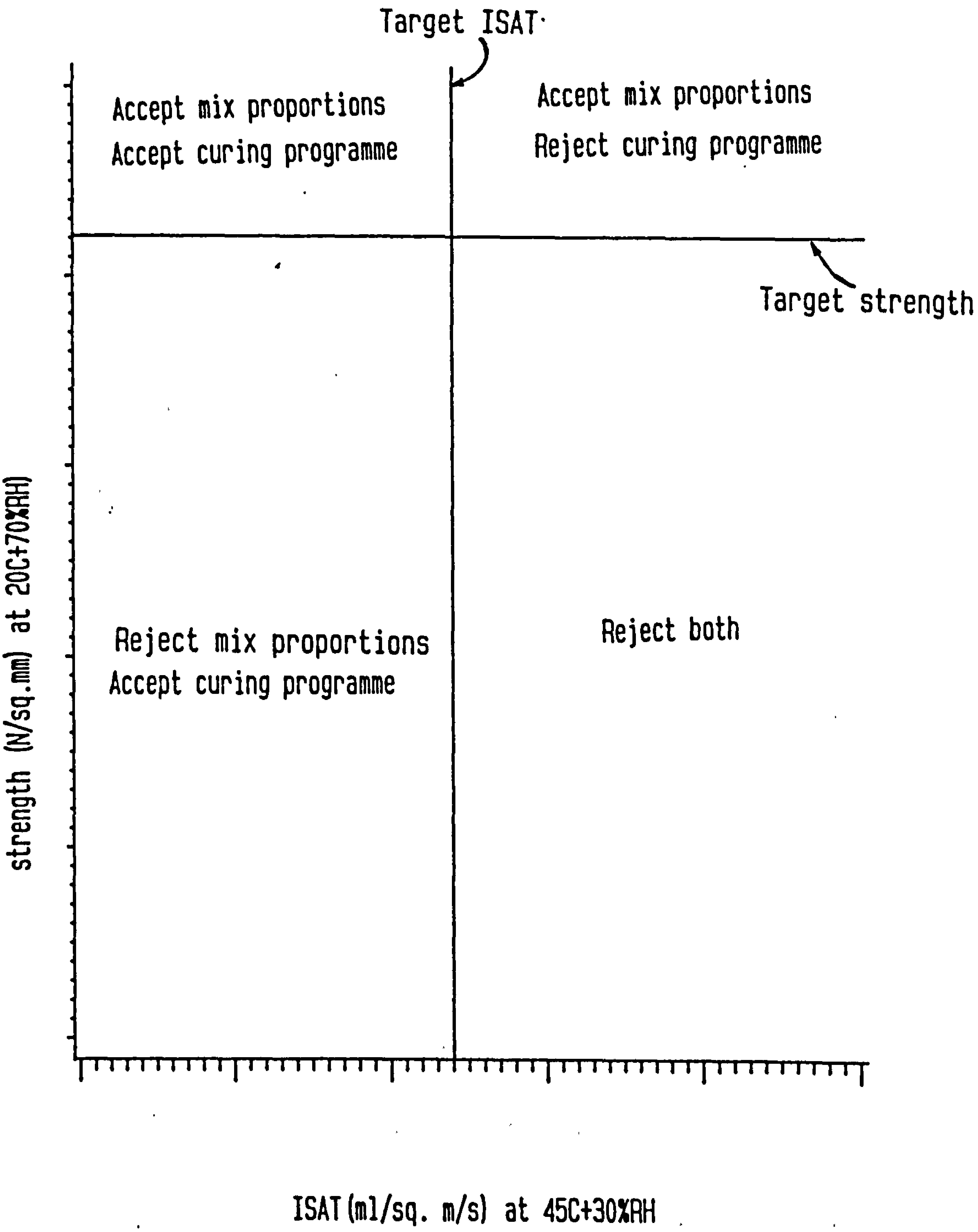


Fig. (6.34) Basis for quality control programme to verify both mix proportions and curing effecincy

For example, Fig. 6.35 uses the idea described in Fig. 6.34 for the results of all mixes cured at 45°C+30%RH. The 'target' ISAT value are assumed to be those for three-day cured plain OPC samples of mix 2 stored at 45°C+30%RH. The reason for choosing three days of curing is because three days was found in Chapter 5 to be the maximum critical curing period beyond which little changes in the pore structure were observed. It is understood that this idea is based on few laboratory results where the actual site circumstances could be very different. A need exists to see whether this idea is practically usable and what kind of modifications are needed.

