THE ABRASION RESISTANCE OF CONCRETE WITH PULVERISED FUEL ASH

by

MIRIAM PHITIDES

Thesis submitted for the degree of
Master of Philosophy

The University of Aston in Birmingham

March 1991

THE UNIVERSITY OF ASTON IN BIRMINGHAM

"The abrasion resistance of concrete with pulverised fuel ash"

by

Miriam Phitides

Thesis submitted for the degree of Master of Philosophy

March 1991

Summary

This thesis describes an investigation of the effect of abrasion resistance of concrete containing pulverised fuel ash.

The test method is based on wear produced by rotating steel wheels running in a circular path. The abrasion resistance is expressed in terms of the depth of the groove produced by 15 minutes of abrasion. This test has been used in the present study to assess the abrasion resistance of the various test surfaces.

Numerous factors influence the abrasion resistance of floor slabs, a most significant being curing, strength grade and trowelling intensity. These factors have not been adequately tested with mixes containing pulverised fuel ash, and so this research work was structured to examine the resistance to wear of concrete with pulverised fuel ash.

The experimental investigation was formulated in three separate but related phases and these may be briefly summarised as follows:

1. The development of basic mix design data from a series of trial mixes containing PFA to be used for the design of the mixes for the main investigation.

2. To study the abrasion resistance of concrete mixes containing PFA using the rolling wheel apparatus developed at Aston University. This macrostudy of abrasion resistance to place particular emphasis on the influence of the curing regime and the age at test on the performance of the test slabs.

3. Through a parallel study, of microscopic characteristics of individual mixes, to identify those factors that particularly influence the abrasion resistance of concrete mixes containing PFA.

The experimental results revealed that positive curing has a major influence on the abrasion resistance of PFA concretes. With a given water/cementitious material ratio, the abrasion resistance is influenced by the combined effects of PFA content and curing regime.

Further improvements in abrasion resistance were detected at a later age.

Well cured concrete appeared to be relatively independent of PFA content up to 40 percent but the performance of air cured slabs appears to be inversely proportioned to PFA content.

Key Words: PFA, Abrasion, Concrete, Wear, Curing

This thesis is dedicated

to my parents

ACKNOWLEDGEMENTS

I wish to express my gratitude to Dr R J Kettle for his constant help, encouragement and valuable guidance throughout this investigation.

Also thanks are due to C Thomson, J Hollins, Dr M Sadegzadeh and all who helped to make this research possible.

I am deeply indebted to my husband for his continual encouragement throughout the duration of the research.

I also wish to thank Mrs W Groves for typing this thesis.

Finally I would like to thank the Central Electricity Generating Board for the total financial support during the period of the research.

LIST OF CONTENTS

LIST OF CONTENTS continued

LIST OF CONTENTS continued

LIST OF CONTENTS continued

LIST OF APPENDICES

LIST OF FIGURES AND HISTOGRAMS

LIST OF FIGURES AND HISTOGRAMS continued

LIST OF FIGURES AND HISTOGRAMS continued

LIST OF FIGURES AND HISTOGRAMS continued

LIST OF FIGURES AND HISTOGRAMS continued

LIST OF TABLES

LIST OF PLATES

CHAPTER ONE

INTRODUCTION

1.0 INTRODUCTION

The abrasion resistance of a concrete slab in an industrial environment may be defined as the ability of the concrete surface to resist being worn away by rubbing, rolling, sliding, cutting and impact forces.

The floor user judges the performance of a floor by the characteristics of its surface and additionally requires a floor which will resist any damaging agency to which it is exposed. Such agencies will primarily damage the surface and the nature of the attack will be largely controlled by the activities undertaken within the particular environment. The nature of the attack could range from chemical spillage to physical damage and it is this latter mechanism with which this investigation is concerned. Typical factors likely to produce surface abrasion include impact of objects dropped onto the floor or dragged over it and abrasion produced by wheeled and tracked vehicles travelling over it.

During the past 20 years a considerable amount of laboratory-based research has been undertaken to assess the abrasion of concrete floors. However, very little work to date has been reported on the abrasion resistance of concrete containing cement replacement materials. This investigation has therefore been directed towards this topic and is concerned with the abrasion resistance

of concrete slabs containing pulverised fuel ash (PFA) as a cement replacement. The long term consequences of damage to the floor in industrial or warehouse premises can be significant for the essential repairs can be expensive and disruptive. Thus, it is necessary to provide a clear assessment of the abrasion performance of concretes containing PFA so that decisions can be taken relating to their incorporation in industrial floors.

Research on abrasion resistance has been recorded for more than 85 years (21) although little research has been undertaken in the UK during the past 20 years, even though the annual cost of floor construction and repairs in this country is in excess of several hundred million pounds.(15) There is no universal classification system by which industrial floors may be rated in terms of abrasion resistance although there are several general classification systems for floors (34, 6). Indeed concrete floors are still invariably specified in terms of compressive strength rather than abrasion resistance.

This partly arises from the lack of a universally accepted test for measuring the abrasion resistance of concrete. Although the ASTM has detailed (8) (67) several tests, there is no current British Standard test for making such assessments. However, recent research at Aston University has led to the development of an appropriate apparatus and test method (65) (40), which is

now gaining acceptance (22), (17), (18), within the industry. The test method is based on rotating steel wheels running in a circular path. The abrasion resistance is expressed in terms of the depth of the groove produced by 15 minutes of abrasion. This test has been used in the present study to assess the abrasion resistance of the various test surfaces.

Numerous factors influence the abrasion resistance of floor slabs, among the most significant are curing, strength grade and trowelling intensity. It has been suggested (59) that, for a given set of materials, the resistance of concrete to wear (both erosion and abrasion) improves as its strength increases. However this hypothesis has not been adequately tested (25) with mixes containing PFA, and so this investigation was structured to examine this hypothesis for mixes both with and without PFA.

Following preliminary testing, to provide mix design data, the investigation was divided into two series. In the initial series a range of mixes was produced by the simple substitution of cement with PFA on an equal weight basis. This clearly produced mixes with a range of strength. In the second series PFA substitution ranged from 0 to 40 percent but the individual mix designs were modified so that the strength was constant. In order to understand the mechanisms involved in

developing abrasion resistance, test specimens were also subjected to micro structural analysis using microhardness techniques and mercury intrusion porosimetry (MIP).

In view of the acknowledged importance of curing to the long term performance of concrete containing PFA, the role of the curing regime was also included in the study. This involved monitoring the abrasion resistance of slabs at ages of 28 days, 3 months, 6 months and 12 months, so that any long term benefits arising from the incorporation of PFA could be established.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

This literature review is divided into two parts. The first part deals with the abrasion resistance of concrete, including the development of an accelerated abrasion test apparatus with a standardised testing procedure. The remainder of the review is devoted to the use of PFA in concrete and includes its production, its influence on the properties of concrete leading to recommendations for the use of PFA in concrete mixes.

2.2 INVESTIGATION OF SLIDING FRICTION

The three basic laws of friction which were initially presented by Coulomb (25) can be presented as follows:-

(1) Frictional resistance is proportional to the weight of the object which is being removed.
(2) Frictional force is independent of apparent area of contact.
(3) The interfacial resistance between two surfaces is independent of the velocity of sliding.

Of these three basic factors, the greatest concerns have been associated with the influence of speed.

Indeed the effect of speed on the value of the coefficient of friction was first discussed by Coulomb

(26). In the second chapter of his classical work on friction "Theorie des machines simples" Coulomb reached the conclusion that the frictional force during sliding was independent of speed for oak sliding on oak. Subsequently, in 1785, the English investigator Vince (80) showed that the textile materials exhibited a marked increase in the coefficient of friction with increasing speed.

Experiments carried out in 1829 by Rennie (61) using metals, iron, stone, ice, leather and fibrous materials (textiles) showed that for all except the textiles, the coefficient of friction was independent of the speed. However, for the fibrous materials, the coefficient decreased with increasing speed. In his text "Friction and Wear" Kragelskii (42) makes the reservation that the softer types of wood, stone and metals behave similarly to the fibrous materials. It is, however, necessary to clarify the difference between the kinematic and static coefficients of friction.

The third law implies that the force required to start sliding is the same as that to maintain sliding, at any specified velocity. Dokos (31) demonstrated that the static, coefficient of friction (surfaces at rest) is a function of time of contact, while the kinetic coefficient of friction (surfaces in motion) is a function of velocity.

In a series of brilliantly executed experiments Morin (50) rectified most of Coulomb's results and also arrived at the conclusion that the coefficient of friction of a moving object is independent of speed.

2.3 ABRASIVE WEAR

This can be defined as the unintentional removal of material from the surface of bodies moving in contact with one another and may be due to attrition by sliding, scraping or percussion.

The resistance of concrete to abrasion is difficult to assess as the damaging action varies depending on the exact cause of wear and no single test procedure is ideal to satisfactorily evaluate all the loading conditions, with tests ranging from simple rubbing tests to rolling balls or dressing wheel through to sandblasting may each be appropriate in different cases. The ASTM standard C418-76 prescribes the procedures for determining wear by sandblasting but it is not obvious how this should be used as a criterion of wear resistance under different conditions (53).

2.3.1 Abrasion Resistance PC Concrete

The abrasion resistance of concrete has been defined by the ACI (7) as the ability of a surface to resist being

worn away by rubbing and friction. The more extensive definition, provided by the ASTM, develops the term by extending abrasion to include erosion by cavitation and impingement (9) and defines abrasion as wear by the displacement of materials from a solid surface due to hard particles or hard protuberances sliding along the surface.

Prior (57) has classified the wear of concrete surfaces by abrasion into four main categories:-

(1) Wear on concrete road surfaces due to foot traffic, light trucking and skidding, scraping or sliding of objects on the surface (attrition).
(2) Wear on concrete road surfaces due to the movement of heavy vehicles (attrition plus scraping plus percussion).
(3) Wear on hydraulic structure, such as dams, spill ways, bridge and tunnel due to the abrasive action by materials carried by water at low velocities, known as abrasive erosion (attrition plus scraping).
(4) Wear on concrete dams, spillways and tunnels, where a high hydraulic gradient is present, generally known as cavitation erosion.

2.4 METHODS OF TEST FOR ABRASION RESISTANCE

All the research on wear resistance of concrete has been

based on accelerated wear tests. Some of the earliest work by Abrams (3) involved the abrasion of concrete specimens by impact with steel balls. Other workers have used shot blasting, rotating steel wheels, rolling steel balls, rubber tyres with chains, rotating pads, dressing wheels and reciprocating rubbing.

An earlier survey, presented by Sadegzadeh (65), revealed that there was no simple apparatus which would simulate all the actions to which a concrete floor could be exposed during service. He identified that many test methods (2) have been used to try to assess the abrasion resistance of concrete. These have included ratler type tests, shot blast tests, reciprocating tests, revolving disk method, dressing wheels, rotating ball bearings and rolling wheels. Sadegzadeh clearly demonstrated (65) the shortcomings with each of these tests and this led him to the need to develop a reliable test (apparatus and procedure) for assessing the abrasion resistance of concrete. A number of performance criteria for an abrasion test were also presented (39) and these were used in the development of an appropriate test method.

Having completed his review, he concluded that a method based on rolling wheels presented the most favourable route for further development. Indeed his final apparatus was based on earlier work undertaken by Chaplin

(23) at the C & CA. This apparatus performed well in the earlier study (40) and has subsequently been used to test a large number of concrete floors (40). It was therefore decided to adopt this apparatus for the proposed study and the equipment shown in plates 2.1 and 2.2. It consists of a rotating steel plate which carries three hardened steel wheels. As the plate is rotated these rotary wheels wear a circular groove in the concrete surface and the depth of this groove provides a measure of abrasion resistance. Further details of the adopted test apparatus and experimental procedure are given in Chapter 5.

2.5 FACTORS INFLUENCING THE ABRASION RESISTANCE OF CONCRETE

The main factors that are considered to have a significant effect on the abrasion resistance of concrete may be summarised as follows:

1. Compressive strength
2. Finishing techniques
3. Curing
4. Surface treatments
5. The physical properties of aggregates.

The prime factor is the quality of the exposed surface of the concrete slab and all these factors affect this quality it is essential to realise the complexity of this

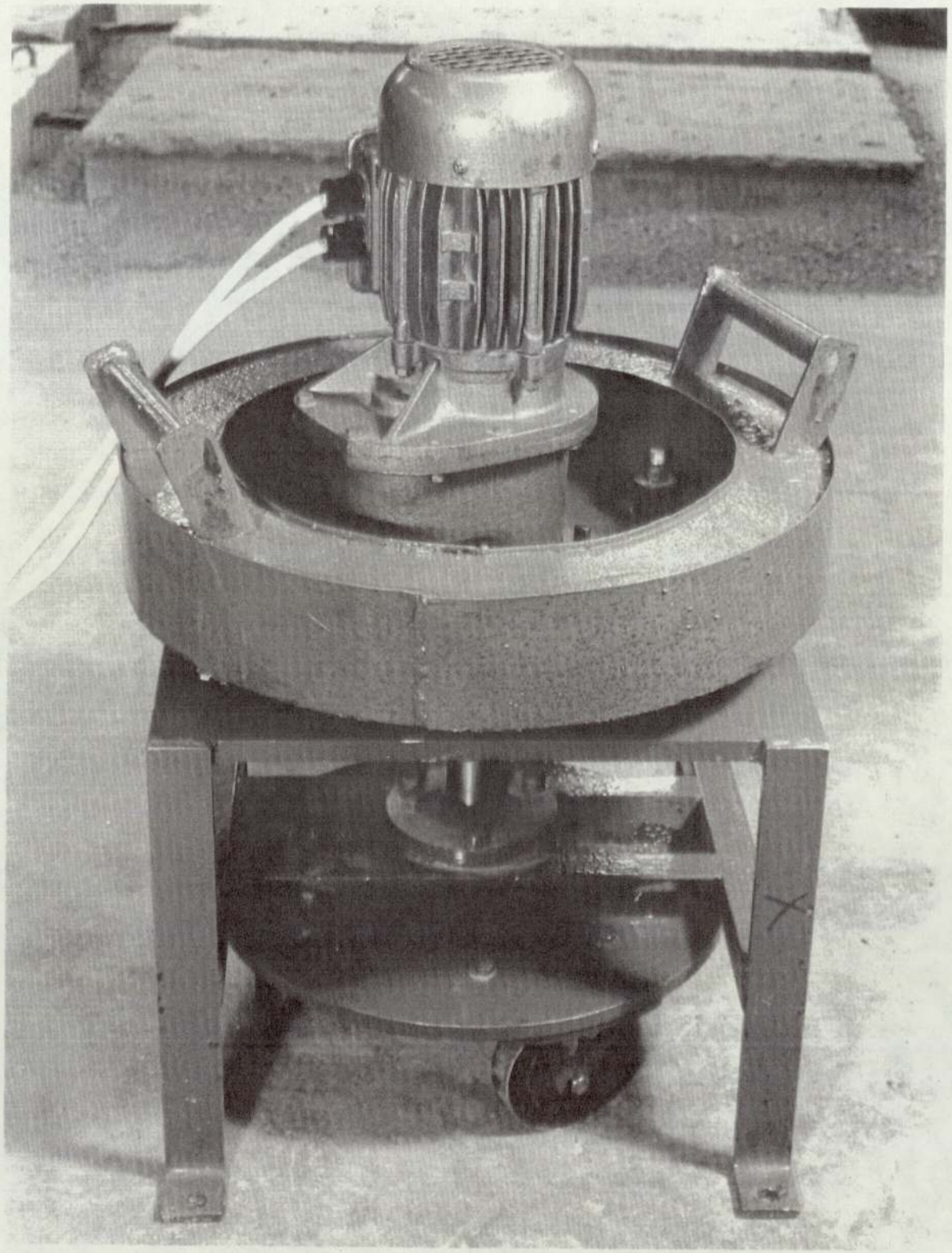


PLATE 2.1 THE BASIC ACCELERATED ABRASION APPARATUS WITH THE LEAD COLLAR

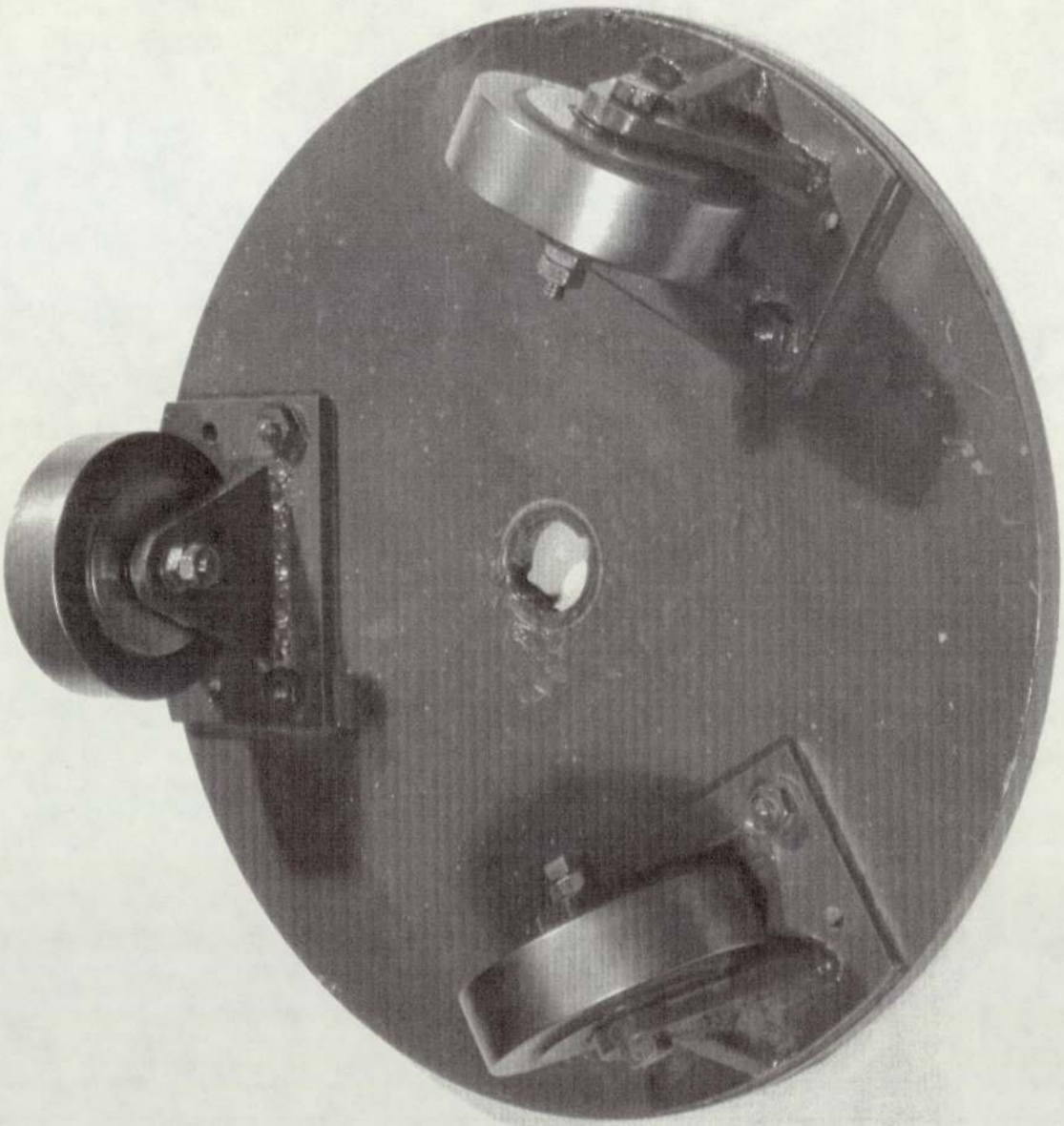


PLATE 2.2 THE ROLLING WHEELS TYPE OF HEAD

surface layer for, while the above list represents the prime factors influencing the quality of this layer, it is also influenced by other factors such as the cement content, water/cement ratio, the extent of hydration and carbonation and the porosity. Furthermore, the abrasion resistance mobilised by the concrete surface will be influenced by the nature of abrading action.

2.5.1 Compressive Strength

The relationship between the abrasion resistance and compressive strength of concrete has been the subject of many investigations (3, 69, 39). It has been generally concluded that compressive strength is the most reliable predictor of abrasion resistance, with in general, the abrasive resistance increasing with compressive strength. Smith (75) found that the abrasion resistance of concrete varied directly with both compressive strength and cement content, with the strength being related to porosity. Indeed it has been suggested (64) that the strength may not be the key factor but is partly a simple substitute for a more complex factor such as porosity. Sadegzadeh (65) demonstrated that the significance of the apparent relationship between compressive strength and abrasion resistance can be markedly influenced by finishing techniques and curing. However, some concluding data has been reported by Rushing (64) who found that some mixes with high compressive strength exhibited lower abrasion

resistance than mixes with lower compressive strengths but, again, this finding may be due to the role of other factors such as curing regime, finishing technique and changes in cement content.

2.5.2 Finishing Techniques

Fresh concrete invariably contains more water than is necessary for hydration and sometimes more fine material than is necessary to fill the voids between coarse aggregate particles. During compaction and finishing some segregation occurs of the constituents of concrete with the coarse aggregate tending to sink to the bottom and a layer of mortar forming at the surface. This process is known as bleeding and, if the concrete is left to harden from this state the resultant surface will be extremely weak and very easily be abraded owing to the very high water/cementitous ratio. To prevent this, the concrete surface is usually trowelled after the bleed water has evaporated to recompact it and reduce the surface mortar to a condition comparable with that of a low water/cement ratio mortar.

Data by Sadeqzadeh (65) have shown that for the purpose of assessing the influence of the various types of finishing techniques on the abrasion resistance of concrete, it is important to understand the influence of the placing, compacting and screeding operations, and the

role of finishing procedure. During the compaction operation the concrete segregates as a result of vibration. This causes the uppermost part to contain more fines so that the cement content of the surface of concrete is larger than that in the bottom layer but, due to the migration of water, this surface also has a higher water/cement ratio than the interior. The lower section of the concrete on the other hand, contains more coarse aggregate and has a lower water/cement ratio. Furthermore, compaction results in a decrease in both the air content and the average size of the air voids although, it has been found that vibration tends to produce a higher air content in the upper portions of the concrete relative to that in the lower layer. At the completion of compaction, the floor slab is left for a waiting time as the bleed water rises to the exposed surface (bleeding is a form of segregation) leading to a further increase in the water content of this surface layer. Some of this rising water may also become trapped and form water voids beneath coarse aggregate particles and perhaps even beneath sand particles and immediately underneath the surface. This rising water leaves behind capillaries, and since all the voids are orientated in the same direction, the permeability of the concrete in a horizontal plane may be increased (65).

It was found, generally, that both the requirements for the evaporation of bleed water, and the desired state of

hydration coincided. It is at this stage that the finishing operations can commence. The efficiency of these operations, in compacting the surface layer, depends on the energy applied to the surface ranging from a low level with hand finishing to the high energy levels associated with power floating and trowelling. Indeed the results obtained by Sadegzadeh (65) demonstrated that the hand finishing technique was unable to perform the finishing task efficiency, thus reducing the abrasion resistance of the specimen slabs. Indeed, the abrasion resistance of specimens subjected to the hand finishing (HF) technique was generally significantly lower than those subjected to the power finishing (PF) technique, see figure 2.1. The main differences between hand finishing and power finishing is that, the latter is capable of applying vibration and more pressure to the surface of the concrete than the former.

The vibration produced by the power equipment is at a maximum nearest to the surface of the concrete. This vibration is effectively revibration or delayed vibration, since it is applied several hours after the screeding operations. The effect on concrete of revibration and delayed vibration has been studied by a number of investigators. It is generally agreed that revibration some 2 to 6 hours after mixing, increases the compressive strength of concrete, compared to the

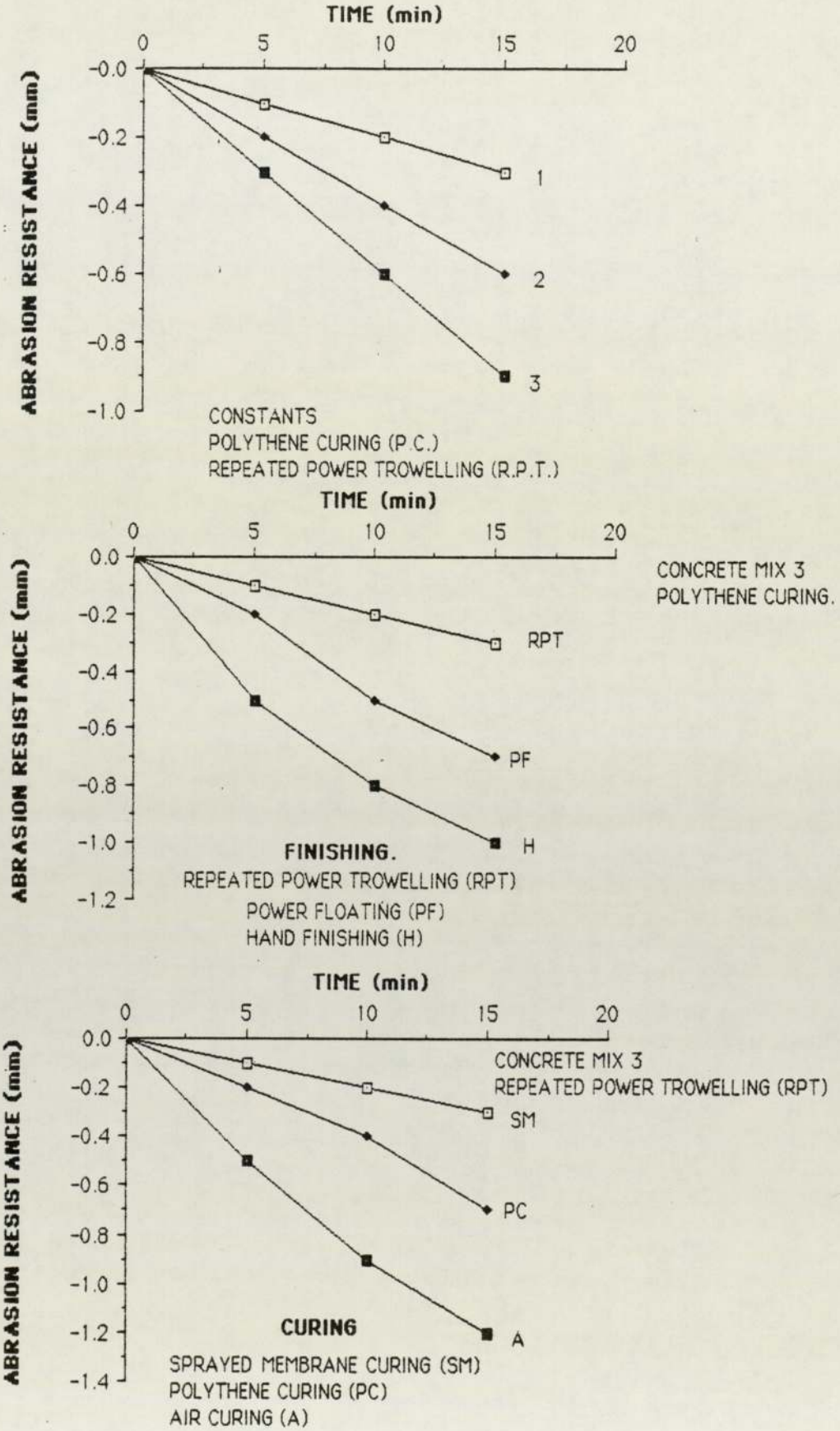


FIG. 2.1 FACTORS AFFECTING ABRASION RESISTANCE

strength of non-revibrated concrete.

This phenomenon may be explained by the following:-

i) The closing of microcracks between the paste and aggregates that formed due to the restraint offered to the early shrinkage of the cement paste.

ii) The reduction of the pore volume in the revibrated concrete, due to the reduction or elimination of water and air pockets present under aggreates.

iii) The structure of cement paste and the hydration process may be influenced by revibration. It has been reported that the revibration of neat cement paste may result in strength increase.

2.5.3 Curing

Curing is an important factor as it has been proven that proper curing increases the compressive strength of concrete (56) and reduces the porosity it is therefore clear that controlled curing will also improve the abrasion resistance of concrete.

Curing is the process of keeping concrete damp so that hydration, the reaction of cement with water, can

continue. Though concrete hardens in a few hours, it continues to gain strength indefinitely if kept moist.

If concrete dries out too soon, it will achieve only a fraction of its potential strength. Curing is simple, often neglected - but of tremendous importance. All concrete should be well cured, but floors are especially demanding because they have a large area exposed to drying. In floor construction, poor curing creates a weak surface that will have a low resistance to wear.

The many curing methods can be divided into three general types:

1. Wet curing methods.
2. Waterproof sheet materials.
3. Curing components.

The wet curing methods work by keeping the concrete constantly supplied with water. The other methods work by retaining the water already present within the concrete.

Studies in the UK suggest that floors cured under polythene can be several times more wear resistant than air cured floors (see chapter 5). American research has produced similar results for floors cured under wet hessian (Burlap) (33).

Some curing compounds produce extremely good test results. There appears to be a double effect; besides keeping in moisutre, the compound fills pores in the concrete making the surface more desirable. Because some compounds are designed to weather away in a short time this double effect may be temporary.

2.5.4 Surface treatment applied to hardened concrete

A wide range of surface treatments are available for application to concrete floors, both in the fresh and the hardened states. Many of these products have been examined on an individual basis but the only documented study which attempted to compare the affect of different treatments on abrasion resistance was reported by Kettle and Sadeghzadeh. This work shows that in surface seals (acrylics, etc) performed significantly better than surface hardeners (i.e. silicates and flourosilicates) with the greatest improvements being reported with relatively low grade concrete. Surface hardeners are salts, typically sodium silicate or magnesium fluoro-silicate dissolved in water. They have small but measureable effect on wear resistance. In one experiment, silicate hardeners improved the wear resistance. In one experiment, silicate hardeners improved the wear resistane of poorly cured slabs by 15% to 38% (66).

Hardeners are cheap and may be useful where a modest improvement in wear resistance is called for. For example, if a floor shows depth of wear just over the maximum allowed - say, 0.23mm when the specification allows 0.20mm - then a silicate hardener might bring the floor into compliance.

Resin seals impregnate the floor surface with polymer resins. Many proprietary products are available, based on epoxy, polyurethane, and other resins. Some resin seals show up extremely well in wear tests. In one experiment, the use of a moisture - curing polyurethane resin shifted floor slabs from poor quality to good (see table 2.2) (66). Surface hardeners and resin seals are also used to repair existing floors. Sometimes curing can be re-started by soaking the dry concrete with water a process that might be called "late curing".

British researchers have studied the effect of late curing making tests on three kinds of surfaces:

1. Slabs cured properly under polythene for 7 days.
2. Slabs exposed to air for 28 days.
3. Slabs exposed to air for 28 days and then soaked and cured under polythene for 7 days.

Group 1 showed better results than group 2 as expected. What was surprising was group 3 - the late cured slabs -

Category			Code
Mix			
Cement content (kg/m^3)	Free water/cement	28 day compressive	
365	0.41	65	1
345	0.52	47	2
300	0.65	29	3
Finishing technique			
Handfloat and trowel			H
Power float and 1 initial pass of power trowel			PF
Vacuum de-watering followed by PF			VD
Power float and repeated passes of power trowell over a period of several hours			RPT
Curing			
Air			A
Wet hessian			WH
Polythene sheet			PC
Resin based sprayed on membrane - 90% efficiency			SM
Liquid surface treatments			
Sodium silicate			Si
Magnesium fluorosilicate			
In surface seals - 3 types			ISS
Control specimen - no hardening			O
Dry shake surface treatments			
Metallic			M
Natural			N
Cement			C

TABLE 2.1 KEY TO LABORATORY INVESTIGATION

Quality of concrete slab	Abrasion depth (mm)
Good	<0.2
Normal	0.2-0.4
Poor	>0.4

TABLE 2.2 CLASSIFICATION OF CONCRETE FLOOR SLABS IN A MEDIUM INDUSTRIAL ENVIRONMENT

showed markedly better wear resistance than air cured slabs, though not as good as group 1 (22).

2.5.5 The physical properties of aggregates

Fine aggregate is usually sand - either natural or manufactured. Its role in concrete is to fill the voids between the pieces of large aggregate. It also forms part of the mortar paste which makes a concrete floor finishable. Designers typically specify fine aggregate according to a national standard. But this approach does not guarantee that the aggregate will be good for floor construction.

In the UK, BS882 defines fine (and coarse) aggregates. In America the corresponding standard is ASTM C33. Both standards deal mainly with the size of the aggregate particles. Unfortunately, size is only one property - and possibly not even the most important property where surface matrix is concerned.

Some fine aggreates make finishing easier. Others produce concrete that is hard to finish. The reasons for this difference are not clear but particle size has little to do with it. Shape may be a factor, with rounded aggregate promoting a better finish. Fine aggregate is an important factor in the wear resistance of concrete. Tests have shown that concrete made with

natural sand is much more resistant than concrete made with crushed rock fines (22).

For good wear resistance natural sand is required complying with BS882.

2.5.6 Summary of Sadegzadeh's Investigation

Most of the factors discussed above were investigated by Sadegzadeh (65) in his work on the abrasion resistance of plain concrete. It is clear that this work represents the most extensive study of abrasion resistance that has been undertaken in this country during the past 20 years. Accordingly it is considered necessary to deal separately with the major aspects of this study as they relate to the present investigation.

The initial phase of Sadegzadeh's work was concerned with the development of the apparatus and testing procedure for reading abrasion resistance and this is referred to in detail in chapter 5. The experimental investigation concentrated on three major factors, these being:-

(a) Finishing technique
(b) Curing regime
(c) Surface treatment

The individual factors are listed in Table 2.1 together

with an appropriate key for identification. A large number of abrasion tests were performed on full scale slabs using the rotating wheel apparatus. Typical results are shown in Figure 2.1 and, although they represent only a small proportion of the total data (65), they illustrate the influence of the various factors given in Table 2.1.

The results clearly demonstrate that: The finishing procedure is more critical than the initial mix proportions, and indicated that the compressive strength is not necessarily an appropriate means for specifying the quality (abrasion resistance) of a concrete floor. Repeated power finishing and vacuum de-watering produced highly significant improvements in the abrasive resistance of all the concrete mixes.

The following curing regimes were investigated:

1. Exposure to air (AC)
2. Polythene sheeting (PS)
3. Curing compound (CC)

Curing was found to be important in controlling abrasion resistance and, in particular, it is of prime importance with the higher water/cement ratio mixes. The application of concrete surface hardeners (e.g. sodium, silicate, magnesian, fluoresilicate) increased abrasion

resistance of concrete only very slightly. They were reported (12) to be more effective on mixes with lower water/cement ratios. The data also indicated that positive curing (polythene or membranes) was more effective in increasing the abrasion resistance, than the subsequent application of surface hardeners. Thus it is the combination characteristics that primarily controlled the abrasion resistance of concrete.

The abrasion resistance was greatly increased by the spray application of a resin-based curing membrane, 90 per cent efficiency curing compound. However in-surface seals, based on polymers in aromatic solvents, were found to produce significant increases in the abrasion resistance. The metallic aggregate dry of all the mixes. Similarly , dry shakes applied to the surface of the fresh concrete improved the abrasion resistance, although this improvement may be partly attributable to the repeated power trowelling process which is an integral part of the compacting of such surfaces. Indeed, while the dry shakes containing metallic aggregates produced the most resistant floor surfaces, those containing natural aggregates did not produce significant improvements in the abrasion resistance in comparison to that of slabs subjected to repeated power finishing.

A microstructural study was carried out to elucidate the mechanisms by which each variable affected the structure

of the surface layer of the concrete. Mercury intrusion porosimetry and microhardness traverses were found to be the most effective, quantitative methods, while other techniques provided qualitative supporting evidence. The mercury intrusion porosimetry demonstrated that the finishing techniques, curing regimes and surface treatments influenced the pore structure of the matrix within specimens. In particular, it revealed changes in the porosity of the surface matrix, which was subsequently shown to be a major factor controlling abrasion resistance. The microhardness traverse further demonstrated that the abrasion resistance was directly related to both the porosity and the hardness of the surface matrix. The results of the microstructural study were used to explain the manner in which repeated power finishing was so effective of increasing abrasion resistance. It was demonstrated that this technique reduced the pore volume by bringing particles in the surface matrix into closer contact, after allowing the bleed water to evaporate, so that it could not have become trapped in the surface.

A number of abrasion tests were also performed on in-service floors and this provided valuable information regarding the wearing qualities of concrete floor slabs in various industrial environments. Furthermore a performance criterion was proposed for assessing the quality of concrete floor slabs in terms of their

abrasion resistance. This is given in Table 2.2 and relates, only, to slabs in a medium industrial environment where vehicles with polyurethane or rubber tyres are frequently used in handle moderately heavy loads (up to 3000 kg). This concept has been developed (65) more recently and details of this more comprehensive classification are given in Table 2.3.

2.6 USE OF PFA IN CONCRETE

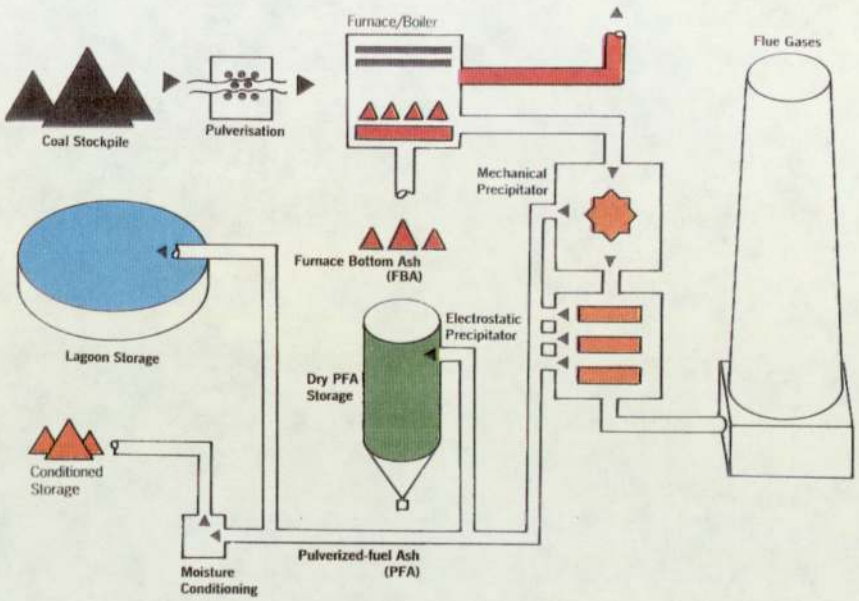
2.6.1 Introduction

The introduction of dry combustion furnaces to burn pulverised coal, has become the most widespread method for generating electricity. The fine ash precipitated from the exhaust gases, as distinct from furnace bottom ash, is known in the UK as Pulverised Fuel Ash (PFA). In the UK this is produced at power stations by the combustion of bituminous coal which consists of carbonaceous matter and a mixture of various minerals (shales, clays, sulphides and carbonates).

The method of extracting the PFA from the flue gases varies with the design of plant and a typical arrangement is shown in Figure 2.2. In some cases the flue gases pass through a cyclone collector which removes most of the coarser solid material. Subsequently the flue gases pass over electrostatic precipitators, placed

TABLE 2.3 Proposed classification for abrasion resistant industrial concrete floors.

Abrasion resistance class	CP 204 class	Duty	Application	Maximum depth of wear by C&CA accelerated abrasion test	Type of concrete	Concrete grade	Minimum cement content	Type of coarse aggregate	Type of fine aggregate	Finishing process	Curing type and duration
				(mm)		(N/mm^2)	(kg/m^3)				
Extremely high	Special	Severe abrasion and impact	Very heavy duty engineering workshops etc	0.05	Special mixes proprietary sprinkle finishes	Special mixes and proprietary sprinkle finishes cannot be classified by strength grade or minimum cement content and may contain aggregates which do not meet the specific requirements of CP 204 or BS 882. Special finishing techniques may be used. Although a limiting value of 0.05 mm depth of wear is suggested, the suitability of concrete flooring in this class should be established with the manufacturer or contractor and where appropriate using other more severe abrasion tests.					
Very high	AR 1	Very high abrasion steel wheel traffic and impact	Heavy duty industrial workshops, special commercial etc	0.1	High strength toppings, traditional granolithic and other special mixes	C60+ or proportion mixes such as 1:1:2	475	Aggregates complying with recommendations of BS 882 Table 3 for Heavy duty floor finishes	Natural sand complying with BS 882 grade M or grade C other than soft limestone, sandstone, or other poor quality fine aggregate	Trowelling 3 times or more	Surface wetting on the day after casting then closely covered with polythene sheeting for 7 days minimum or If no other surface treatment is to be applied, use a 90% efficiency resin based curing compound complying with the Department of Transport Specification applied immediately after final
High	AR 2	High abrasion steel or hard plastic wheel traffic	Medium duty industrial and commercial	0.2	Direct finished concrete	C50	400	Aggregates complying with BS 882 other than soft limestone, sandstone or other poor quality aggregates		Trowelling 3 times or more	
Good	AR 3	Moderate abrasion rubber tyred traffic	Light duty industrial and commercial	0.4	Direct finished concrete	C40	325		Natural sand complying with BS 882 or other suitable approved aggregate	Trowelling 3 times or more or early age grinding	
Nominal	-	Low abrasion foot and pneumatic tyred traffic	Very light duty industrial and commercial	0.8	Direct finished concrete	C40	325	Any suitable approved aggregate	Any suitable approved aggregate	Trowelling twice or more or early age grinding	



Ash Production and Collection.

FIGURE 2.2 ASH PRODUCTION AND COLLECTION

in series, to remove the finer particles. In other systems the cyclone collection stage is omitted and only precipitators are used (12).

PFA consists of aluminosilicate glass spheres together with small quantities of crystalline materials such as quartz, mullite and oxides of iron. The properties of PFA will vary depending upon the type of coal burnt and the furnace firing conditions, thus there is considerable variation between the ashes from different power stations or in the quality of ash from the same power station over a period of time. However, the composition of the glassy materials is relatively consistent between sources (82). In general the particle size and quantity (36) of the extracted ash decrease as the flue gases pass through the various stages.

2.7 PROPERTIES OF PULVERISED-FUEL-ASH

2.7.1 Chemical Composition

Principally PFA consists of spherical particles aluminosilicate glass containing some calcium, magnesium and alkali metals within the glass structure. There may also be small quantities of crystalline compounds such as quartz, mullite and certain iron oxides, notably haemalite and anagnetite. In addition, sulphate is present generally in the form of calcium sulphate but

occasionally as potassium sulphate, where it occurs primarily as surface coatings on the ash particles. Finally PFA contains some residual partially-burnt coal which generally appear as coarse, porous particles. The composition of a typical PFA produced in the UK is given in Table A2. Appendix A.

Methods for determining the reactivity of an ash with portland cement, have been obtained by measuring the strength development of a standard mortar or concrete, but these methods do not give a true indication of the glass reactivity. They assess the combined effects of reactivity, fineness and chemical composition on the hydration of Portland cement and, in some cases, the water reducing characteristics of an ash (16). Such tests, however, provide a useful indication of the overall behaviour of an ash in a cementitious system.

2.7.2 Physical properties

The shape, fineness, particle size, distribution, density and composition of the fly ash particles influence the properties of both the freshly mixed concrete and the strength development of the hardening concrete. Although it does not significantly influence the behaviour of PFA in concrete, the colour of the ash will also be dependent on the source and other properties.

2.7.2.1 Particle Shape

Particle size and shape characteristics of PFA are dependant upon the source and uniformity of the pulverised coal. Lane and Best (1982) (43) reported that the shape of PFA particles is a function of particle size.

PFA particles are predominately spherical with a small proportion of these being hollow (cenospheres) although irregular-shaped particles (especially partially - burnt coal) and agglomerations of spheres also occur.

Sieve residue measurements whilst not giving an overall picture of particle size, do permit determination of large particle content.

The reduced water demand of PFA concrete has been related to ash particle size but neither surface area nor sieve residue appear to conform to a unique relationship with water demand.