6.7 - Conclusions:

The results analyzed in this chapter relate to the effects of curing durations, curing environments and the addition of pfa or ggbs on the strength and some durability- related properties of concrete mixes. To simulate in-place casting, the following procedures were taken: 1) Moisture loss was allowed to take place only from the top-as-cast face of the sample 2) The initial mix temperature was as close as possible to that of the respective environment 3) Curing periods ranging from nothing to 28 days were used. The effect of cement type was investigated on the basis of equal workability (i.e. 50-75mm of slump) which resulted in the water/cement ratio for the OPC/pfa mix being slightly lower than that for plain OPC or OPC/ggbs mixes. All tests were carried out at 28 days of age and the conclusions drawn from them are summarized as follows:

6.7.1 - The Relationships between Tests Results:

1 - A significant linear relationship was found between the results of the test for water absorption and initial surface absorption (ISAT).

2 - The relationships between the results of the relative air permeability and either water absorption or ISAT were nonlinear.

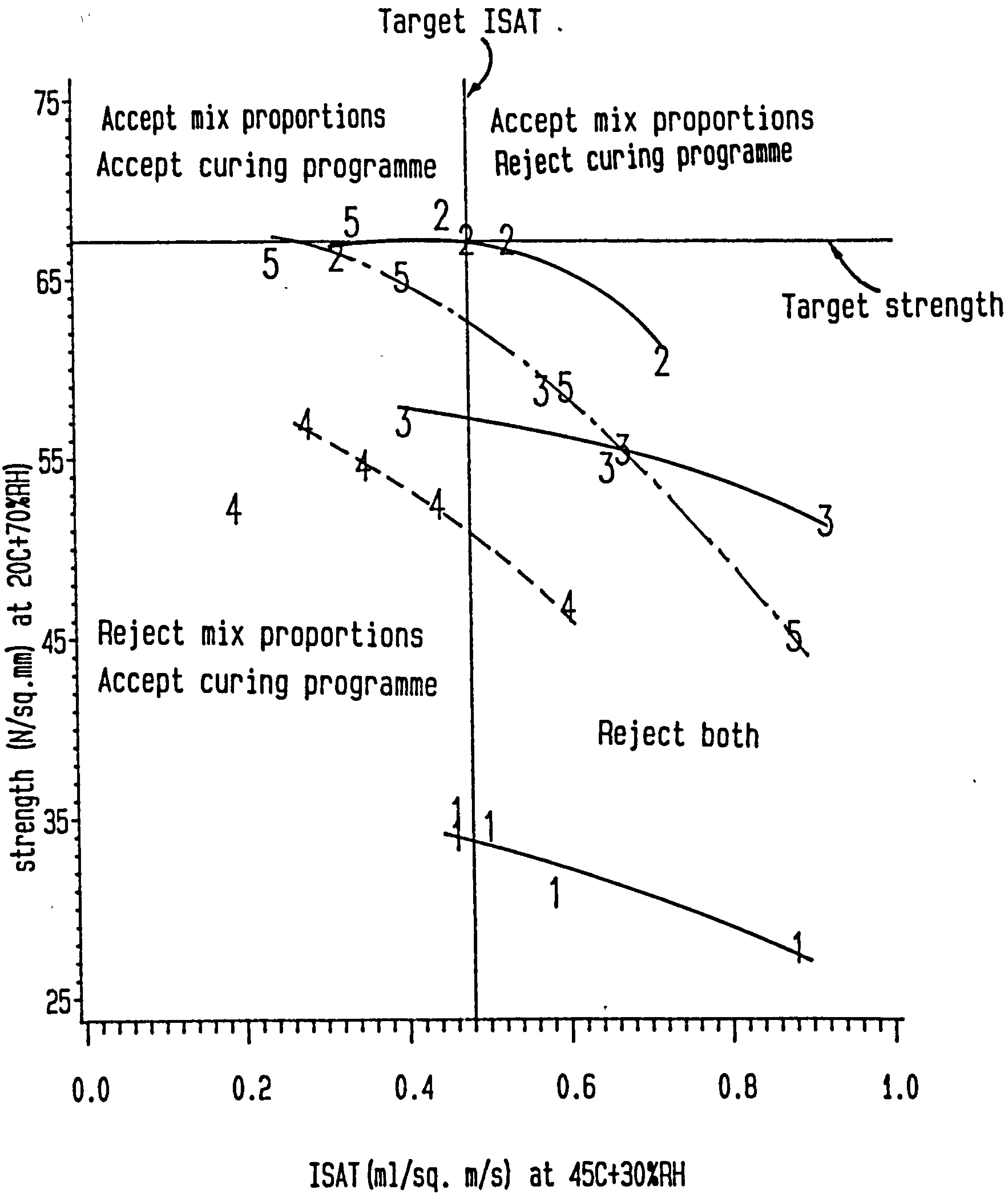


Fig. (6.35) The relationship between ISAT and compressive strength of different mixes, slump=50-75mm for all but mix 3 1=opc (c.c.=275kg/cu.m), 2=opc (c.c.=400kg/cu.m), 3=as 2 but twice as workable, 4=as 2 but 30%pfa, 5=as 2 but 60%ggbs

3 - While the results of each of the mixes separately indicate that there was an inverse relationship between the results of the strength and either water absorption, ISAT, Figg test or porosity, there was no unique relationship for all mixes collectively.

6.7.2 - Compressive Strength:

1 - Curing durations had practically no effect on the strength of plain OPC mixes in all environments and a similar trend was seen for the OPC/pfa samples cured for periods of one day or more. In addition, curing periods of up to three days were seen to significantly influence the strength of the OPC/ggbs samples at 20°C+70%RH and 35°C+70%RH. The strength of the slag samples kept at 45°C+30%RH were however, like OPC, not affected by curing durations.