Particle shape has also been considered an important factor in determining the water demand of an ash.

A "shape factor" parameter has been proposed as a method for assessing the workability - improving characteristics of an ash (43). Specific surface area measured (MSA) by

air permeability is plotted against surface area calculated (CSA) by assuming that the ash consists of discrete spheres. Ashes with only spherical particles fall on a straight line where MSA = CSA, whilst ashes with irregular or agglomerated particles would fall to one or other side of the straight line.

There is some evidence to show that ashes lying closest to the line produce more improvement in concrete workability.

2.7.2.2 Specific Gravity

According to Luke (1961) (85) the specific gravity of solid fly ash particles ranges from 1.97 to 3.02 but is normally in the range of 2.2 to 2.8, which is less than that of the cement (typically 3.15) which it is used to replace. High specific gravity is often an indication of fine particles.

2.7.3 Classification of Ashes - USA and UK

BS 3892: Part 1: 1982

This part of BS 3892 specifies requirements for the chemical and physical properties, sampling, testing and certification of pulverised - fuel ash suitable for use with Portland cement in concrete for structural purposes.

For this part of the standard-pulverised fuel ash is defined as a solid material extracted by electrostatic and mechanical means from the flue gases of furnaces fired with pulverised bituminous coal.

BS 3892: Part 2: 1984

This part of BS 3892 specifies requirements at delivery for the chemical and physical properties, sampling, testing and marking of two grades of pulverised-fuel ash suitable for use with Portland cement.

It does not apply to ash used in grouts for ducts for prestressing tendons. It covers other uses of PFA and specified two grades of ash A and B, with higher sieve residues than in Part 1 and, for grade B a higher loss-on-ignition. The publication in 1982 of Part 1 of the BS 3892 introduced rigorous quality requirements for PFA as a cementitious component of structural concrete, and included a water requirement test for the PFA in a standard mortar. The objective was to specify a PFA with good pozzolanic and water-reducing properties and of low variability suitable for demanding uses in concrete manufactured in accordance with BS 8110:1985.

BS 6610: 1991

This British Standard specifies requirements for the

composition and the manufacture and for the strength, physical and chemical properties of pozzolanic pulverised-fuel ash cement as "characteristic" values.

Requirements for marking, provision of information, sampling and testing for acceptance at delivery are also specified. This standard specifies requirements for cement as commonly used in Western Europe.

Other types of cement standardised in the UK are defined in BS12, BS146, BS915, BS1370, BS4027, BS4246, BS4248 and BS6588.

Composite cements in UK are now covered by the standards given in Table 2.4.

Table 2.4 British Standards for Composite Cements

British Standard Number	Title	Common Description	Amount of Secondary Material %
146	Portland-blast furnace cement	PBF cement	0-65
4246	Low heat Portland-blastfurnance cement	Low heat PBF cement	50-90
6588	Portland pulverised fuel ash cement	Portland PFA cement	15-35
6610	Pozzolanic cement with pulverised-fuel ash as a pozzolana	Pozzolanic cement	35-50

ASTM C311-90

Standard test methods for sampling and testing fly ash or natural pozzolans for use as a mineral admixture in Portland cement concrete.

These test methods cover procedures for sampling and testing fly ash and raw or calcined pozzolans for use as a mineral admixture in Portland-cement concrete.

ASTM C618-89a

Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for use as a mineral admixture in Portland cement concrete. It covers fly ash and raw or calcined natural pozzolan for use as a mineral admixture in concrete cementitious or pozzolanic action, or both, is desired, or where other properties normally attributed to finely divided mineral admixture may be desired or where both objectives are to be achieved.

Fly ash is defined as finely divided residue that results from the combustion of ground or powdered coal. Pozzolans - sliceous or siliceous and aluminous materials which in themselves possess little or no cementitous value but will, in finely divided form in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitous properties.

Classification according to ASTM C618-89a.

Class N - Raw or calcined natural pozzolans that comply with the applicable requirements for the class, such as some diatomaceous earths, opaline cherts and shales, tuffs and volcanic ashes or pumicites, any of which may or may not be processed by calcination and various materials requiring calcination to induce satisfactory

properties, such as some clays and shales.

Class F - Fly ash normally produced from burning anthracite or bituminous coal. This class fly ash has pozzolanic properties.

Class C - Fly ash normally produced form lignite or subbituminous coal. This class of fly ash, in addition to having pozzolanic properties, also has some cementitious properties. Some class C fly ashes may contain lime contents higher than 10%.

2.8 CHEMICAL ACTIVITY OF PFA IN PORTLAND CEMENT

The principal product of the reactions between PFA and calcium hydroxide and the trace alkalis in concrete is essentially, the same as that of the hydration of Portland cement, namely Calcium-Silicate-hydrate (C-S-H). The morphology of the product from the involving the Class F PFA reaction is suggested to be more gel-like and denser than that from Portland cement (38).

The reactions between PFA and calcium hydroxide depend largely upon the breakdown and dissolution of the glassy structure by the hydroxide ions and the heat mobilized during the early hydration of the Portland cement fraction. The reaction of the PFA continues to consume calcium hydroxide to form additional (C-S-H) as long as

calcium hydroxide is present in the pore liquid of the cement paste. Regourd (1983) (60) indicated that a very limited, immediate chemical reaction also takes place when fly ash is mixed with water, preferentially releasing calcium and aluminium ions to solution. This reaction is limited, however, until additional alkali or calcium hydroxides or sulphates are available for reaction.

The amount of heat evolved as a consequence of the reactions in concrete is usually reduced when PFA is incorporated as a portion of the cementitious material in concrete. The fact that rate of the hydration increases directly with temperature and cement content, is directly related to the temperature rise with the hydrating paste, and there should be no doubt that it is the "glass" in PFA that is reactive to the strongly alkaline pore fluids produced as a result of Portland cement hydration. The hydroxyl ions from the cement release the silica in the glass of PFA for combination into C-S-H gel creating, in turn, the conditions for the release of more hydroxyl ions from the PFA glass, which aid the progression of the pozzolanic reaction.

The hydration reactions involving Portland cement, PFA and water explain the temperature changes and improvements of concrete to a large extent. Clarifying the basic principles of PFA reaction makes it possible to

identify (60) the primary factors which in practice, will influence the effectiveness and selection of PFA for use in concrete.

These factors include:

(a) The chemical and phase composition of the PFA and of the Portland cement.
(b) The alkali hydroxide concentrations of the treating system.
(c) The morphology of the PFA particles.
(d) The fineness of the PFA and the Portland cement.
(e) The development of heat during the early phases of the hydration process; and
(f) The reduction in mixing water requirement when using PFA.

2.9 THE EFFECT OF PFA ON THE PROPERTIES OF CONCRETE

The following properties have been identified as being influenced by the incorporation of PFA in the fresh concrete:

1) Workability
2) Bleeding
3) Time of setting
4) Finishability
5) Pumpability

Items 1-4 are of critical importance in producing a good quality surface. In particular, Sadegzadeh (53) has drawn attention (65) to the roll of waiting time (bleeding) on the quality of the surface layer produced by particular finishing techniques. These factors are considered in the following sections.

2.9.1.1 Workability

The absolute volume of cement plus fly ash normally exceeds that of cement in similar non-fly ash concrete mixtures. This can be attributed to the lower density of the ash, as compared with cement. Thus, although the mass of the ash is similar or equal to that of the cement being replaced, the ash occupies a greater volume than the cement and so improves the mobility and hence workability is due to changes in the flow characteristics of the paste. Cabrera (19) demonstrated that the spherical ash particles reduce internal friction and so aid mobility. Consequently the generally spherical-shaped fly ash particles normally permit a reduction in the water content for a given slump (11) so that the water/cementitious ratio can, if necessary, be simultaneously reduced to achieve the required 28 day strength. This water reduction by fly ash, through the use of further increases the solids-to-liquid ratio with additional beneficial results.

2.9.1.2 Bleeding

Bleeding is the accumulation of water on the fresh concrete surface. Concrete bleeds because water is the lightest component of the mix. The heavier components tend to settle, with water rising to the top. If water rises to the slab surface faster than it evaporates there, the concrete bleeds. The problem with bleeding is that floor finishing must not start until the bleed water disappears. If the floor is floated or trowelled with bleed water present the finished surface will be weak because of a very high water-cement ratio.

Bleeding varies in degree from a few isolated puddles which soon dry up to a continuous sheet of water several millimetres deep.

The rate of bleed is generally reduced in PFA concrete by virtue of the increased volume of fines and reduced water content.

By using PFA in air-entrained and non air entrained concrete mixtures usually reduces bleeding by providing greater volume of fines and a lower water content for a given workability. An investigation (11) clearly demonstrated the effects of the addition of PFA on the bleeding capacity of fresh concrete and typical data is shown in Figure 2.3

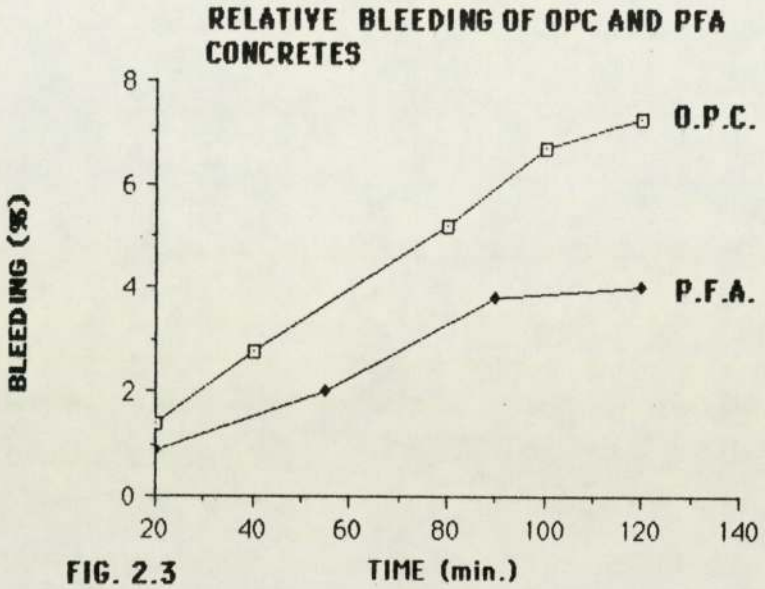

RELATIVE BLEEDING OF OPC AND PFA CONCRETES
BLEEDING (%)
8
6
4
2
0
20
40
60
80
100
120
140
TIME (min.)
O.P.C.
P.F.A.

FIG. 2.3

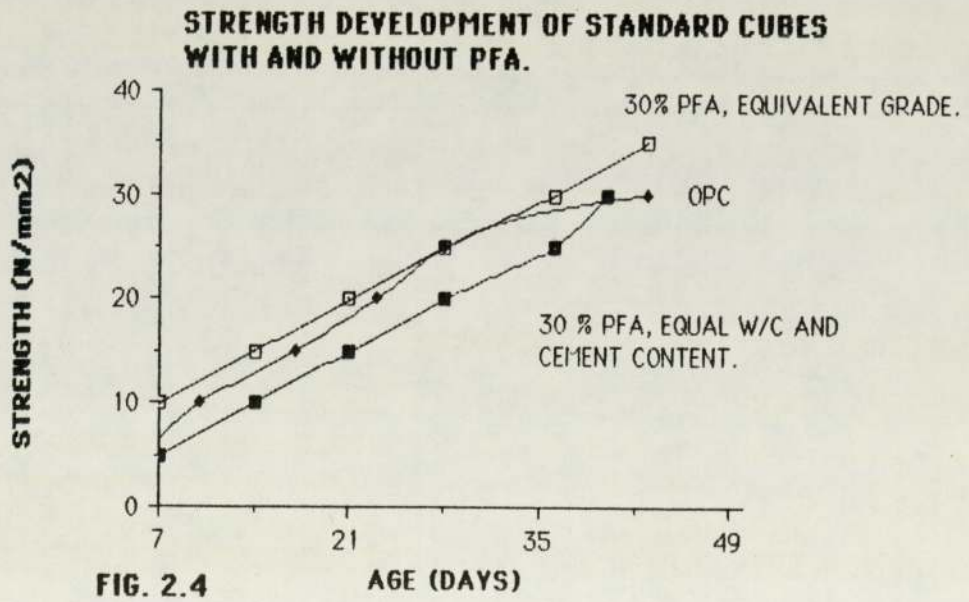

STRENGTH DEVELOPMENT OF STANDARD CUBES WITH AND WITHOUT PFA.
STRENGTH (N/mm2)
40
30
20
10
0
7
21
35
49
AGE (DAYS)
30% PFA, EQUIVALENT GRADE.
OPC
30 % PFA, EQUAL W/C AND CEMENT CONTENT.

FIG. 2.4

2.9.1.3 Time of setting

The use of fly ash may extend the time of setting of the concrete. Generally Class F fly ash generally extends the time of setting, while Class C fly ash may extend, reduce or have no significant effect on the time of setting. (53).

As most UK ashes would be classified as Class F, it is clear that they would also be likely to extend the setting time. In modern floor construction it is normal practice to have a waiting time, between compaction and subsequent finishing, to allow the bleed water to rise and evaporate as the mix stiffens. Clearly with the inclusion of PFA influencing both the bleeding rate and the setting time, it is likely that these changes could also influence the quality of the finished surface.

2.9.1.4 Finishability

As most PFA concretes have longer times of setting than similar plain concrete, they would need to be finished at a later time. Failure to do so could lead to the bleed water being trapped under the top surface creating a plane of weakness. The longer time of setting may increase the chances of plastic shrinkage or surface cracking under conditions of high evaporation rates so that stiffening of the concrete must be monitored.

Using very wet mixtures containing PFA with significant amounts of very light unburnt coal particles or (cenospheres) can cause these particles to migrate upward and collect at the surface leading to creation of a layer. This is unlikely to be major problem in floor construction since such mixes do not normally have excessively high water contents.

2.9.1.5 Pumpability

Improved pumpability of concrete has been reported (11) when PFA is in the mix and this can also be attributed to the improvement in mobility and cohesiveness of the fresh concrete. This property was not considered to be relevant to this investigation.

2.9.2.1 Compressive strength and strength development

Both the strength at any given age and the rate of strength gain are affected by the incorporation of PFA in concrete. The extent of these changes are dependent on the characteristics of the particular PFA, the cement with which it is used and proportions of cement and fly ash in the particular concrete.(11) The rate of initial strength gain is reduced since a proportion of the cement has usually been replaced with PFA. Thus the early (7 day) strength value will also be reduced. However, as the rate of strength contribution from the hydration of

Portland cement slows, the developing pozzolanic reaction between the fly ash and the calcium hydroxide, produced the cement hydration, contributes to the increased strength gain at later ages providing the concrete is kept moist.

This behaviour is illustrated (11) in Figure 2.4 which shows that a PFA concrete with a lower strength at early ages may have higher strength at later ages than a similar concrete without PFA (16). This higher rate of strength gain will continue with time and can result in long term strengths that are higher than can be achieved by using additional cement (16). Indeed it is clear (see Chapter 4) that, by adjusting the water/cementitious ratio of the PFA-mix, it is possible to achieve similar early stage strength development as that of control mix and still retain the long-term (post 28 days), strength development. For this to occur it is essential to maintain a positive curing regime so that these reactions can be sustained.

As a consequence of this reduction in the initial rate of strength development, there is an accompanying reduction in the initial rate of heat evolution. This is one of the major reasons for using PFA concrete since, by reducing the initial rate of heat evolution, this can limit the extent of early age, thermal cracking, although this is not usually a major concern in concrete floor construction.

3.1 SCOPE OF THE INVESTIGATION

3.1 General Outline

The general aims of the investigation reported in this thesis are all related to the abrasion resistance of concrete mixes containing pulverised fuel ash (PFA), and may be briefly summarised as follows:-

1) To develop a basic mix design procedure, using data from a series of trial mixes containing PFA, for the design of the mixes for the main investigation.
2) To study the abrasion resistance of concrete mixes containing PFA, using the rolling wheel apparatus developed at Aston (65). This macrostudy of abrasion resistance placed particular emphasis on the influence of the curing regime and the age at test on the performance of the test slabs.
3) To identify, through a parallel study of the microscopic characteristics of individual mixes, those factors that particularly influence the abrasion resistance of the mixes containing PFA and so to compare their behaviour with that similar plain concrete mixes.

3.2 Concrete Mix Design

It was decided to produce specific data for the mix

design so that this would enable exact changes to be made to the mix proportions while maintaining the target 28 day strength values within the limited range, 25 to 40 MPa, usually associated with concrete ground floor slabs. In addition, the process of producing these trial mixes increased the awareness of the characteristics of concrete containing PFA in both the fresh and the hardened states. A total of 16 mixes were produced at this stage with the water-cement ratio ranging from 0.37 to 0.65 and cement replacement levels of 0, 30, 40 and 70 percent (on a simple weight basis). From the accumulated 28 day cube strength data a series of charts were produced for use in the subsequent mix design calculations.

For the main investigation the study was divided into two series as follows:-

Series A

Mixes designed on a simple replacement basis with cement being replaced by PFA on a 1:1 weight basis, so that the water-cementitious ratio remained constant.

Series B

Mixes designed for a specified strength level so that the incorporation of PFA is accompanied by a change in the water-cementitious ratio.

In designing these mixes it was essential to consider the workability of the fresh concrete, since the finishing of the surface of the slab is influenced by the properties of the fresh concrete, particularly workability, bleeding and setting time. It was, therefore, necessary to also consider these factors when formulating the mixes to be used in both series.

3.3 MACROSTUDY OF ABRASION RESISTANCE

In this study the abrasion resistance of concrete slabs was assessed using the rolling wheel machine developed at the Cement and Concrete Association (65) and Aston University (65). The test procedure followed that established by Sadegzadeh in an earlier study (65) so that comparison could be made between the currernt results of this investigation and those reported (65) by Sadegzadeh. Previous work (65) has shown that the abrasion resistance of a given concrete is significantly influenced by the particular finishing procedures. It was, therefore, decided to adopt a single technique for use throughout this investigation, namely power finishing consisting of one period of power floating followed by a single period of power trowelling to complete the production of each slab.

The experimental investigation was structured to assess the effect of three key factors on abrasion resistance:-

(1) PFA content, ranging from 0 to 40 percent.

(2) Curing regime - air, polythene sheeting and membrane spray.

(3) Age, testing being undertaken at 28 days, 3 and 6/12 months.

Two series of mixes were produced for this investigation based on (a) simple cement replacement and (b) constant strength. Some seven different mixes were produced using 1:1 replacement of cement with PFA and a further four mixes were produced on the basis of constant strength.

3.4 MICROSTUDY OF ABRASION RESISTANCE

While the macro-study could provide evidence of changes in the abrasion resistance of concrete following the use of PFA as a cement replacement, it would not provide information on the micro-structure of concrete. This information was considered essential in developing an explanation of the behaviour on the macro-scale of both the plain and modified concretes. The main purpose of the micro-structural study was, therefore, to examine the micro-structure of the concrete in order to seek supporting evidence for the explanations of the behaviour observed in the macro-study.

Many techniques have been used to access the microstructure and porosity characteristics and cemented-

based materials but, in this investigation, it was decided to restrict the study to two techniques: Mercury, Intrusion Porosimetry (MIP) and Microhardness Transversing. These two techniques had previously been used by Sadegzadeh in his investigation (65) of plain concretes and had yielded useful information.

CHAPTER FOUR

MATERIAL PROPERTIES AND THE MIX DESIGN

4.1 INTRODUCTION

This chapter outlines the details of the materials used for the manufacture of the test specimens, although the details of the procedures for specimen manufacture are given in Chapter 5 and 6. As an essential prerequisite to specimen production, it was necessary to produce mix designs for the concretes containing PFA and these are detailed in this chapter. It was decided to base the design of these mixes on the performance of a number of trial mixes produced from the selected materials and the resulting data are provided together with the particular procedures used for the mix design.

4.2 CEMENT

All the concrete specimens have been prepared from a single batch of blended, ordinary Portland cement of constant uniformity, supplied in bags by the "Blue Circle" Cement Company and subsequently stored in sealed tins. The chemical analysis of this cement is given in Table A.3 of Appendix A.

4.3 PULVERISED FUEL ASH

This is the by-product from power station furnaces fired by pulverised coal. It can be used as a constituent of a Portland Pozzolanic cement or it can be added at the mixer with the cement and aggregate. For use in

concrete, PFA has to be carefully selected and the properties, such as carbon content and grading, carefully controlled, the main requirements being given in BS 3892 (16). The particular ash was supplied by the CEGB and its chemical analysis is in Table A.2 of Appendix A together with the relevant requirements from BS 3892 (16).

4.4 AGGREGATE

4.4.1 Coarse Aggregate

The coarse aggregate was bunter quartzite, an upper Trent Valley aggregate from Weeford Quarry. The 20-10mm aggregate was natural and the 10-5mm was crushed.

4.4.2 Fine Aggregate

The fine aggregate was blended to conform to the grading curve given in Figure A.1 of Appendix A. The blended fine aggregate was natural sand and may be considered to conform to the "Zone 2" sand in the BS 882:1973 grading zone. Both the coarse and the fine aggregate were washed at the source, and dried in the laboratory before use.

4.5 STEEL

Mild steel reinforcing bars were used to reinforce the concrete slab specimens. The size diameter 8-10mm, the

length 99cm, three bars were placed longitudinally in each test slab by length.

4.6 WATER

Throughout the work tap water was used for the preparation of all the mixes.

4.7 MIX DESIGN

4.7.1 General Outline

The main stages in the design of a concrete mix containing PFA can be summarised as follows:-

(1) Establish the properties of the particular PFA, the key parameters being listed in BS 3892.

(2) As the aggregates form the major constituent of the mix, it is essential to assess their properties to ensure they will not impair the quality of the particular mix.

(3) Design the PFA concrete mix. This may be based on one of several suggested methods, e.g. Dunstan (32), Idor (38), Cabrera (19), or on data established from selected trial mixes. This latter course was adopted for this investigation.

(4) Check the design by producing further (trial) mixes.

The object of the design of any concrete is to select the proportion the available ingredients to produce an economical concrete which will have the desired properties both when fresh and hardened.