2 - The strength of plain OPC or OPC/ggbs samples in hot dry environments was lower than those achieved at normal temperatures (20°C+70%RH) for all curing durations. Nonetheless, no further significant reduction in the strength of OPC and OPC/ggbs samples were observed at 45°C+30%RH when compared to 35°C+70%RH for all curing periods. On the other hand, OPC/pfa mixes were statistically unaffected by the curing environments studied.

3 - The inclusion of 30%pfa resulted in a reduction in the compressive strength when compared with plain OPC at 20°C+70%RH for all curing periods.

4 - The strength of the OPC/pfa samples cured for one day and over were higher than those of plain OPC in the two hot environments whereas uncured samples exhibited similar results.

5 - Uncured slag specimens were weaker than uncured plain OPC in all environments. Nontheless, with the exception of one-day cured samples at 20C+70%RH, the inclusion of 60% slag resulted in generally similar results to the plain OPC mixes in all environments for curing durations of one day and over.

6 - The inclusion of 30% pfa resulted in either similar or stronger samples than those containing 60%ggbs when no curing was carried out.

7 - The inclusion of 60%ggbs result in stronger samples than those containing 30%pfa when cured for one day and over at 20°C+70%RH. However the OPC/pfa mixes showed similar results at 35°C+70%RH but stronger results at 45°C+30%RH when compared to 40/60 OPC/ggbs.

6.7.3- Durability:

Durability of the concrete mixes was assessed using water absorption, ISAT, Figg test and porosity. It was concluded in section 6.6.3 that ISAT was the best test for explaining the effects of curing durations, curing environments and cement type on durability. Hence, the following conclusions are based on the results of ISAT:

1 - Longer curing periods improved the durability characteristics of all mixes in all environments.