Most common requirements for mix design relate to:

(a) Workability

(b) Compressive strength

(c) Durability

4.7.1.2 Compressive strength

As with plain concretes, the compressive strength will be affected by the characteristics of the Portland cement, the water/cementitious but, additionally, allowance must be made for both the characteristics and the amount of PFA used in the mix. There may also be a slower rate of strength development at early ages depending on the mix proportioning method used (52) (29) .However,is no evidence of any increase in the variability of concrete strength when using PFA and no changes need be made to the design margin from that normally used for plain concrete.

4.7.1.3 Workability

Concrete containing PFA may require less water than a similar plain concrete to achieve a given workability although the amount of this reduction will vary.

Mixes often can appear to be more cohesive for the same measured workability and the amount of water required to effect a change in workability is generaly less than that required for plain concrete.

4.7.1.4 Durability

Durability requirements are normally specified in terms of minimum cement content, maximum free w/c ratio and, occasionally, maximum cement content. When PFA is used, specified values should be compared with total cementitious material content and the free water/cementitious material ratio as appropriate. PFA concrete may be successfully produced by modifying an established Portland cement mix. PFA concrete may also be designed without reference to plain concrete and a particular method is given below.

4.7.2 Production of trial mixes

To produce data for the mix design, a series of trial mixes was produced simply by replacing cement with PFA on a simple 1:1 weight basis. Initially seven mixes were prepared to have target 28 day cube strengths in the range of 25 to 45 MPA. From each mix, 6 No. 100 x 100 x 100mm cubes were produced for crushing at 28 days, the results of these tests are summarised in Table 4.1 together with the water/cementitious ratios and ash

TABLE 4.1 SUMMARY OF 28 DAY CUBE TESTS PERFORMED ON ALL THE TRIAL MIXES.

W/C	Ash Content %	Strength at 28 days N/mm2
	Initial Series	
0.65	0	25
0.65	30	25
0.65	40	25
0.65	70	12
0.56	0	43
0.56	40	42
0.44	0	51
0.44	40	36
0.37	0	77
0.37	30	58
0.37	70	12

Second Series

TABLE 4.2 SUMMARY OF 28 DAY CUBE TESTS PERFORMED ON ALL THE TRIAL MIXES.

0.65	30	23
0.65	40	18
0.65	0	37
0.56	0	41
0.37	30	53

replacements levels. To enhance these data further mixes were tested and these results are also included in Table 4.3 and 4.4. These results are plotted in Figures 4.1, 4.2 and 4.3, and this information was used to select mixes for the production of the test slabs.

4.7 Mix Selection

Some eleven mixes were selected for this investigation. As the majority of ground floor concrete slabs have 28 day strength values between 25 and 35 MPa, it was decided to base mix selection around this figure. Thus in the first series (Mixes 1-7) it was decided to select a control mix with a water/cement ratio of 0.65 and to simply replace the cement on a 1:1 basis with 10, 20, 30 and 40 percent PFA. Two further mixes, with higher target strengths, were also included for comparative purposes. In the second series, four further mixes were selected and variations in both water/cement ratio and replacement level were made to produce a target 28 day strength of 35 MPa. These mixes were selected for the results plotted in Figure 4.3 and all the mixes are summarised in Table 4.2 with full details of these mixes given in Appendix B.

TABLE 4.3

W/C	Ash Content PFA %	Strength at 28 days N/mm2
0.37	0	70
0.44	0	51
0.56	0	42
0.65	0	37
0.37	10%	58
0.44		47
0.56		36
0.65		32
0.37	20%	53
0.44		42
0.56		31
0.65		28
0.37	30%	53
0.44		37
0.56		26
0.65		23
0.37	40%	46
0.44		35
0.56		22
0.65		18

TABLE 4.4 SUMMARY OF CONCRETE MIXES.

Mix No	Water/cementitious Ratio	Ash Content
Mix 1	0.65	30
Mix 2	0.37	30
Mix 3	0.65	40
Mix 4	0.65	0
Mix 5	0.56	0
Mix 6	0.65	10
Mix 7	0.65	20
Mix 8	0.44	40
Mix 9	0.56	10
Mix 10	0.46	30
Mix 11	0.51	20

RATE OF COMPRESSIVE STRENGTH Y'S WATER CEMENT RATIO. (P.F.A. =0%).

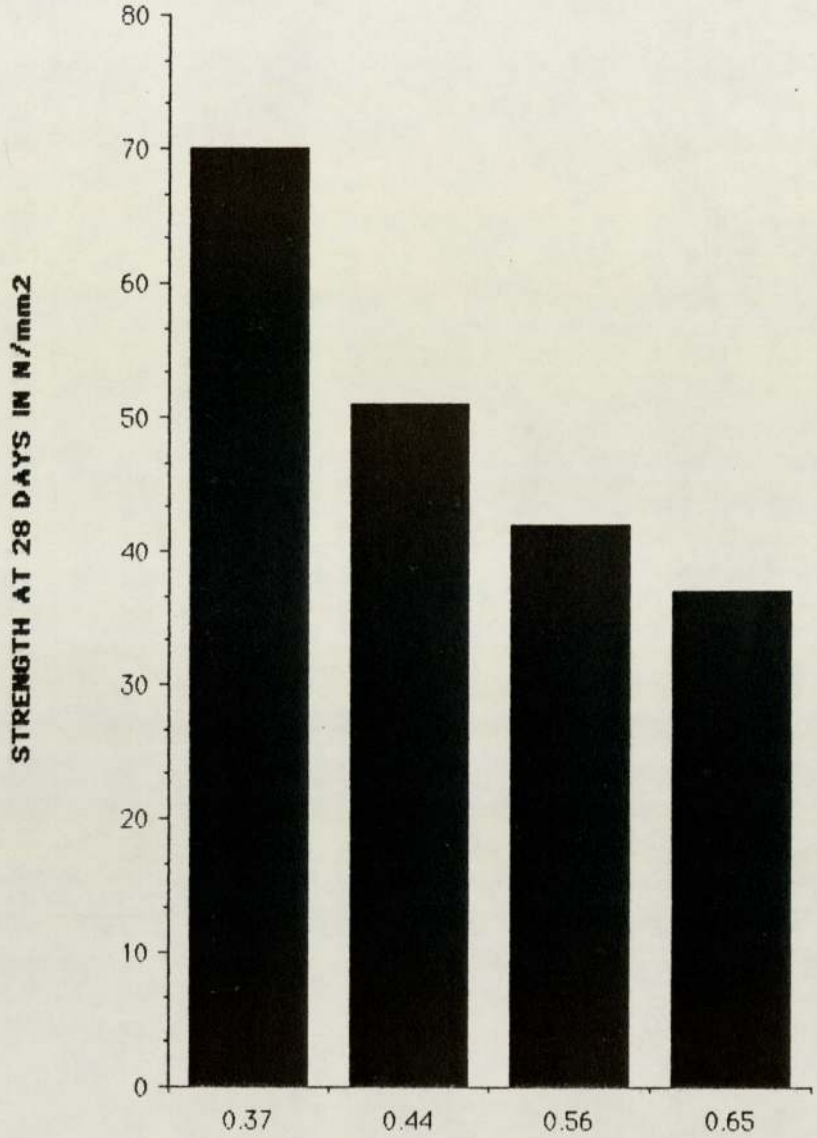


FIG. 4.1

RATE OF COMPRESSIVE STRENGTH V'S WATER CEMENTITIOUS RATIO FOR DIFFERENT P.F.A. CONTENTS.

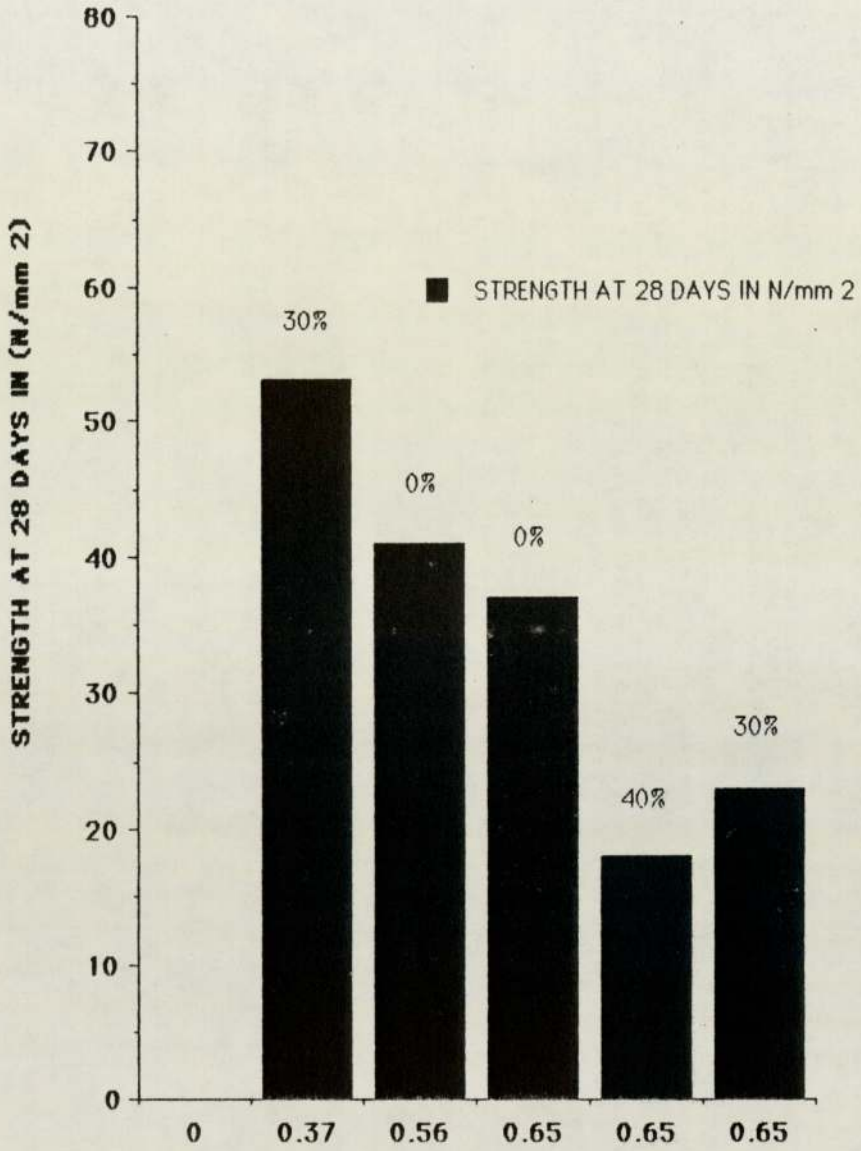


FIGURE 4.2

RATE OF COMPRESSIVE STRENGTH Y'S WATER/ CEMENTITIOUS RATIO FOR FIVE DIFFERENT P.F.A. CONTENTS.

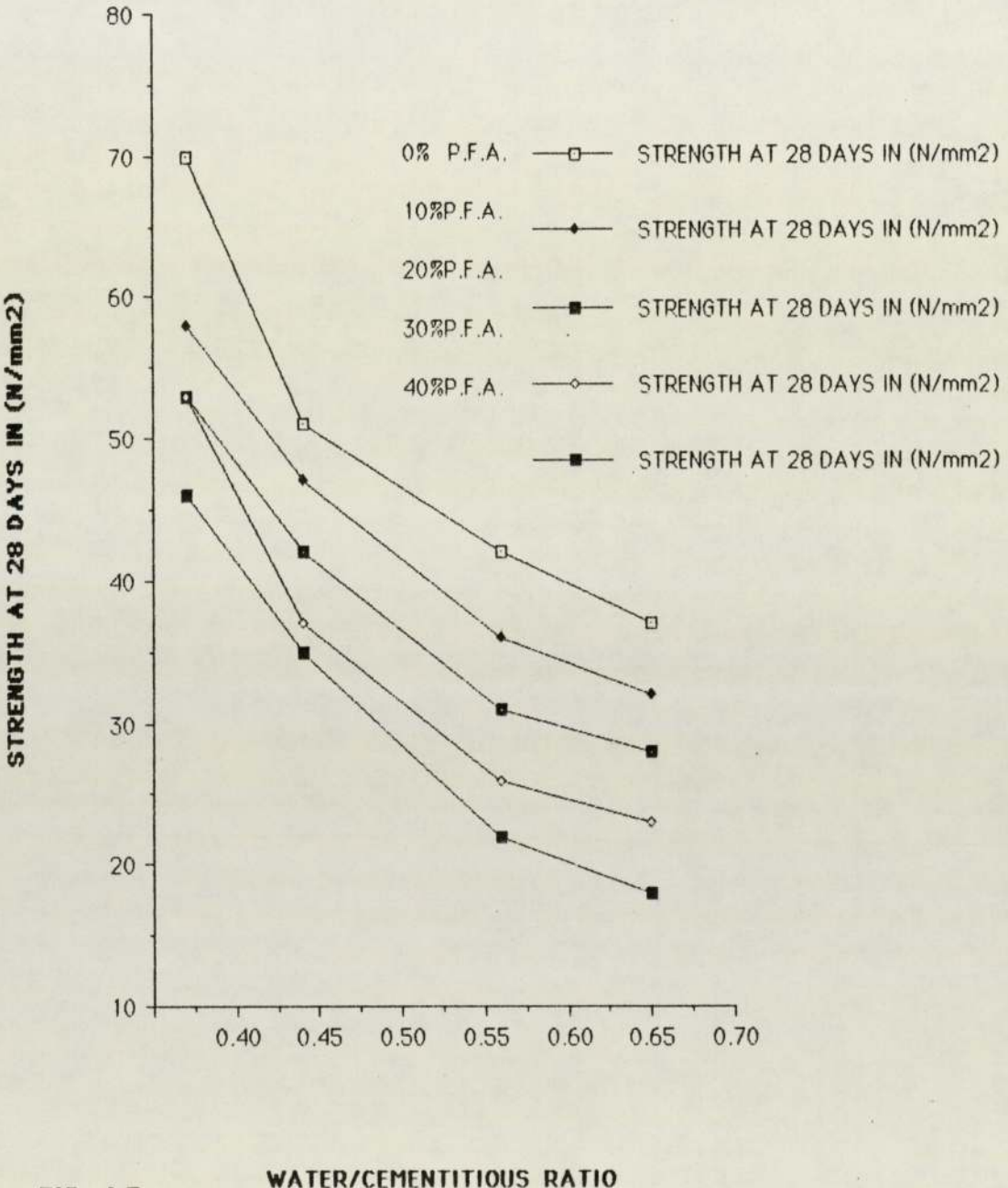


FIG. 4.3

CHAPTER FIVE

MACROSTUDY OF ABRASION RESISTANCE OF CONCRETE WITH PFA

5.1 INTRODUCTION

For many years research has been undertaken to investigate various aspects of the abrasion resistance of concrete, such work beiNg almost entirely laboratory-based. An extensive literature survey revealed (21) that there was no simple apparatus which would simulate all the abrasive actions to which a concrete floor could be exposed during service. To measure the abrasion resistance of a concrete floor a portable accelerated abrasion test apparatus and standardised testing procedure was introduced (21). It was essential to use an appropriate test system. The basic design of the apparatus is similar to that developed by C & CA and is shown in plate 2.1. The basic design consists of a rotating plate carrying three case hardened steel wheels shown in plate 2.2. These wear a circular groove and the depth of this groove provides a measure of abrasion resistance.

To date, no major investigations have been undertaken to determine the abrasion resistance of concrete made with Portland cement and PFA. It is generally considered (24) that, for a given set of materials, the resistance of concrete to wear (both erosion and abrasion) improves as its strength increases. Thus it could be hypothesised that concretes of equal strength made with and without PFA would exhibit similar resistances to wear. Taking

this hypothesis a stage further, since a PFA concrete designed for an equal 28 day strength with a given plain concrete has a potential for developing higher long-term strength, it should also proportionally exhibit greater resistance to abrasion. However there is insufficient data to conclusively support this simple, though logical, deduction, with opinion evenly balanced between those (44) (68) who have shown the use of PFA having no adverse effect and those to have shown that its use may reduce the resistance of concrete to wear (1) (46). This lack of data, therefore, provided a rational for this research which was undertaken to investigate the abrasion resistance of concrete mixes containing PFA. The structure and properties of the surface of concrete are known to be significantly dissimilar from those of the interior of the material. However in spite of the obvious importance of the surface zone, with respect to durability of the concrete, there has been little research aimed specifically at characterising surface structure of concreting containing PFA.

This chapter outlines the details of the procedure for specimen manufacture and details of the laboratory procedures adopted for this investigation.

5.2 LABORATORY PROGRAMME

Eleven mixes were used (Mix 1-11) in this laboratory programme and the individual mix designs are summarised in Table 4.2 with batch details being given in Appendix B. Mixes 1-7 were designed on a simple replacement basis and have target 28 day cube strengths ranging from 25 to 60 MPa. For the trial final, stage four mixes were selected (Mix 8-11) to cover the expected range of free water/cementitious ratios and replacement level to produce a target 28 days strength of 35Mpa, typical for concrete floor slabs.

All the mixes, 1-11, were used to produce test slabs of dimensions 2.0 x 1.5 x 0.1m. These were manufactured using a standardised procedure prior to being subjected to surface finishing. The main stages of this procedure are summarised in the following sub-sections.

5.2.1. Slab Production

5.2.1.1 Reinforcing bars

In order to prevent breakage and to assist the subsequent handling, it was necessary to place reinforcing bars in the slabs. Three longitudinal bars were used for each small slab 1.0 x 0.5 x 0.1m, the big slab being sub divided into six smaller ones, these were

10mm diameter and 950mm in length placed parallel at a spacing of 125mm . All three bars were placed at mid-depth, 50mm below the surface in the test slab.

5.2.1.2 Mixing of concrete

All the concrete was mixed in a 500Kg capacity laboratory mixer. For each large slab two identical mixes were batched. Each mix was dry mixed for 30 seconds before the required water was added, and this was followed by wet mixing for a further two minutes before discharge into wheelbarrows. From each mix five 0.1 x 0.1 x 0.1m cubes were taken for the purpose of quality control.

5.2.1.3 Placing and spreading

The first mix was transported by wheelbarrows to the mould, and a short-handled, square-ended, shovel was used to deposit and spread this concrete into the mould avoiding segregation as shown in plate 5.1. The first mix was used to fill the bottom 50mm layer of the mould. The appropriate reinforcing bars were placed on the top of this layer and the second mix was used to fill the mould adopting a similar procedure.

5.2.1.4 Compaction

A 50mm diameter CLIPPER vibrating poker model VP2 was used for compaction. The procedure adopted for

PLATE 5.1 SPREADING AND COMPACTING OF PFA CONCRETE INTO MOULD

compaction involved quickly inserting the top of the vibrator into the concrete and slowly removing it so as to avoid creating a void. A constant pattern of five vibrator strokes was used for the bottom 50mm layer of each small slab and seven vibrator strokes for the top layer.

5.2.2 FINISHING TECHNIQUE

Following completion, the surface of the slab was screeded using a hand-tamping beam operated by two men as shown in plate 5.2. The beam was dropped uniformly on to the concrete, each contact taking place with the concrete. The slab was subsequently left to stiffen as the bleed water came to the surface and evaporated until the slab was amened to be ready for finishing. This was based on previous experience and the criterion being that when the operator stepped onto the slab this produced a footprint with a depth of between 1-5mm. At this stage the initial phase floating - of the finishing procedure was commenced. This operation was performed for a period of 8 minutes, with a rotating disc being evenly passed over the concrete surface. This floating operation caused additional moisture to be brought to the surface and so a further waiting period was needed before the final trowelling operation commenced. This waiting time was again amened in terms of the response to walking on the surface and when the slab was judged to be ready,

PLATE 5.2 SCREEDING BEING PERFORMED BY HANDTAMPING BEAM OPERATED BY TWO MEN

power trowelling was commenced. This was performed for a period of 12 minutes with the rotating plates being evenly passed over the concrete surface. Initially the blades of the trowelling head were used without any tilt, after the first four minutes the blades were half tilted and after a further four minutes, the blades were fully tilted. The power trowelling operation needed no skill, as opposed to the hand trowelling. The floating and trowelling operations were each performed only once.

The use of power equipment is shown in plate 5.3.

5.2.3 CURING REGIMES

Several investigations (69) (70) (4) have shown the importance of controlled curing in the production of concrete with a high abrasion resistance. The method of curing is a major factor influencing the abrasion resistance of concrete. In general polythene sheeting or curing membranes appear to be the most efficient regimes. Investigations of concretes containing PFA have also shown (35) (24) the importance of careful curing in the production of such concretes. It was, therefore, essential to assess the influence of the curing regime on the abrasion resistance of concretes containing PFA and, for this work, three regimes were investigated.

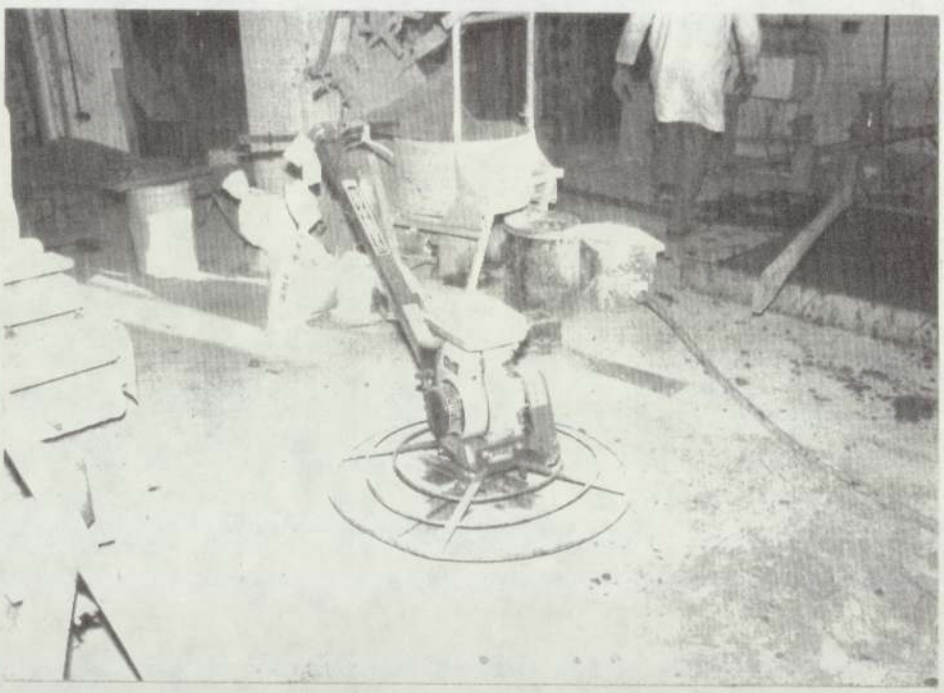


PLATE 5.3 THE FLOATING AND TROWELLING OPERATIONS PERFORMED WITH THE USE OF POWER EQUIPMENT

5.2.3.1 AIR CURING

After the slabs were demoulded and separated the next morning, they were subject to air curing and were left exposed in the laboratory for periods of 28 days, 3 months and 6/12 months depending on the age of testing the particular specimens.