2 - The hotter environments of 35°C+70%RH and 45°C+30%RH had adverse effects on the durability properties of plain OPC when compared to those cured at 20°C+70%RH.

3 - The durability results of OPC/pfa samples were generally seen to be unaffected by the different curing environments.

4 - OPC/ggbs samples cured at 45°C+30%RH were seen to produce similar results to those produced at 20°C+70%RH whereas curing at 35°C+70%RH showed in general worse results.

5 - A Comparison of the three different cements shows that the inclusion of pfa produce generally similar or better durability results compared with plain OPC or OPC/ggbs samples in all environments.

6 - The inclusion of 60%ggbs was, in general, seen to produce better durability results than plain OPC in all environments for curing periods of seven days or more whereas the opposite was true for curing periods of three days or less.

6.7.4 - Quality control:

1 - A comparison between the different tests used indicates that the cube strength is the best test for the verification of mix proportions and that ISAT is the best for detecting the effects of curing periods and curing environments.

2 - In order to verify both the mix proportions and curing programme, compressive strength (carried out as usual at 20C) and ISAT (carried out in situ) should be performed simultaneously.

CHAPTER SEVEN

CONCLUSIONS AND SUGGESTED FUTURE RESEARCH

7.1 - Conclusions

The following conclusions are based on tests conducted on both concrete and mortar mixes and deal with the effects of curing durations, curing environments (similar to those found in Middle Eastern countries), and the addition of either pfa or ggbs on certain properties of the two materials. The initial mix temperatures of both the concretes and the mortars were controlled to be as close as possible to that of the environments in which they were placed and in all cases moisture loss was allowed to take place only from the top-as-cast face of the sample. The effect of cement type was examined on the basis of constant workability (i.e. 50-75mm of slump) in the case of concrete but at a constant water/cement ratio in the case of mortar. The duration of curing ranged from no curing at all to 28 days in all three environments and all tests were carried out at 28 days of age. The properties of the materials under investigation were compressive strength and durability.

7.1.1 - Compressive Strength:

The following conclusions regarding compressive strength were drawn from tests carried out only on concrete samples (100 mm cubes).

1 - The curing durations used had little or no effect on the strength of the plain OPC samples in all environments and similar trend was seen for OPC/pfa samples cured for one day or more. In addition, curing periods of up to three days were seen to influence the strength of the OPC/ggbs samples at 20°C+70%RH and 35°C+70%RH. The strength of the slag samples kept at 45°C+30%RH were however, like OPC, not affected by curing periods.

2 - While the compressive strengths of plain OPC and OPC/ggbs samples were adversely affected in the 35°C+70%RH and 45°C+30%RH environments for all curing periods compared with 20°C+70%RH, the strengths of the OPC/pfa samples were not. Nonetheless, no further significant reduction in the strength of OPC and OPC/ggbs samples was observed at 45°C+30%RH compared with 35°C+70%RH for all curing durations.

3 - The inclusion of 60% ggbs resulted, with the exception of those uncured samples, in strength values generally similar to the plain OPC samples in all environments.

4 - For all curing periods, the inclusion of 30%pfa resulted in weaker samples than plain OPC or OPC/ggbs at 20°C+70%RH but produced stronger specimens in the hotter environments of 35°C+70%RH and 45°C+30%RH.

7.1.2 - Durability- Related Properties:

The following conclusions are based on results obtained from testing both the concrete and mortar mixes. The pore size distribution and oxygen permeability results are used in the case of mortar whereas ISAT values are used in the case of concrete.

7.1.2.1 - Curing Duration:

1 - Initial curing periods had significant effects on the durability- related properties of all mixes in all environments as seen from the pore size distribution, oxygen permeability and ISAT results.

2 - As far as steady-state permeability and pore size distribution are concerned, there existed a critical curing period beyond which no further significant effects were observed up to the age of 28 days. This critical curing period was seen to

depend on both the curing environment as well as the cement type.

3 - Plain OPC mortars showed a critical curing period of approximately three days in all environments.

4 - The OPC/pfa and OPC/ggbs mortars on the other hand showed critical curing periods of approximately three days at 20°C+70%RH and 35°C+70%RH and one day at 45°C+30%RH.

7.1.2.2 - Curing Environments

I - Uncured samples:

The hotter the environment, the greater the adverse effect on those uncured samples of all mortar mixes. These effects were more pronounced in the case of mixes containing 60% ggbs than with those made with OPC or with 30/70 blend of pfa/OPC. This effect was not however clearly shown by the ISAT results of the concrete mixes.

II - Samples cured for one day and over:

Plain OPC

The 35°C+70%RH and 45°C+30%RH environments adversely affected the pore size distribution, permeability and ISAT values of the plain OPC mixes compared with the same characteristics achieved at 20°C+70%RH. There was however no significant differences in properties produced in the two hot environments of 35°C+70%RH and 45°C+30%RH.

70%OPC/30%pfa

1 - The OPC/pfa mortar samples exhibited a finer pore structure at 35°C+70%RH for all curing periods when compared to that achieved at 20°C+70%RH.

2 - The permeability of OPC/pfa samples cured at 35°C+70%RH was higher than

that achieved at 20°C+70%RH for curing periods of three days or less but similar permeability results were seen for curing periods of seven days or more.

3 - At 45°C+30%RH, curing the OPC/pfa samples for one day or more produced a significantly finer pore structure, lower permeability and lower ISAT results than OPC/pfa specimens cured for the same period and kept in either the 20°C+70%RH or the 35°C+70%RH environments. In fact, curing the OPC/pfa mortar samples for one day only at 45°C+30%RH produced better durability results than any of the OPC/pfa samples kept at 20°C+70%RH or 35°C+70%RH regardless of curing durations (up to 28 days).

4 - According to the ISAT results, for any given curing period, the curing environments had little effect on the durability- related properties of the OPC/pfa concrete.

40%OPC/60%ggbs

1 - For curing periods of one day or more, the OPC/ggbs samples were seen to exhibit a coarser pore structure, higher permeability and higher ISAT results at 35°C+70%RH than at 20°C+70%RH.

2 - When curing for one day or more at 45°C+30%RH, the inclusion of 60%ggbs resulted in a finer pore structure and lower permeability than specimens cured for a similar period at either 20°C+70%RH or 35°C+70%RH. In fact, curing the slag mortar samples for one day only at 45°C+30%RH produced better durability results than any similar samples kept at 20°C+70%RH or 35°C+70%RH regardless of curing duration (up to 28 days). However, the ISAT results of the slag concretes kept at 45°C+30%RH were similar to those produced at 20°C+70%RH for all curing periods.

7.1.2.3 - The Effects of Cement Type

I - The Influence of pfa

1 - Uncured OPC and OPC/pfa mortar were seen to have similar pore structure and permeability characteristics in all environments.

2 - At 20°C+70%RH, the inclusion of 30%pfa at a constant water/ cement ratio resulted in a coarser pore structure and a higher permeability than plain OPC samples cured for periods of one day and over. Nontheless, the ISAT results were seen to be similar for both mixes for the same periods of curing.

3 - At 35°C+70%RH, the inclusion of 30%pfa resulted in finer pore structures and lower permeablities than plain OPC mortars for curing durations of seven days and over whereas ISAT values for the concrete mixes were either similar or lower for all curing durations.

4 - At 45°C+30%RH, curing the OPC/pfa samples for one day or more resulted in significantly better durability- related properties (i.e. pore structure, permeability and ISAT) than plain OPC. Furthermore, one-day cured OPC/pfa mortar samples at 45°C+30%RH produced better durability results than any of the plain OPC samples kept in any of the three environments for any curing period.

II - The Influence of ggbs:

1 - Uncured OPC/ggbs samples exhibited a coarser pore structure, higher permeability and higher ISAT values than plain OPC samples in all environments.