5.2.3.2 PLASTIC SHEETING

Immediately after the finishing operation the selected section of the slab was covered by plastic sheet. The next morning after demoulding this section was wrapped in polythene sheets for 28 days, 3 months and 6/12 months for testing accordingly.

5.2.3.3 CURING COMPOUNDS

The curing compound was sprayed on the required section of the slab, immediately after the last finishing operation, according to manufacturers instructions given in Appendix C. instructions 1 and 2.

A shield was used to prevent contamination of the other sections of the slab. The next morning the slabs were demoulded and separated. At this stage the bottom and sides of these slabs were covered by polythene as shown in plate 5.4 so that moisture loss from these sections

PLATE 5.4 PLASTIC SHEETS COVERING EDGE AND BOTTOM OF SMALL SLABS READY FOR STORAGE

was minimised, thereby simulating the centre of a large slab.

5.3 ABRASION RESISTANCE TESTS

All the slab specimens were tested for abrasion resistance at 28 days, 3 months, 6/12 months using the accelerated abrasion test machine with its rolling wheels head. The test procedure is fully described in Section 5.4.

The machine at the University of Aston was constructed using the specification provided by the C & CA, a working drawing is provided in Figure D.1 Appendix D. A general photograph of the basic abrasion apparatus is shown in plate 2.1. The machine abrades the concrete surface by rolling wheels attached to a rotating plate. The depth of the abrated groove providing a measure of the abrasion resistance.

5.3.1 Test Procedure

The test uses steel wheels travelling in a circular path to simulate the wear caused by industrial vehicles etc. In a fifteen minute test, the wheels wear a ring-shaped groove in the slab. A gauge measures the depth of the groove before and after the test to determine the depth

of wear. A standard survey consists of three 15 minute tests at different locations on the slab. Depth of wear is reported in millimeters. High values mean low resistance to wear. Most concrete slabs show depths of wear between 0.05mm - 1.00mm. Clearly the reliability of the measurements of abrasion resistance are very dependent on the procedures used to assess the depth of the groove and these are commended below:

5.3.2 Method of assessing depth of abrasion

Two devices have been considered (65) for measuring the depth of wear, a bridge micrometer as used at the C & CA shown in plate 5.5 and a dial gauge mounted on a metal bridge and a marking out template as used at Aston, shown in plate 5.6. As both devices produced (65) similar results a dial gauge was used.

During this study it was observed that the depth of the abrasion path was not uniform. This gave rise to the concern that significant variations may result in the measured depth of abrasion, depending on the location of the measuring points around the abrasion path. In addition there could be variations across the width of the groove formed by the wheels, the normal practice being to take the readings in the centre of this groove i.e. 10 mm from each side.

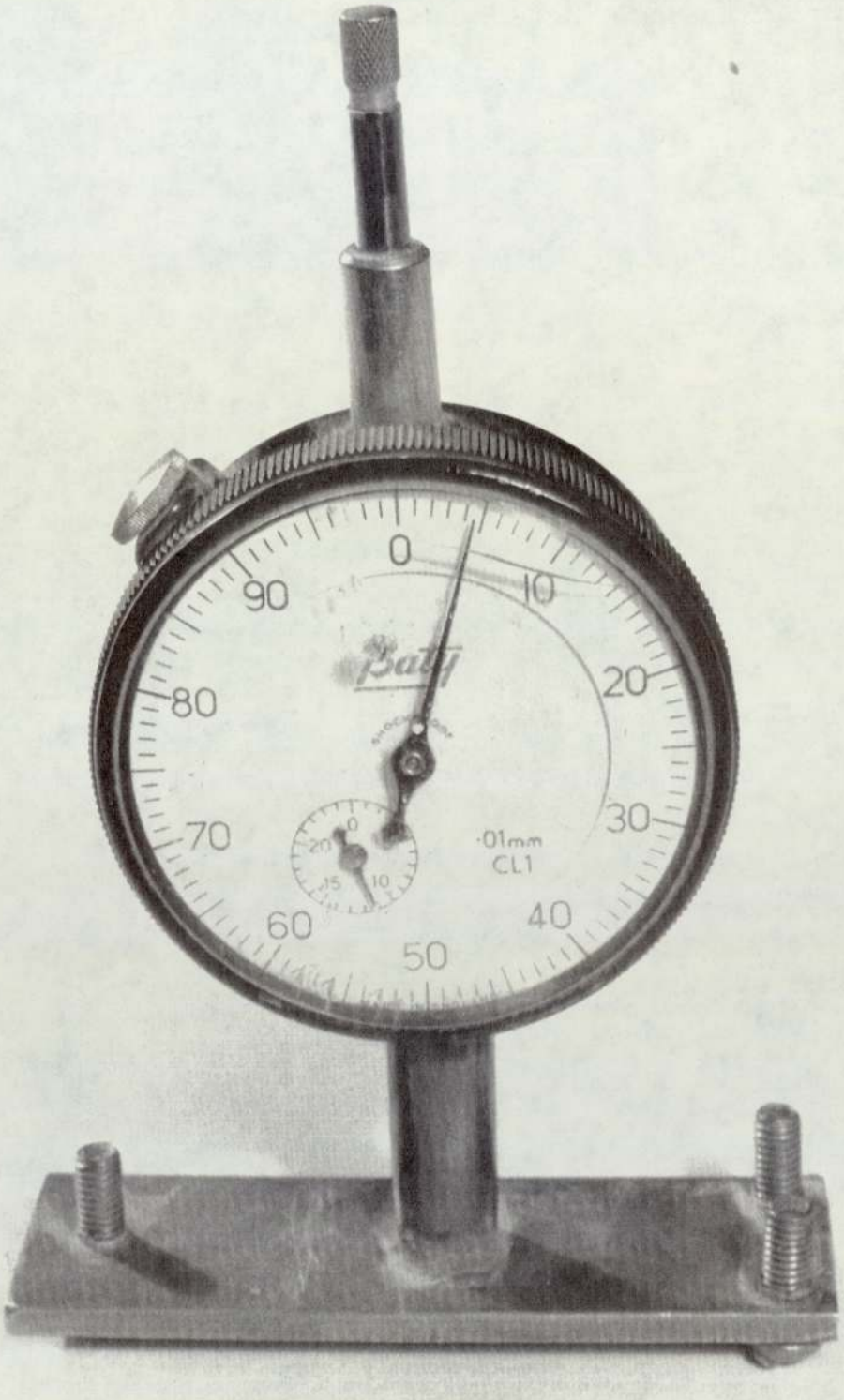


PLATE 5.5 A BRIDGE MICROMETER USED FOR MEASURING DEPTH OF ABRASION

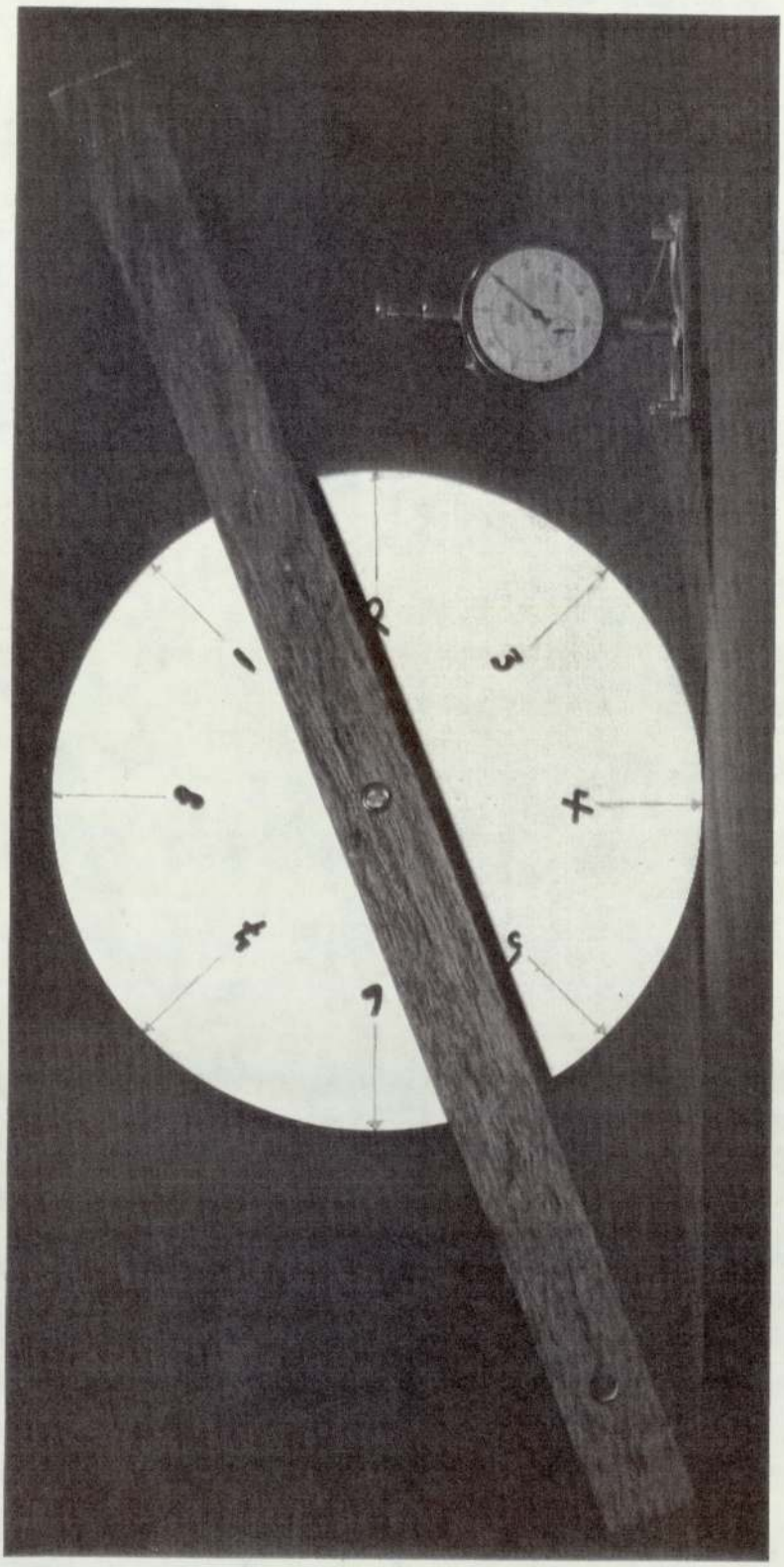


PLATE 5.6 THE DIAL GAUGE USED AT ASTON - AND MARKING OUT TEMPLATE BEING USED TO MARK OUT GAUGE POSITIONS PRIOR TO AN ACCELERATED ABRASION TEST

For each slab three circular abrasion paths were made one on the left, one in the middle and one on the right hand side as shown in plate 5.7.

5.3.2.1 Frequency and Location of the Readings

The number of measurement locations around the abrasion path was eight equally spread positions. Readings were recorded after 5, 10 and 15 minutes of exposure to abrasion and typical graphs of abrasion depth against time of abrasion are given in Figures 5.1 to 5.5. It was considered that these particular plots would be valuable in assessing the performance of the various water/cementitious ratios and curing regimes rather than merely measuring the depth of abrasion after the standard test period of 15 minutes.

Detailed results of the abrasion depth for the different mixes are given in Tables F.1 to F.11 , with plots of these results being given in Figures F.1 to F.23, in Appendix F.

5.4 STRENGTH TESTS

Five 100mm cubes were made from the concrete used to produce each 2.0 x 1.5 x 0.1m slab, and these cubes were water cured for 28 days. They were tested at 28 days in a grade A testing machine (300 tons AVERY

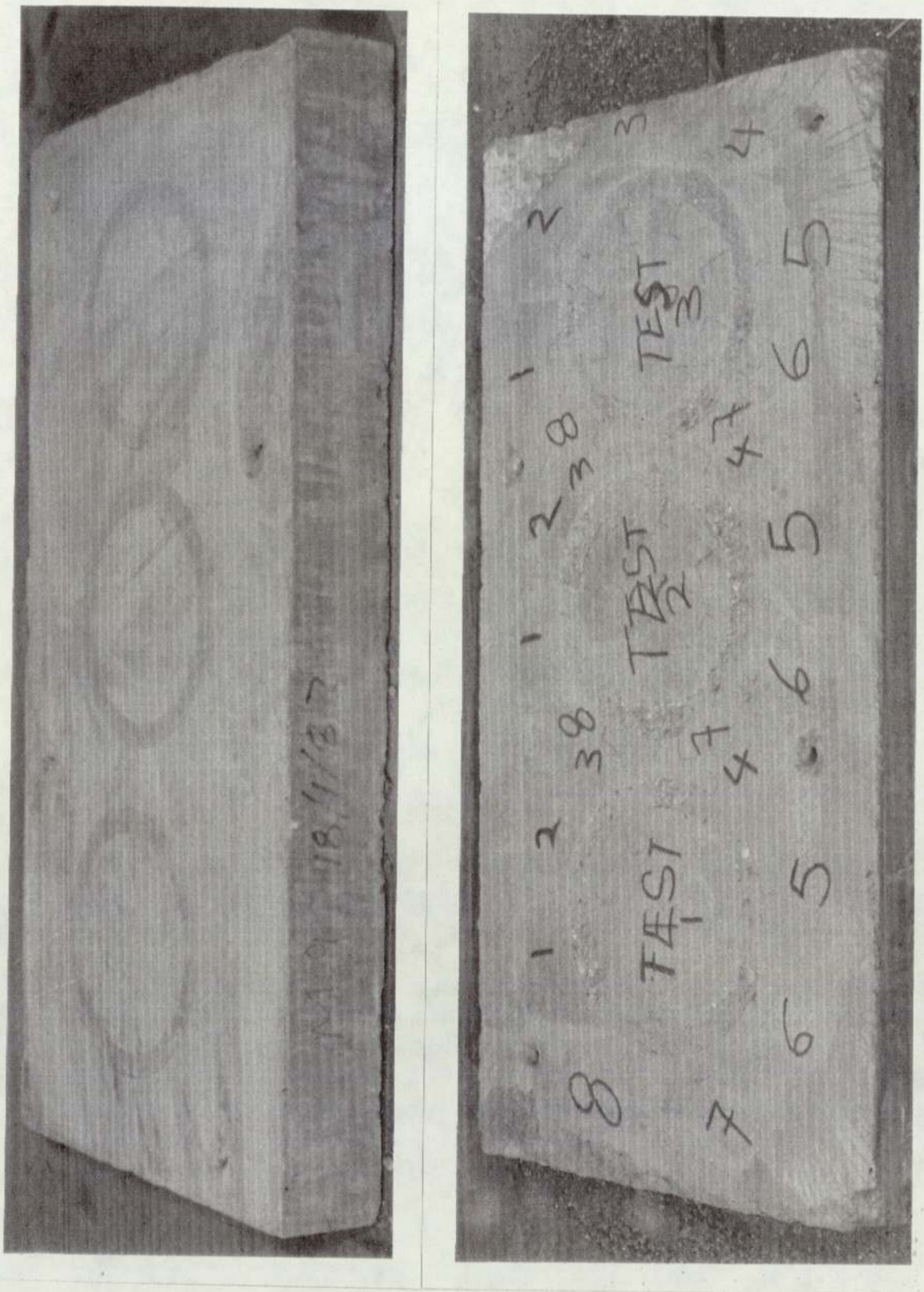


PLATE 5.7 CIRCULAR PATHS OF THE WEAR DEPTHS ON TWO TEST SLABS SUBJECTED TO AIR CURING AND POLYTHENE SHEETING

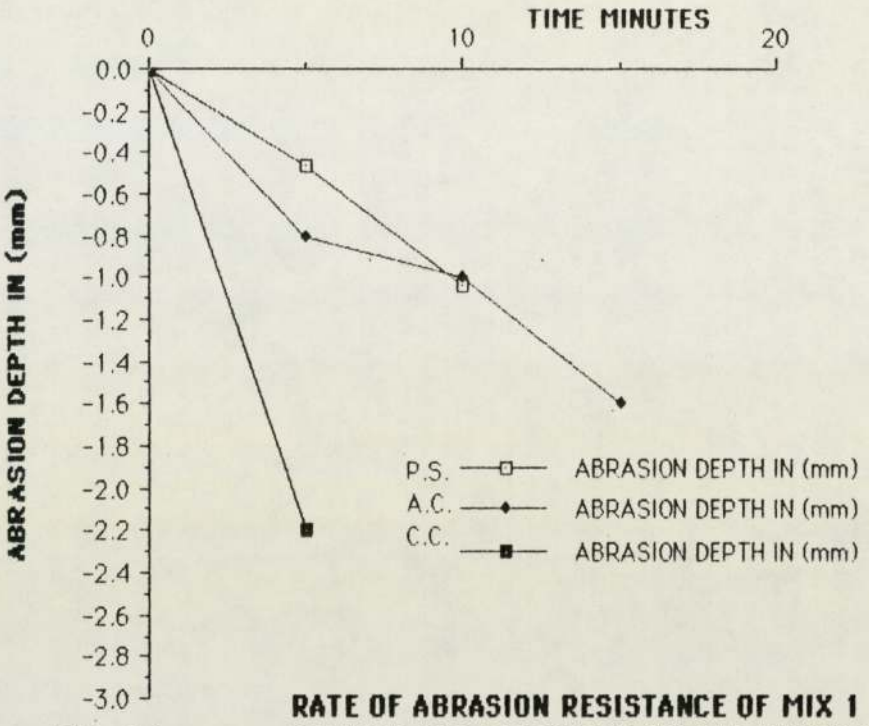


FIG. 5.1 RATE OF ABRASION RESISTANCE OF MIX 1 AT 28 DAYS FOR DIFFERENT CURING REGIMES.