2 - At 20°C+70%RH, for mortar samples made to a constant water/cement ratio, the inclusion of 60%ggbs resulted in a coarser pore structure, higher permeability and higher ISAT results for curing periods of three days or less but similar or better results were seen for curing periods of seven days or more when compared with plain OPC.

3 - AT 35°C+70%RH, OPC/ggbs samples exhibited a coarser pore structure and higher permeability than plain OPC samples for all curing periods and higher ISAT values for curing periods of 7 days or less.

4 - At 45°C+30%RH, curing the OPC/ggbs mortar samples for one day or more resulted in significantly better pore structure and permeability characteristics than plain OPC and lower ISAT values for curing periods of three days or more. Moreover, curing the slag mortar samples for one day only at 45°C+30%RH produced better durability results than any of the OPC samples kept in any of the curing environment for any curing period.

III - Comparison Between OPC/pfa and OPC/ggbs

1 - Uncured OPC/pfa samples showed better pore structure, permeability and ISAT characteristics than uncured OPC/ggbs samples in all environments.

2 - At 20°C+70%RH, the slag samples showed similar but more often better durability- related characteristics than the pfa samples for curing periods of three days or more.

3 - The pfa samples showed consistently better pore structure, permeability and ISAT characteristics than the slag samples for curing durations of one day and more at 35°C+70%RH or 45°C+30%RH.

7.1.3 - Quality Control:

1 - To verify mix proportions and the curing programme, cube strength (carried out as usual at 20°C) as well as some form of durability- related test (carried out on site) should be performed.

2 - A comparison of the durability- related tests carried out in the work reported here indicates that either the ISAT or the steady-state permeability test are best suited for such a purpose.

7.2 - Suggested Future Research:

1 - Following the results and conclusions reported here, the following recommendations are made for areas where future research work is considered necessary:

I - The results of the test for 28-day compressive strength showed that, in the majority of cases, they were only slightly affected by periods of curing. Although an explanation for this unexpected trend was provided, further research is needed to explain more fully this behaviour.

II - More information is required on the influence of initial mix temperature on both strength and durability of concretes kept under conditions similar to those used in this study.

III - It was expected that the environment of 45°C+30%RH would prove to be the more aggressive of the two hot environments used. This however was not the case especially when considering the durability- related properties of blended cement samples (i.e. curing the OPC/pfa and OPC/ggbs samples for one day or more at 45°C+30%RH resulted in a finer pore structures and lower permeability than curing for the same periods at 35°C+70%RH). The influence of temperature and humidity alone needs to be studied to try and evaluate which parameter is having the greatest effect and to establish whether or not there exists a 'critical' environment.

IV - In addition to the fact that there is a shortage of data on the behaviour of blended cements in hot climates, the results reported by the author deal with only one level of OPC replacement by either pfa or ggbs. Therefore, it is considered necessary to find out how different levels of both materials will influence the properties of concretes or mortars in hot climates.

V - The initial surface absorption test (ISAT) was seen to be better than either water absorption, Figg test or porosity in detecting the effects of curing durations, curing environments and cement type on concrete. In spite of this, the trends of ISAT were not always similar to those of MIP or steady- state oxygen permeability test. More data is required to try and find out why this should be and to possibly develop an in-situ test which may reflect more closely the trends of MIP or oxygen permeability.

2 - The results reported in the current investigation relate to constant temperature and relative humidity in any one environment. Therefore, a need exists to study the effects of cyclic temperatures and relative humidities on the properties of concretes made with plain OPC, OPC/pfa and OPC/ggbs.

3 - A long term project (carried out on site) relating initial curing periods, different cement replacement materials and admixtures on the durability- related properties and strength of concretes under Middle Eastern conditions.

4 - A study of the implementation of the proposed quality control programme under actual site conditions. This study should look into improving such a model or even finding a better alternative.

5 - An investigation into the effects of curing periods on the carbonation rate of plain OPC, OPC/pfa and OPC/ggbs mixes.

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