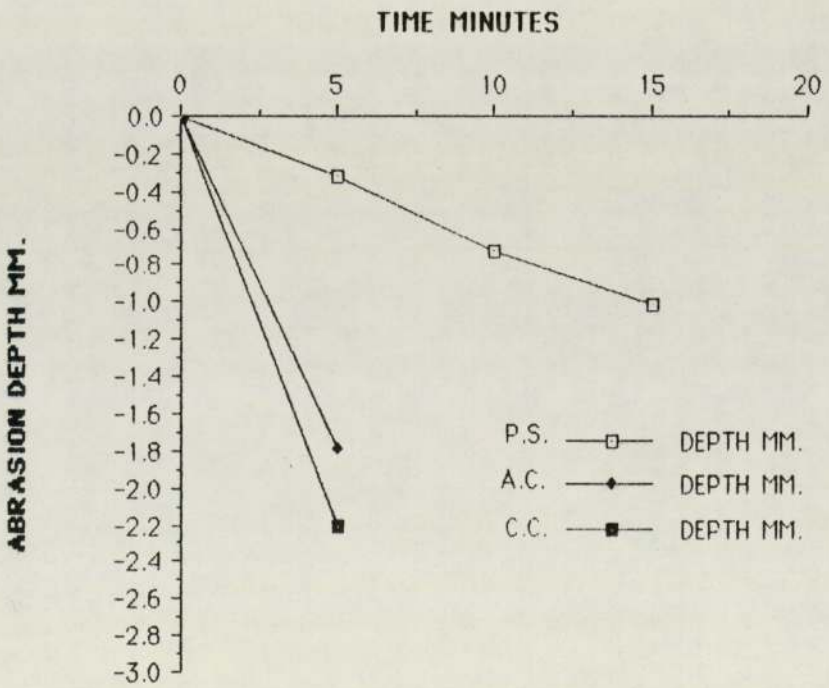


FIG. 5.2 RATE OF ABRASION RESISTANCE OF MIX 1 AT 90 DAYS FOR DIFFERENT CURING REGIMES

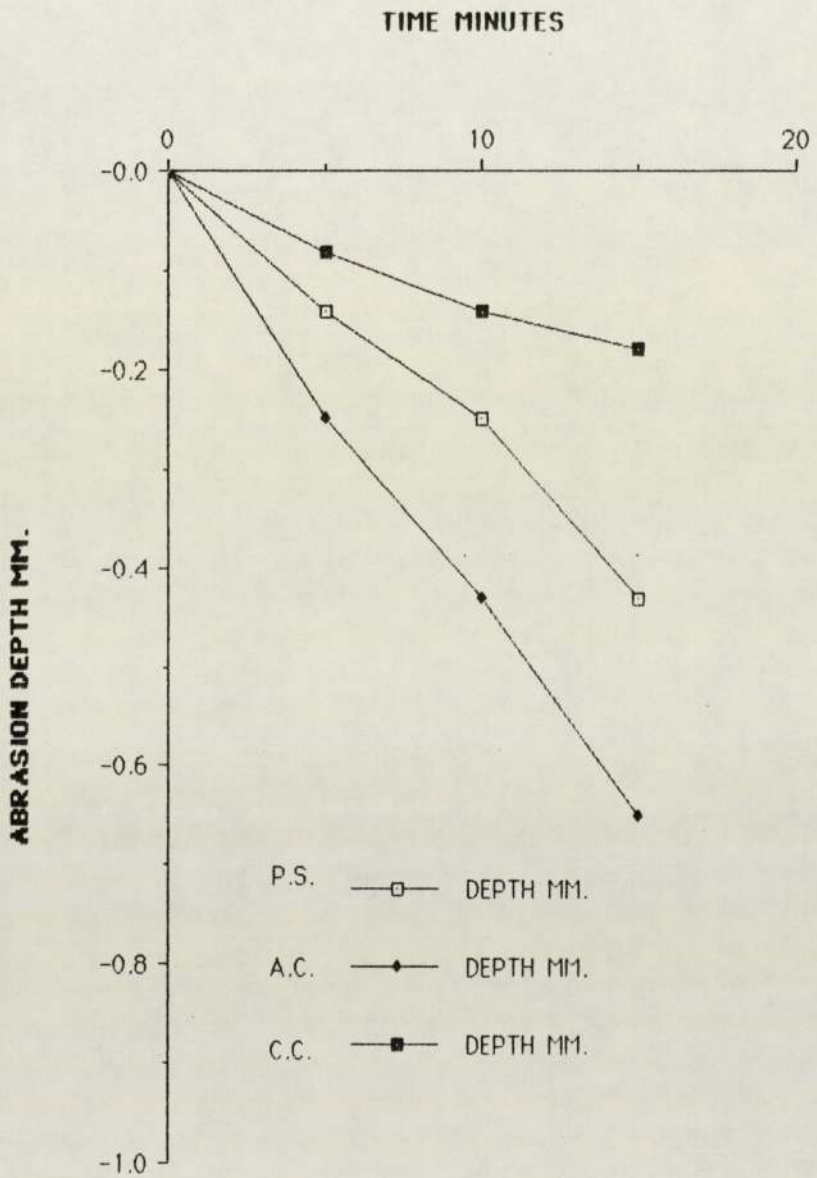


FIG. 5.3 **RATE OF ABRASION RESISTANCE OF MIX 2 AT 28 DAYS FOR DIFFERENT CURING REGIMES.**

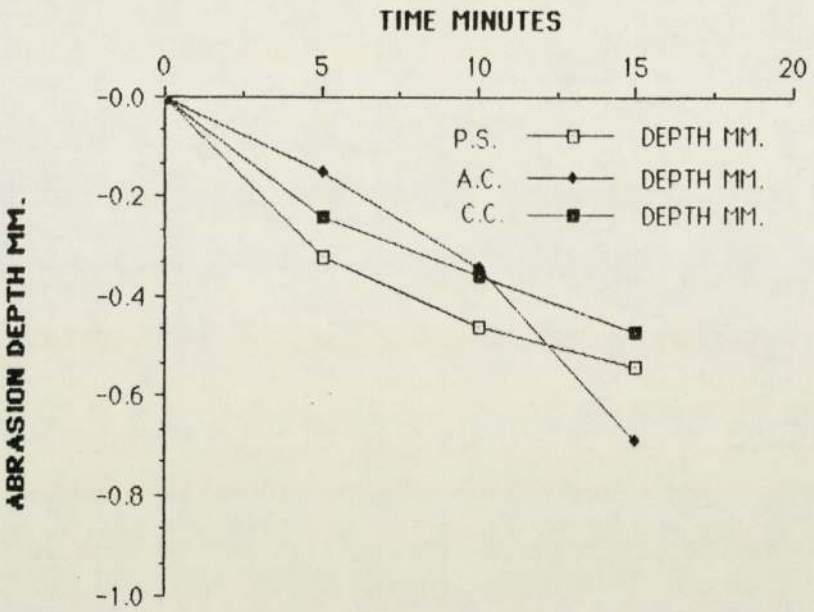


FIG. 5.4 RATE OF ABRASION RESISTANCE OF MIX 2 AT 90 DAYS FOR DIFFERENT CURING REGIMES.

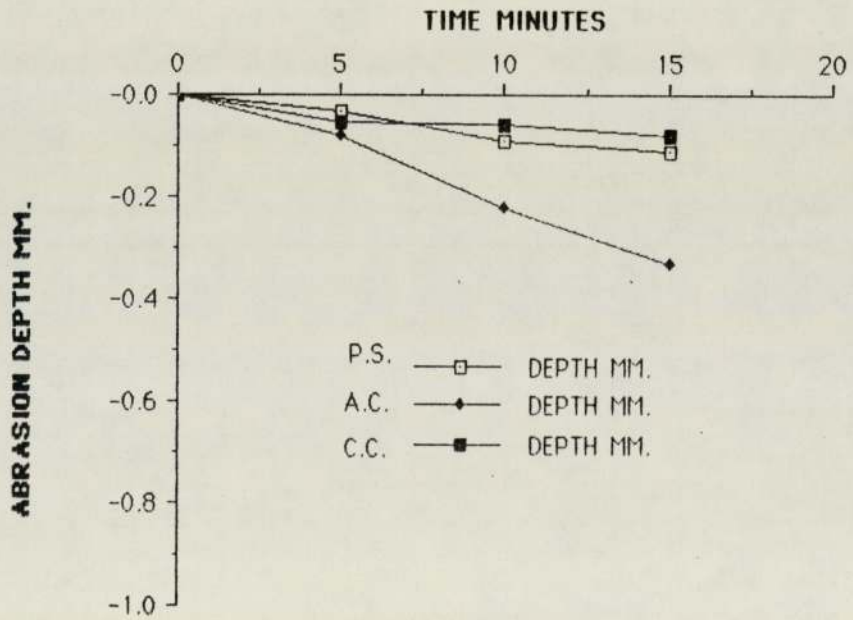


FIG. 5.5 RATE OF ABRASION RESISTANCE OF MIX 2 AT 180 DAYS FOR DIFFERENT CURING REGIMES.

DENISON) in accordance with BS 1881 Part 4: 1970. The mean value of the compressive strength of each set of five cubes was recorded and the summary of these results is provided in Table 4.3

By using the results from mixes 1, 3, 4, 6 and 7 it is possible to establish the relationship between the strength of concrete and the level of PFA replacement for mixes with the same water cementitious ratio and this is shown in Figure 5.6. This clearly shows that, for the same water cementitious ratio of 0.65, the 28 day compressive strength decreases as the PFA content increases.

5.5 DISCUSSION OF EXPERIMENTAL RESULTS

Many factors have been shown to influence (24) the abrasion resistance of floor slabs produced from plain concrete, the most significant being curing regime, strength grade and finishing technique. This particular investigation has studied the influence of a number of factors - PFA content, water/cementitious ratio, age, curing regime and strength - on the abrasion resistance of concrete with PFA content ranging from 0 - 40 percent.

Considering the abrasion results for Mixes 1, 3, 4, 6, 7 it can be seen from Figures 5.7 to 5.10 that the abrasion

INFLUENCE OF P.F.A. CONTENT FOR THE SAME WATER/CEMENTITIOUS RATIO OF 0.65 ON THE STRENGTH AT 28 DAYS.

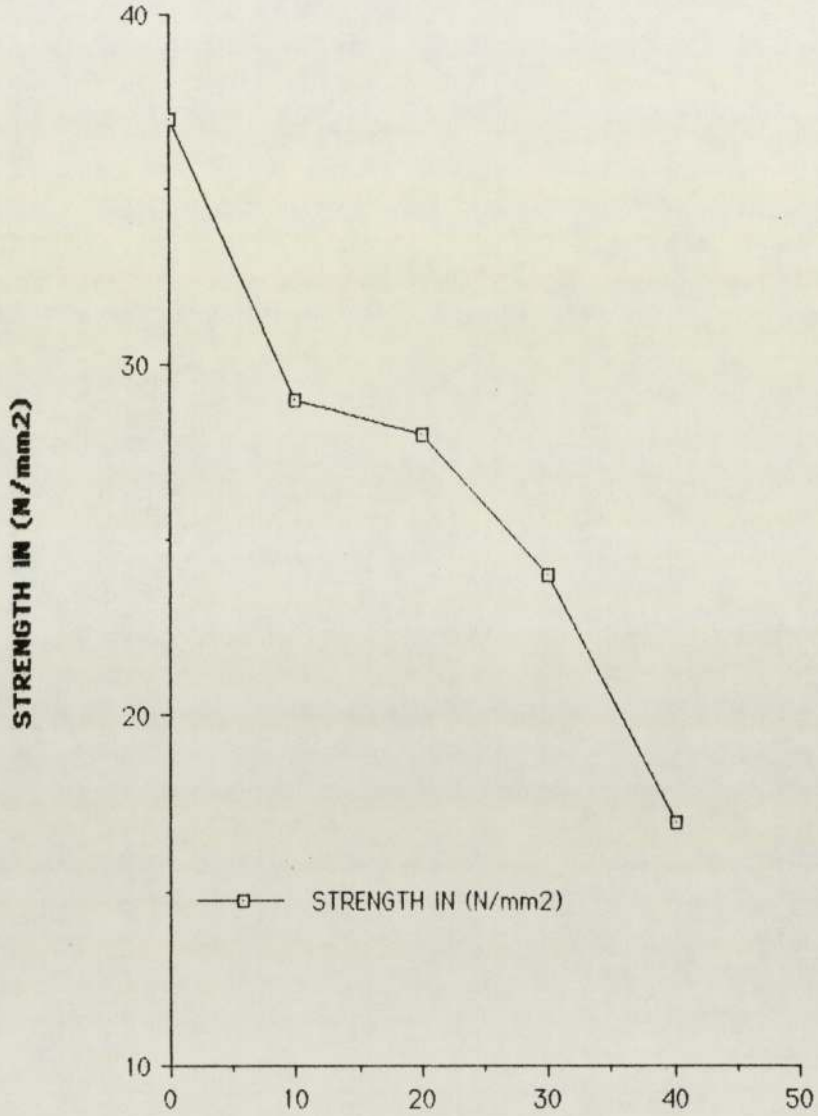


FIG. 5.6

resistance for concrete with a constant water/cementitious ratio (0.65), has been influenced by curing regime age at test and level of PFA replacement. From these graphs it is clear that the largest abrasion depths were produced from those specimens subjected to air curing. These results clearly demonstrate the benefit achieved by using positive curing - polythene sheeting or curing membrane - on PFA concretes. These benefits can be seen at all the selected levels (0 to 40%) of replacement used in this study.

Age plays an important role in the behaviour of PFA concretes since the strength development is influenced by the pozzolanic reactions. Materials containing finely divided reactive silica, such as PFA, are added to concrete to take advantage of the pozzolanic products formed when silica reacts with free lime. This reaction is a slow one, taking place over many months. Pozzolanic reactions are much slower than normal so hydration reactions to start and so time is a major factor in this development. The influence of age on the abrasion resistance of PFA concrete can be examined by using the data from mixes 8 to 11 and this is shown in Figures 5.11 to 5.14 where the abrasion depths are plotted against age. These results show that, for well-cured concrete (polythene sheeting regime) there is a significant increase in abrasion resistance with age. The results for the air cured specimens do not clearly

FIG. 5.7

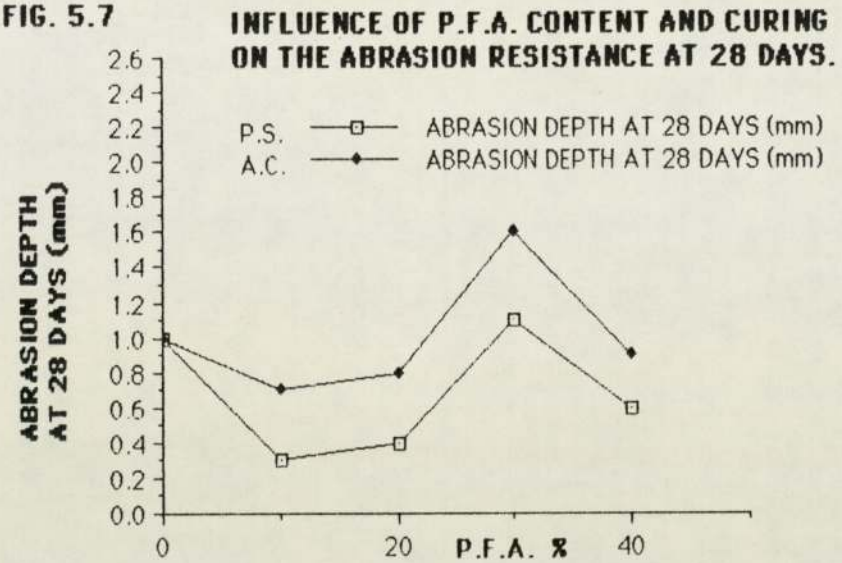
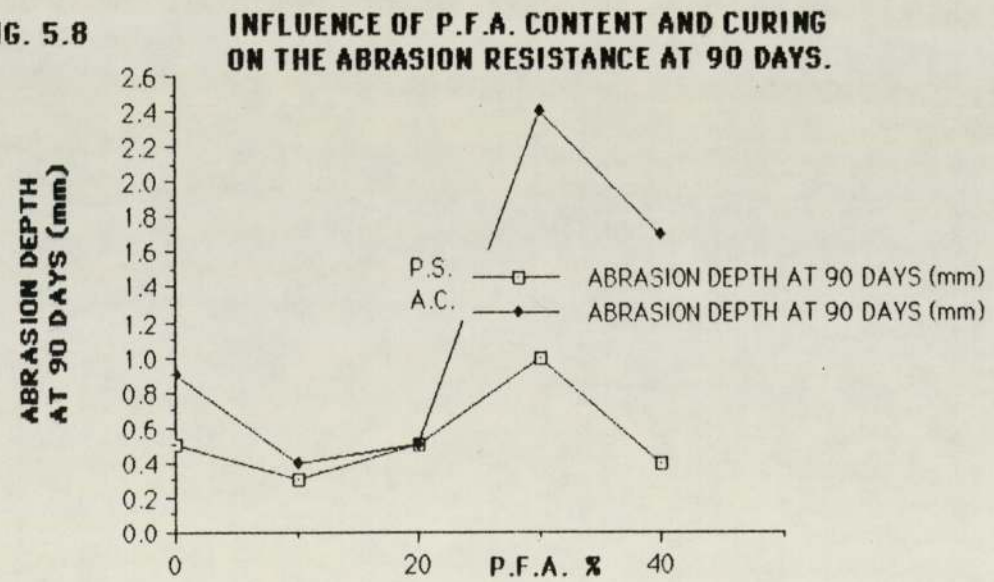

INFLUENCE OF P.F.A. CONTENT AND CURING
ON THE ABRASION RESISTANCE AT 28 DAYS.
ABRASION DEPTH AT 28 DAYS (mm)
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
P.S.
A.C.
ABRASION DEPTH AT 28 DAYS (mm)
ABRASION DEPTH AT 28 DAYS (mm)
0
20
P.F.A. %
40

FIG. 5.8


INFLUENCE OF P.F.A. CONTENT AND CURING
ON THE ABRASION RESISTANCE AT 90 DAYS.
ABRASION DEPTH AT 90 DAYS (mm)
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
P.S.
A.C.
ABRASION DEPTH AT 90 DAYS (mm)
ABRASION DEPTH AT 90 DAYS (mm)
0
20
P.F.A. %
40

ABRASION DEPTH AT 28 DAYS V'S P.F.A. CONTENT FOR THE SAME W/C RATIO OF 0.65 AND DIFFERENT CURING REGIMES.

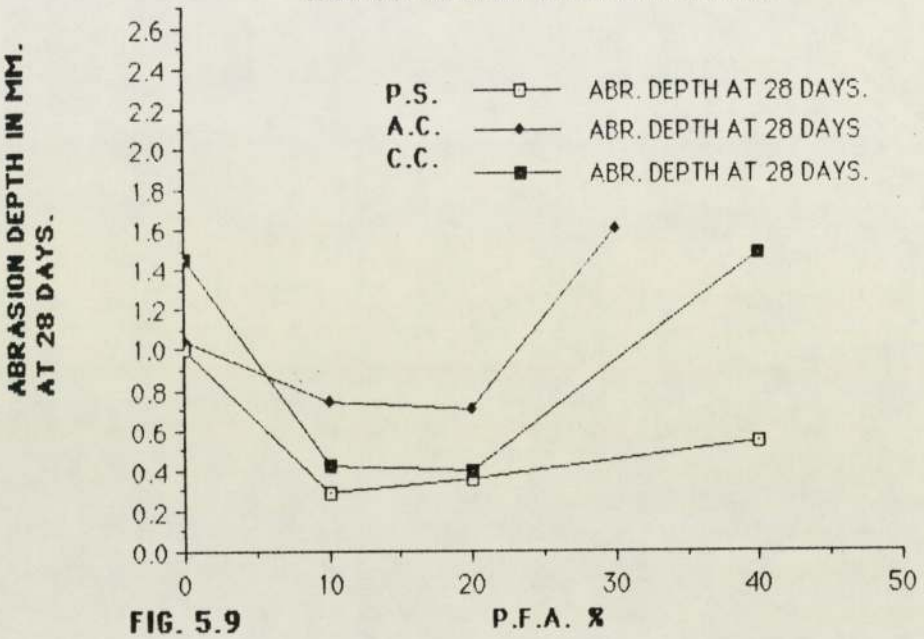


FIG. 5.9

ABRASION DEPTH AT 90 DAYS V'S P.F.A. CONTENT FOR SAME W/C OF 0.65 AND DIFFERENT CURING REGIMES.

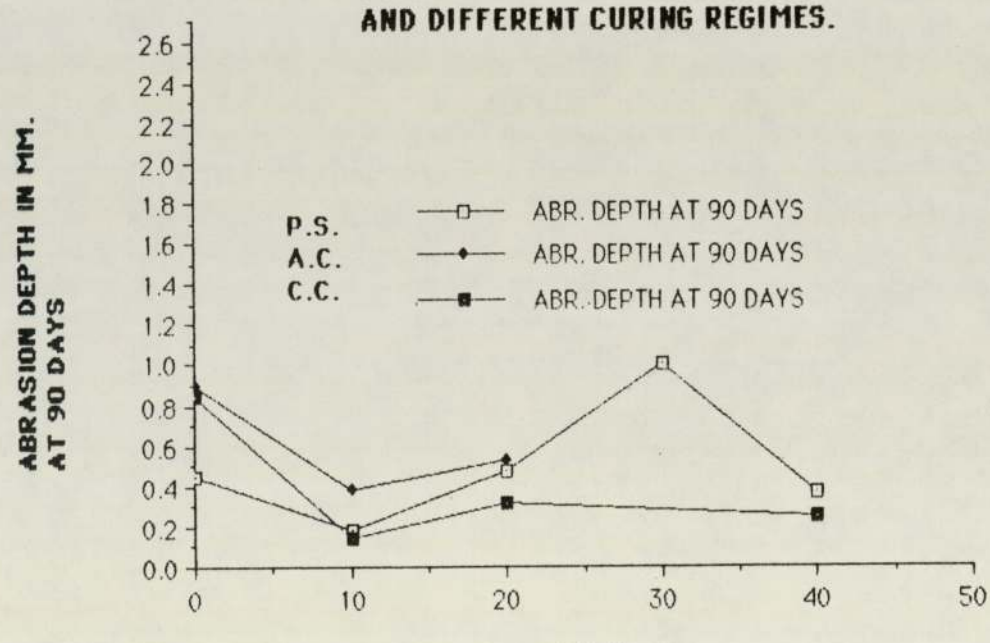


FIG. 5.10

FIG. 5.11 ABRASION DEPTH OF MIX 8 (W/C=0.44, P.F.A.=40%) Y'S AGE FOR A.C. AND P.S. CURING REGIMES.

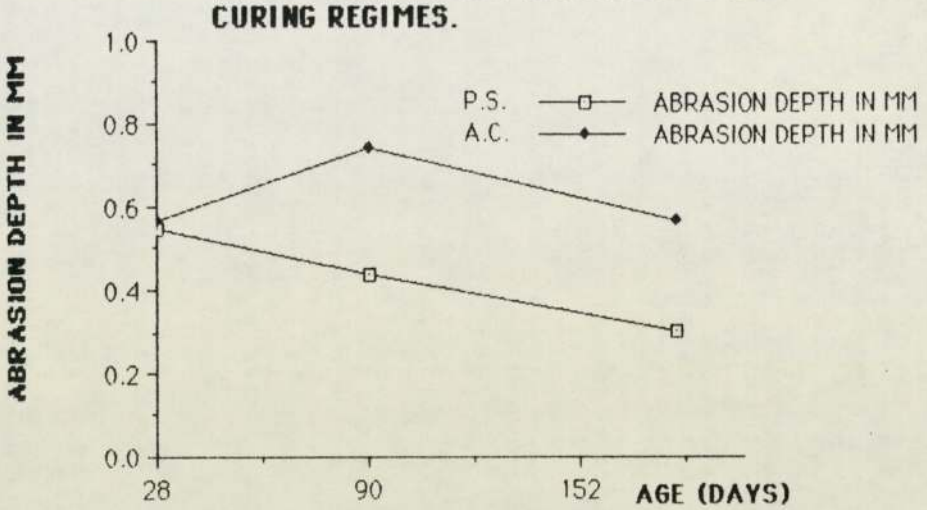


FIG. 5.12 ABRASION DEPTH OF MIX 9 (W/C=0.50, P.F.A.=10%) Y'S AGE FOR A.C. AND P.S. CURING REGIMES.

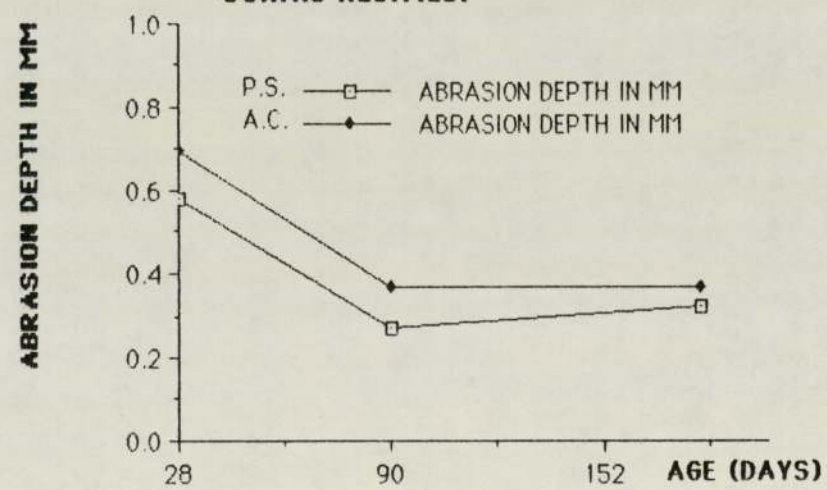


FIG. 5.13 ABRASION DEPTH OF MIX 10 (W/C=0.46, P.F.A.=30%) V'S AGE FOR DIFFERENT CURING REGIMES.

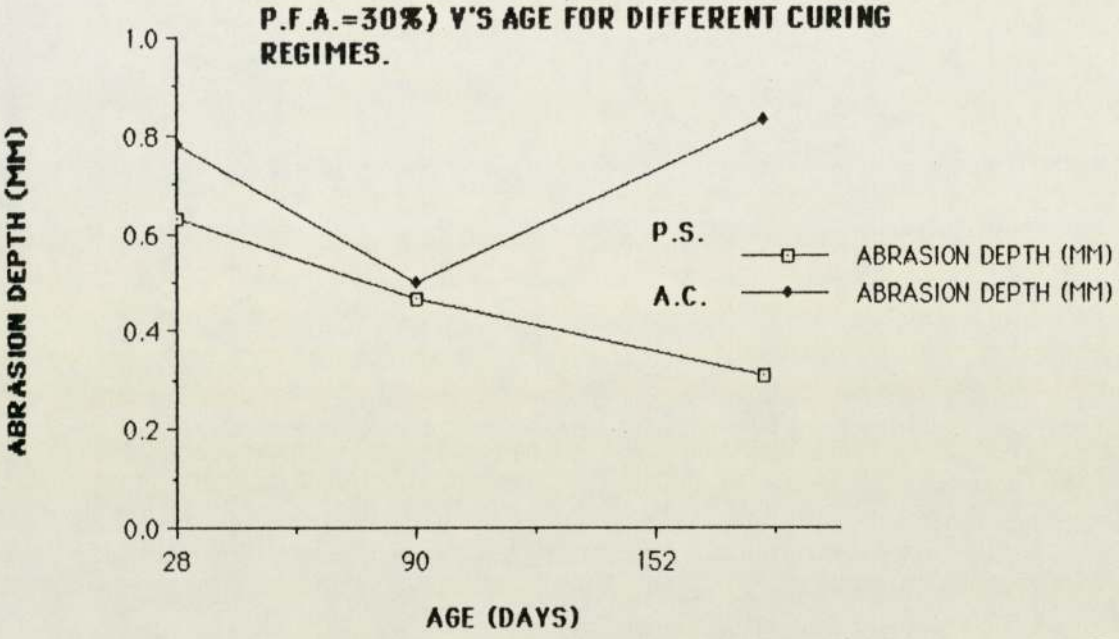


FIG. 5.14 ABRASION DEPTH OF MIX 11 (W/C=0.51, P.F.A.=20%) V'S AGE FOR DIFFERENT CURING REGIMES.

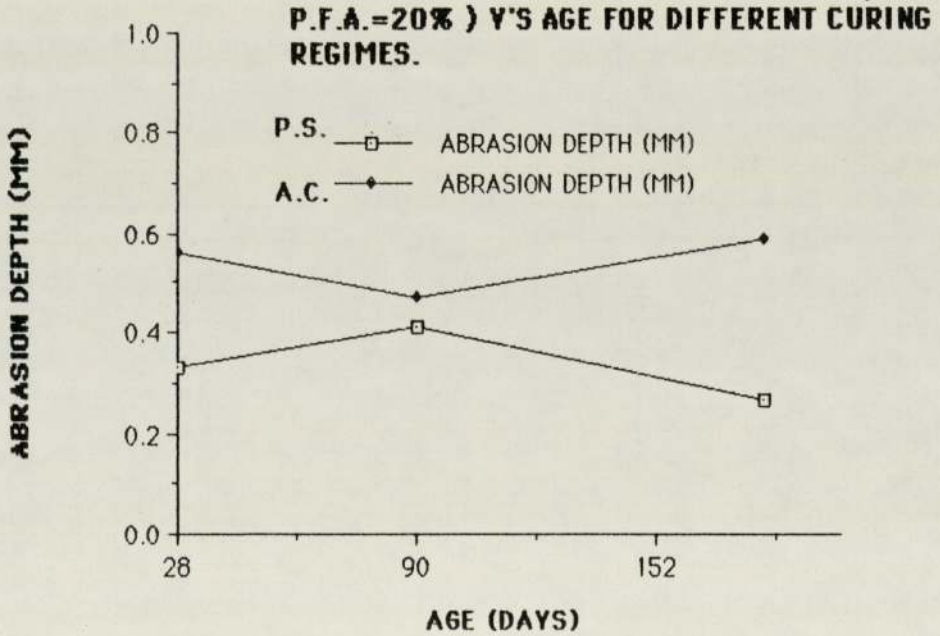


exhibit such a long-term improvement in abrasion resistance.

This is to be expected for the pozzolanic reaction depending on the availability of free lime from cement hydration. This hydration process requires the provision of adequate curing, moisture loss causes the process to cease. Clearly the polythene sheeting enable cement hydration to continue for a sufficient time to produce adequate free lime for the long term pozzolanic reactions. However the air cured concrete rapidly dried and as hydration slowed, this would limit the pozzolanic reactions so that there was little evidence of the long term improvements in abrasion resistance observed with the polythene cured samples.

These observations would suggest that the potential durability of well-cured PFA concrete can be greater than that of a similar OPC concrete. This is due to both the continued production of hardened paste by the pozzolanic reactions involving PFA, which subsequently reduce the porosity of the paste structure, and to the modified chemistry of the cement matrix. Both these factors can be expected to improve the strength and durability of the concrete.

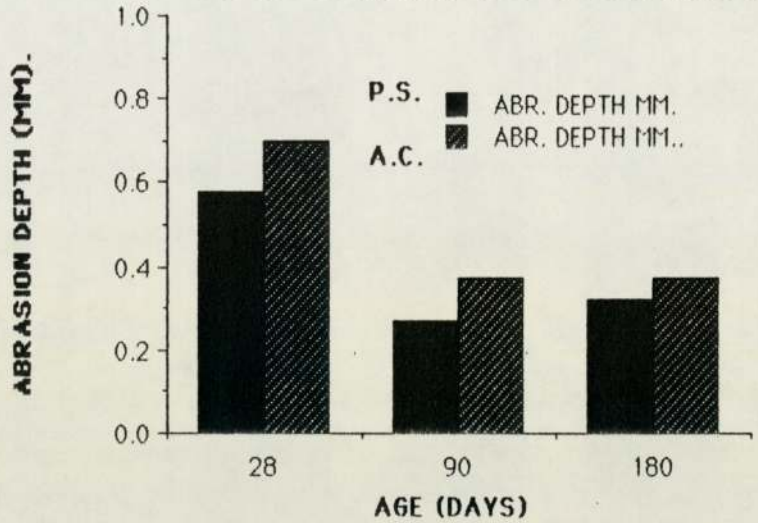
The histograms, shown in Figures 5.15 - 5.18, can also be used to further examine the role of age and curing

regime on abrasion resistance, since good curing for longer periods of time should be expected to improve the performance of a PFA concrete. For mixes 8 and 10, with water/cementitious ratios of 0.44 and 0.46 and respective PFA contents of 40 and 30 percent, the behaviour of the surface matrix to abrasion with respect to time appears to be similar when PS curing is employed, with increases in abrasion resistance accompanying prolonged PS curing.

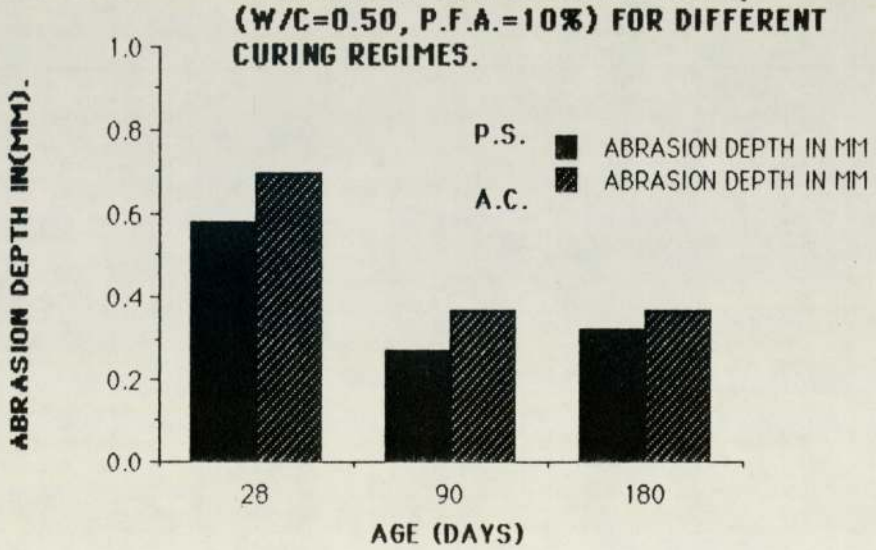
For mixes 9 and 11, cured with PS at 180 days, similar abrasion depth results were obtained although replicate specimens subjected to air curing produced widely different abrasion depths, indicating that the role of the curing regime was also affected by the constituents of the particular mixes. However these histograms further support the conclusion that age improves the abrasion resistance of PFA concrete when subjected to prolonged PS curing. The histographs clearly show, for all these mixes (8-11), that the abrasion depths of the air cured specimens were higher than when the same mixes were cured with polythene sheeting. As expected for each of these mixes, the higher abrasion resistance was achieved at 90, or 180 days when subjected to PS curing.

The results have clearly demonstrated the influence of curing an abrasion resistance and it has been acknowledged (65) that good curing particularly beneficial in improving the quality of the surface layer

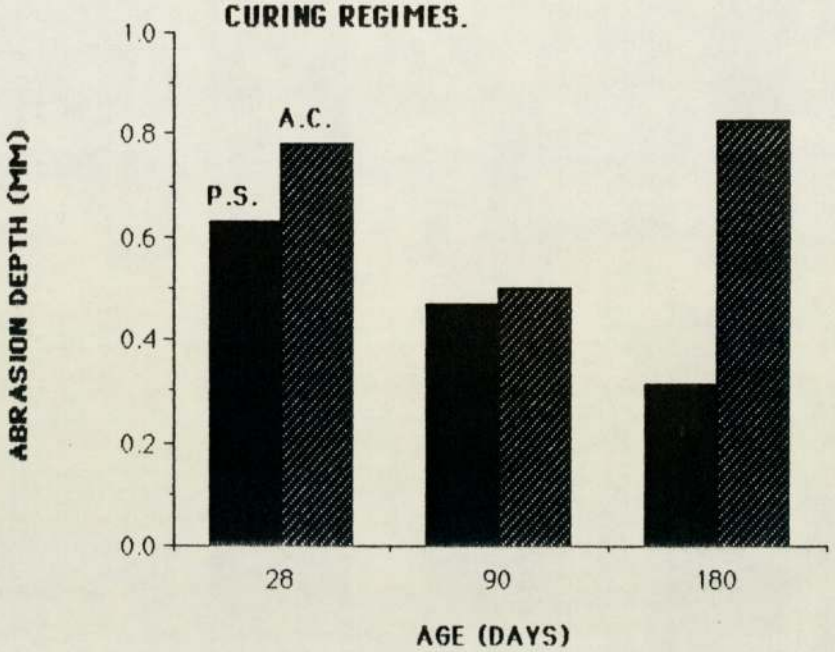
HIS. 5.15 **ABRASION DEPTH Y'S AGE FOR MIX 8 (W/C=0.44, PFA=40%) FOR DIFFERENT CURING**



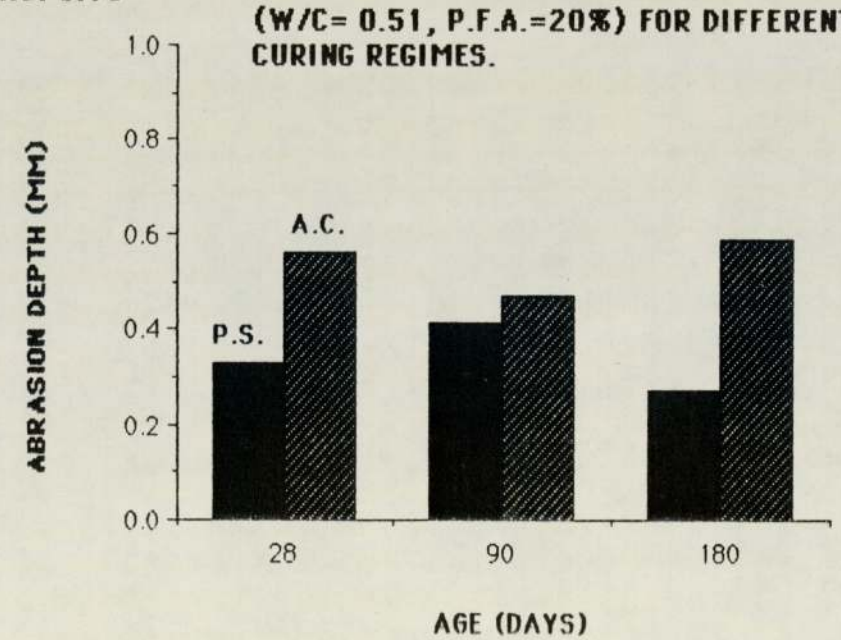
HIS. 5.16 **ABRASION DEPTH Y'S AGE FOR MIX 9, (W/C=0.50, P.F.A.=10%) FOR DIFFERENT CURING REGIMES.**



HIS. 5.17 ABRASION DEPTH Y'S AGE FOR MIX10, (W/C=0.46, P.F.A.=30%) FOR DIFFRENT CURING REGIMES.



HIS. 5.18 ABRASION DEPTH Y'S AGE FOR MIX 11 (W/C= 0.51, P.F.A.=20%) FOR DIFFERENT CURING REGIMES.



of concrete sections. Given the importance of this surface layer to the abrasion resistance, the porosity and structure of the cement matrix at both the surface and centre of slab have been examined in detail and the data is presented in Chapter Six.

It is reasonable to assume that the slower the rate of reaction, the longer the curing period that will be required to ensure that the potential properties are achieved; hence PFA concretes would be expected to need longer curing periods where durability is recognised as a potential problem. As it is shown in the histograms in Figures 5.15 to 5.18 better results were achieved at 180 days with polythene sheeting curing regime. The strength in Figure 5.6 shows that when the content of PFA is decreased the compressive strength increases, for the same total cement content. A combination of these two observations is provided by comparing Figures 5.7 and 5.8 which show that, for replacement levels above 15%, the abrasion resistance decreases as the PFA content increases for the same water/cementitious ratio and that prolonged curing improved the abrasion resistance. Generally mixes with replacement levels below 15% achieved a similar, long-term performance to that of the corresponding plain concrete (PFA content - 0%).

In Figures 5.19 and 5.20 it can be observed that generally the higher the compressive strength, the lower

the abrasion depths for concrete cured for 180 days, both for air and polythene sheet curing. Of course, the air cured specimens show higher abrasion depths again compared to the same samples cured with polythene sheeting. The difference in abrasion depths, between samples which were air cured and samples which were cured under polythene sheeting tends to reduce as the compressive strength increases and this is clear from Figures 5.19 and 5.20. This again demonstrates the vital role of positive curing if the durable long-term benefits are to be obtained with concretes contained PFA. However, given the influence of curing regime on abrasion resistance, it is clear the compressive strength is not a reliable guide to the abrasion resistance.

In Figures 5.21 to 5.23, histographs are presented to illustrate the relationship between abrasion resistance and water/cementitious ratio for concretes with constant PFA content of 30 percent. It is clear that the abrasion resistance is increased as the water/cementitious ratio is decreased, with the relationship again being influenced by the curing regime. The water/cementitious ratio is the most important factor for the production of concrete of consistent strength and its influence on abrasive resistance is demonstrated although the role of other factors, such as PFA percentage and age, must also be considered.

FIG. 5.19 ABRASION DEPTH Y'S STRENGTH FOR DIFFERENT MIXES (1-11) USING P.S.,A.C.,C.C.,CURING REGIMES.

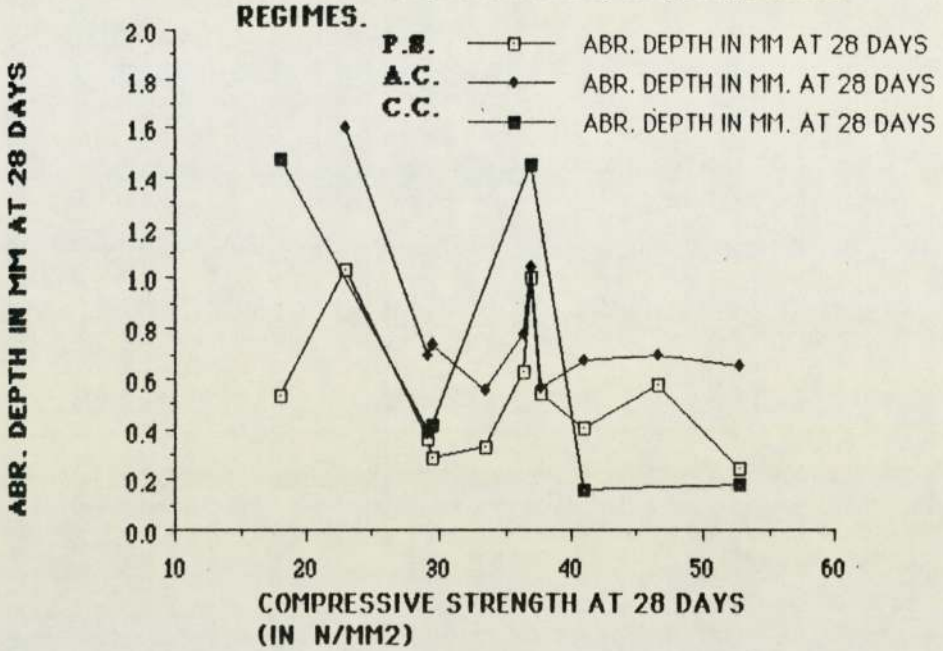
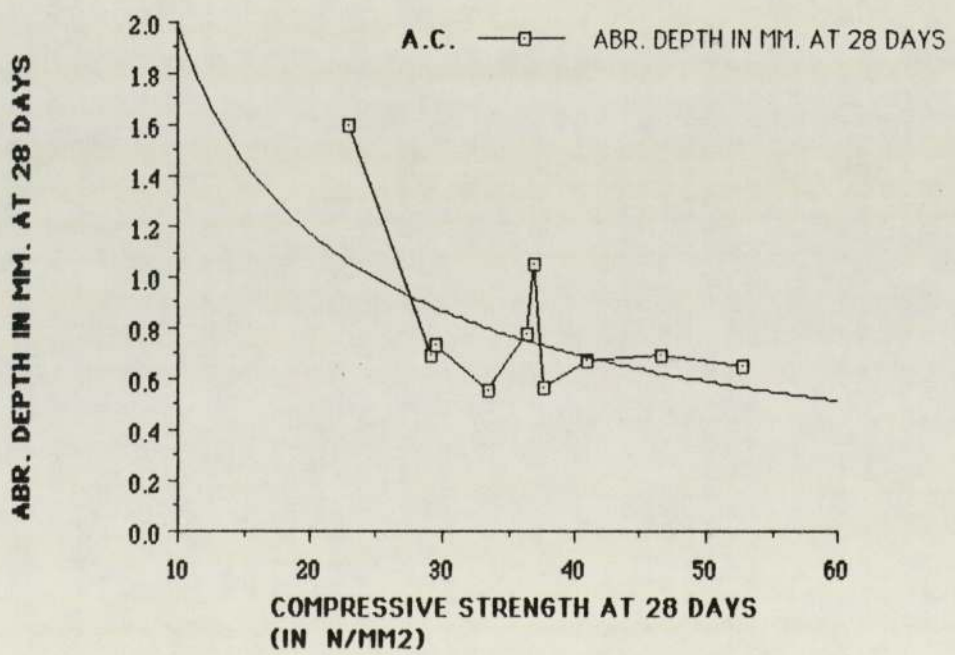
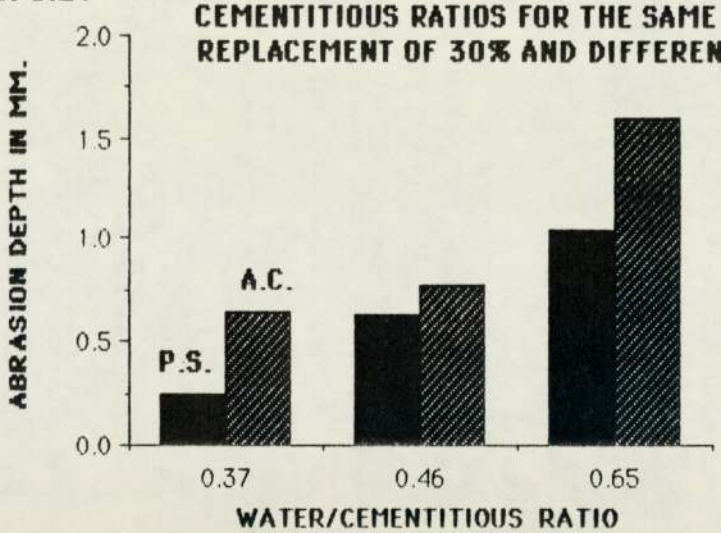


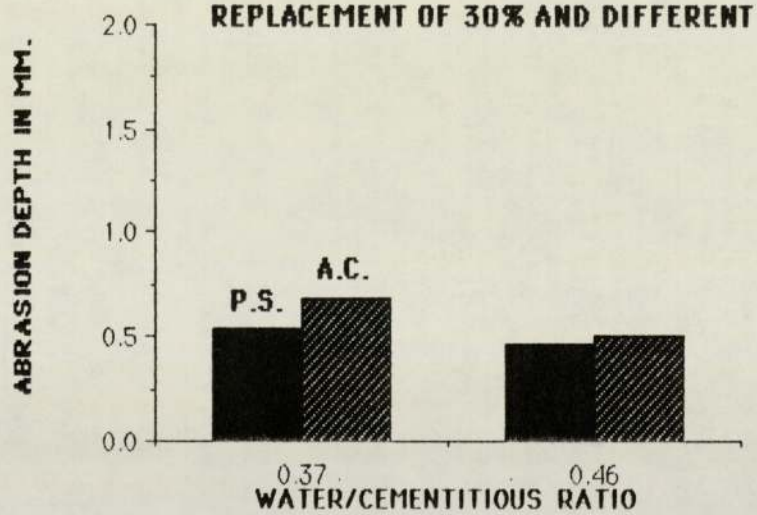
FIG. 5.20 ABRASION DEPTH Y'S STRENGTH FOR MIXES (2-11) USING A.C.



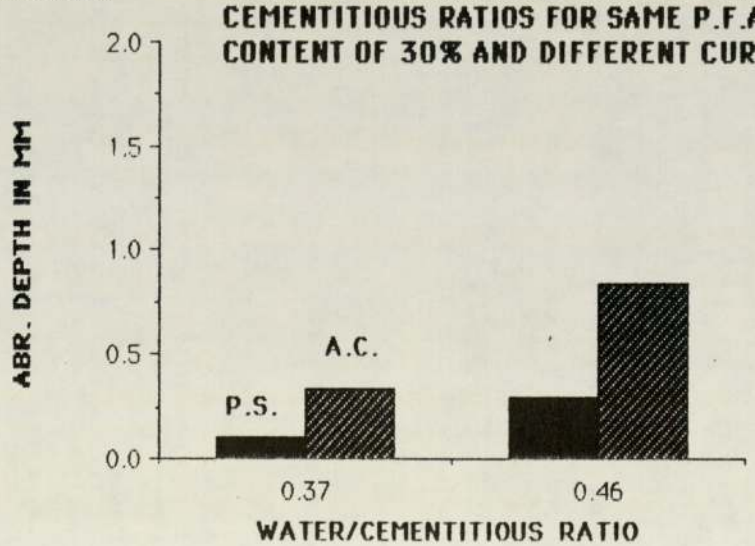
HIS. 5.21 ABRASION DEPTH AT 28 DAYS Y'S WATER CEMENTITIOUS RATIOS FOR THE SAME P.F.A. REPLACEMENT OF 30% AND DIFFERENT CURING



HIS. 5.22 ABRASION DEPTH AT 90 DAYS Y'S WATER CEMENTITIOUS RATIOS FOR THE SAME P.F.A. REPLACEMENT OF 30% AND DIFFERENT CURING



HIS. 5.23 ABRASION DEPTH AT 180 DAYS Y'S WATER CEMENTITIOUS RATIOS FOR SAME P.F.A. CONTENT OF 30% AND DIFFERENT CURING.



5.6 Summary of Main Observations

The experiment has shown that, on the macro-scale, a number of factors influence the effects of PFA additions on the abrasion resistance of concrete. These may be listed as follows:

1. Level of PFA replacement
2. Curing regime
3. Age
4. Compressive strengh

CHAPTER SIX

MICROSTUDY OF ABRASION RESISTANCE OF CONCRETE WITH PFA

6.1 INTRODUCTION

This microstudy was undertaken so that an assessment could be made of the various mechanisms by which the addition of pulverised fuel ash influenced the abrasion resistance of concrete. Attention was directed at techniques which had been employed in an earlier study (65) of abrasion resistance. This work, by Sadeqzadeh, (65) clearly showed the importance of the structure of the surface skin (2mm) to abrasion resistance of plain concentre. He demonstrated that changes in performance could readily be related to the porosity and microhardness of this layer.

It was considered that the information obtained with these two techniques would be useful in developing explanations for the performance of the various mixes monitored in the microstudy.

The previous chapter has demonstrated that the abrasion resistance of concrete slabs was influenced by the PFA content, curing regime and age. The mechanisms proposed to explain the influence of these variables, on the abrasion resistance, were related directly to the microstructure of the concrete nearest to the surface.

To substantiate these proposals it is therefore, necessary to examine the microstructure of the affected

concrete and this was undertaken using the following and techniques:-

(a) Mercury Intrusion porosimetry

(b) Microhardness examination.

6.2 MERCURY INTRUSION POROSIMETRY METHOD

Mercury intrusion porosimetry (MIP) involves forcing mercury into the vacated pores of a body by the application of pressure. If the pores are assumed to be cylindrical, the Washburn equation may be used to relate pore size to intrusion pressure, the equation can be written as:-

$$d = \frac{4\gamma\cos\theta}{P}$$

Where P = applied pressure

d = pore diameter

γ = surface tension

θ = contact angle of mercury on the pore wall.

The derivation of the equation is given in Appendix G. The technique involves determining the volumes of mercury that may be forced into the interstices of the test material under various pressures. The porosimeter consists of a pressure generator, a means for determining

the volume of the mercury intruded, a vacuum pump and vacuum indicator. A sample cell and reservoirs for the mercury and the pressure transmitting fluid complete the basic elements of the equipment.

Prior to testing the specimens are dried to remove any moisture, and the system is evacuated to remove any gases or vapours so that the mercury is free to penetrate without additional impediment. The amount of mercury which penetrates the pores is proportional to the pore size and pressure applied. Further details of the equipment are given in Figure H1 in Appendix H and the procedure for operating the equipment is fully described in the instruction manual (47).

The main limitations for the MIP techniques may be summarised as follows:

(1) The Washburn (81) equation assumes that the pores are all circular in cross-section but, in reality, this is not the case. However the effect of this limitation should not be significant in the present study, since it only affects the calculated diameter, the shape of the pore size distribution curve should not be appreciably different. Furthermore as the results are primarily required for comparative purposes with the main interest being in changes rather than the absolute values, this was not considered to be a major difficulty.

(2) The presence of "ink-bottle" pores or other shapes with constricted "necks" opening into a large volume void (54) (5) volume can lead to large errors in the shape of the Pore Size Distributed (PSD) curve.

(3) The compressibility of the material under test is particularly important for materials which have pores that do not connect with the surface, e.g. cork, as such compressibility will increase the measured pore volume.

(4) Similarly, the compressibility of the mercury with increasing test pressure can produce errors but these can usually be eliminated by carrying out a blank run, and this was performed during this work.

(5) The assumption of constant values for both the surface tension of mercury and for the contact angle between mercury and cement paste can lead to errors. According to Rootare the most reliable value for the surface tension of mercury has been obtained by Roberts who reported a value of 485 x 10^{-6} N/mm and this value was used throughout this study. The correct value for the contact angle is a matter of some debate with the contact angles between mercury and a large variety of materials ranging from 112 degrees to 142 degrees (54). The value used in the present programme was 117 degrees which is considered to be appropriate for oven dried

cement pastes (83). It should be noted that the use of an incorrect contact angle does not significantly affect the results when comparisons are being made for materials of the same type, as was the case in the present work.

In considering these limitations of the M.I.P. method it is essential to appreciate that the term "diameter" refers to what usually be termed the "pore entry diameter". At the outset of a mercury intrusion test the sample is surrounded by mercury and, as pressuring proceeds, mercury flows from the surface towards the centre through whatever pores are available. Where the diameter of the flow path flow to a particular internal pore, is smaller in diameter than the internal pore itself, that internal pore will be only intruded after sufficient pressure is applied to intrude the narrower pathway (83). Hence giving rise to the same "pore entry diameter" which represent the diameter, equivalent to the pressure, at which flow commences into the internal pore. Finally isolated pores having no communication with the exterior of the sample cannot be measured regardless of the applied pressure. Whilst the MIP method is not perfect it provides results which are consistent with those from other methods such as capillary condensation technique, and enables measurements to be undertaken across a wide range of specimens.

6.2.1 Specimens under investigation

This phase of the research project was confined to specimens, cured by plastic sheeting and air, produced from mixes 8 to 11. The results of abrasion tests on these mixes, given in Chapter 5, showed that they produced consistent data and from each of these slabs two samples were removed for the MIP study, one being from the surface matrix and the other from the middle of the slab (i.e. 50mm below the surface). A total of 48 MIP tests were carried out for this part of the programme. As these four mixes 8 to 11, also contained different percentages of PFA - Mix 8, 40%,; Mix 9, 10%; Mix 10, 30%; Mix 11, 20% - these MIP tests also provided data that could be used to study the influence of replacement level on the quality of the concrete, particularly the mortar fraction.

6.2.2 Experimental Procedures

A summary of the procedures used for determining the PSD of the samples under investigation is provided in the following paragraphs.

A core of 100mm diameter was taken from the centre of each slab. A 2mm thick section was sliced from the surface matrix of each core using a diamond

cutting wheel. These were broken by hand into small chunks approximately 2-4mm wide and 5-8mm long. A special effort was made to remove as many aggregate particles as possible from these chunks. A similar procedure was used with the samples taken from the middle of the slab. The 100mm diameter cores were cut in half and a 2mm thick section was sliced from the bottom of the top half of the core, i.e. the centre of the slab. The size and the shape of the samples were suitable for both the adopted drying method and the size of the cell for with very small samples, considerable care is needed in interpreting the results as interparticle void space can be included as well as the true porosity.

The chunk samples were oven dried for three days at a temperature of 105°C. These samples were removed from the oven 30 minutes before commencing the experiment and transferred to a $CaCl_2$ desiccator where they cooled to the room temperature in a dry atmosphere. These cool dry chunk samples were placed into a porosimeter cell of known weight and the complete cell weighed to the nearest 0.0001gm in order to determine the sample mass. The porosimeter cell was able to accommodate samples of 5-6gm, corresponding to 3 or 4 chuck samples.

The cell was immediately placed in the pressure

chamber. The samples and the system were evacuated for at least one hour, at a pressure of 20μm Hg, to remove any gases and subsequently, mercury was allowed into pressure vessel until it was full. A sufficient air pressure was admitted into the chamber to permit the mercury outside the sample cell to drain out. The pressure vessel was evacuated again so that the sample was ready for testing. The pressure was gradually increased to atmospheric and the volume of mercury penetrating the sample was measured with a digital counter which was converted into a volume measure as shown in Appendix I. The system was filled with a pressure transmitting fluid and a pressure above atmospheric was applied, using compressed air, up to a maximum pressure of 44000 psi. Errors due to compressibility of the mercury were corrected by carrying out a blank run using only mercury.

6.2.3 Results and Discussion

An example calculation of PSD is given in Appendix J and the detailed results of this study are presented in the form of cumulative pore diameter distribution curves shown in figures K1 to K47 in Appendix K. In these the pore volume (volume of penetrated mercury) expressed in millilitres of pore per gramme of oven dried sample is plotted against the applied pressure expressed in psi.

For each mix - 8, 9, 10 and 11-curves have been plotted for both the surface and middle matrix for both the curing regimes, air and polythene. For all these mixes, data have been obtained for specimens subjected to different curing periods, i.e. at 28, 90 and 180 days, as the performance of PFA concrete is influenced by time. The pore size distribution curves have been obtained from single samples representing each condition under investigation. It was decided to test only single samples as work by other investigators (83), (20), had demonstrated that the test is reproducible. To aid the consideration of the graphs the following notation has been adopted:

a) Poly/s - Polythene Sheeting curing regime at surface matrix.

b) Poly/m - Polythene sheeting curing regime at middle matrix.

c) Air/s - Air curing at surface matrix.

d) Air/m - Air curing at middle matrix.

The typical cumulative distribution curve, shown in Figure 6.1, reveals

a) Total volume of mercury intruded.

b) The pore volume in any pore range.

c) The median pore diameter, the diameter for which 50% of the pore volume is greater and 50% is smaller.

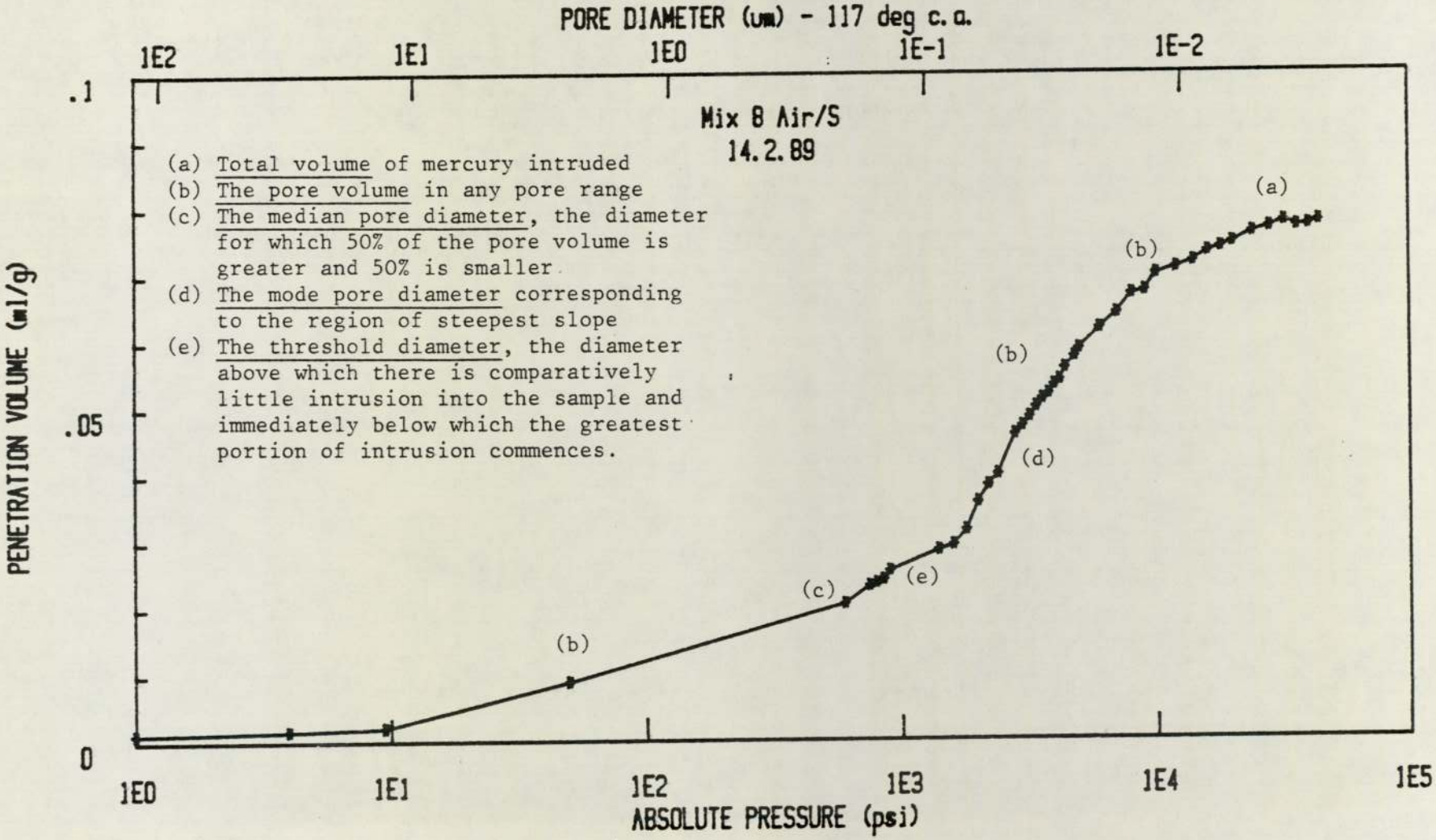

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
.1
.05
0
Mix 8 Air/S
14.2.89
(a) Total volume of mercury intruded
(b) The pore volume in any pore range
(c) The median pore diameter, the diameter for which 50% of the pore volume is greater and 50% is smaller
(d) The mode pore diameter corresponding to the region of steepest slope
(e) The threshold diameter, the diameter above which there is comparatively little intrusion into the sample and immediately below which the greatest portion of intrusion commences.
(a)
(b)
(b)
(d)
(c)
(e)
(b)
PENETRATION VOLUME (ml/g)
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE 6.1

d) The mode pore diameter corresponding to the region of steepest slope.

The cumulative distribution curve also shows the "threshold diameter" which is defined as the diameter above which there is comparatively little intrusion into the sample and immediately below which the greatest portion of intrusion commences.

The pore size distribution curves include the distribution of both voids and pores. The void space is included since the measured volume necessarily includes that of any space existing between the components of the test samples. It is therefore suggested that for pressures below 100 psi the PSD may be distorted by this void space and so should be discarded. Furthermore this factor makes it very difficult to determine the initial pore entry diameter.

As mentioned earlier specimens were tested at different ages, although all had been stored in the laboratory. This exposure to atmosphere could have influenced the PSDs, due to carbonation, most particularly the surface samples. This was not checked but all the samples would have been affected in a similar manner.

6.2.3.1 Initial Observations

The following observations have resulted from examining the general form and appearance of the PSD curves shown in Figure K1 to K47. The total pore volumes have been abstracted from figures K1 to K47 and these are presented in Table 6.1 together with the abrasion resistance results for the two types of curing regimes at 28, 90 and 180 days.

(1) The PSD curves are similar in form.

(2) The air cured samples generally exhibit greater total pore volume and higher initial pore entry diameters than those from similar polythene cured samples this implies that the porosity decreased with polythene curing.

(3) Observing the results from all four mixes for the total pore volume at 180 days, it is clear that the polythene curing produced the least total pore volume in both the surface and the middle matrices although the porosity at the middle is generally greater than that of the surface matrix.

(4) The PSD curves for the samples taken from the surface of the slabs clearly show that mix 8, with the highest PFA content of 40%, had the higher total

TABLE 6.1

Mix No.	W/c/PFA %	Age	Curing Regime	Depth of Abrasion (nn)	Total pore volume ml/g x 10^{-2}		Strength N/mm^2
					Top	Middle	
8	0.44/40	28d	PS	0.50	7.90	9.50	41.2
		90d	PS	0.44	8.00	8.00	
		180d	PS	0.30	8.20	5.50	
		28d	AC	0.60	7.70	7.80	
		90d	AC	0.74	7.20	8.00	
		180d	AC	0.60	8.40	7.30	
9	0.50/10	28d	PS	0.58	5.40	5.20	46.6
		90d	PS	0.27	5.10	4.10	
		180d	PS	0.32	4.60	4.40	
		28d	AC	0.70	-	5.30	
		90	AC	0.40	4.60	5.00	
		180d	AC	0.40	6.20	5.50	
10	0.46/30	28d	PS	0.60	7.40	-	36.4
		90d	PS	0.40	6.10	5.40	
		180d	PS	0.30	5.80	5.20	
		28d	AC	0.80	10.00	5.40	
		90d	AC	0.50	8.00	6.30	
		180d	AC	0.80	8.10	6.50	
11	0.51/20	28d	PS	0.30	6.00	5.80	33.4
		90d	PS	0.40	6.20	6.60	
		180d	PS	0.30	5.60	5.60	
		28d	AC	0.60	7.60	7.60	
		90d	AC	0.50	5.00	6.40	
		180d	AC	0.60	7.20	6.20	

pore volume in comparison with mix 10 with a lower PFA content of 30% and very similar water/cementitious ratios, 0.44 and 0.46 respectively.

(5) The total pore volume taken from the surface matrix at 180 days for mix 8, 9, 10 and 11 show that, for the different water/cementitious ratios and PFA contents, the PSDs were not a direct function of the water/cementitious ratio, i.e. the lowest water/cementitious ratio did not yield the lowest total pore volume as findings of other investigators (83) (30) (10) have suggested. This is attributed to the additional fact that the mixes also contain PFA. At near constant water/cementitious the pore volume appears to increase with PFA content as stated above.

(6) Mix 9 exhibited both the highest abrasion resistance and the least total pore volume at 180 days, and this was apparent for both air and polythene sheet curing. Mix 10 and 11 also produced good results at 180 days, for a polythene sheet curing, in terms of both the total pore volume and abrasion resistance. By examining the results in Table 6.1 for Mixes 9, 10 and 11, with PFA replacement levels of 10, 30 and 20% respectively, mix 10 would appear to be the least expensive of

6.2 ABRASION DEPTH AND TOTAL PORE VOLUME AT 28 DAYS

Mix No.	w/c/pfa %	Curing Regime	Depth of Abrasion (mm) at 15 min	Total Pore Volume (ml/g) x 10^{-2}		Strength N/mm^2
				Top	Middle	
Mix 8	0.44/40	P.S. A.C.	0.50 0.60	7.90 7.70	9.50 7.80	41.2
Mix 9	0.50/10	P.S. A.C.	0.58 0.70	5.40 -	5.20 5.30	46.6
Mix 10	0.46/30	P.S. A.C.	0.60 0.80	7.40 10.00	- 5.40	36.4
Mix 11	0.51/20	P.S. A.C.	0.30 0.60	6.00 7.60	5.80 7.60	33.4

6.3 ABRASION DEPTH AND TOTAL PORE VOLUME AT 90 DAYS

Mix 8	0.44/40	P.S. A.C.	0.44 0.74	8.00 7.20	8.00 8.00	41.2
Mix 9	0.50/10	P.S. A.C.	0.27 0.40	5.10 4.60	4.10 5.00	46.6
Mix 10	0.46/30	P.S. A.C.	0.40 0.50	6.10 8.00	5.40 6.30	36.4
Mix 11	0.51/20	P.S. A.C.	0.40 0.50	6.20 5.00	6.60 6.40	33.4

6.4 ABRASION DEPTH AND TOTAL PORE VOLUME AT 180 DAYS

Mix 8	0.44/40	P.S. A.C.	0.30 0.60	8.20 8.40	5.50 7.30	41.2
Mix 9	0.50/10	P.S. A.C.	0.32 0.40	4.60 6.20	4.40 5.50	46.6
Mix 10	0.46/30	P.S. A.C.	0.30 0.80	5.80 8.10	5.20 6.50	36.4
Mix 11	0.51/20	P.S. A.C.	0.30 0.60	5.60 7.20	5.60 6.20	33.4

these mixes as if has the highest replacement level but, when subjected to polythene curing, its abrasive resistance is lower than that of both Mixes 9 and 11.

(7) The lowest pore volume, determined at 180 days, for both the surface and middle matrix with both curing regimes, was obtained from Mix 9 as shown in Table 6.1.

6.2.3.2 Influence of Mix Characteristics

The results, summarised in Table 6.2 to 6.4, illustrate that curing is a key factor on the performance and durability although the effect on strength is less marked, for example mix 11, with a cube strength at 28 days of 33.4 N/mm^2 gave almost the same total pore volume as mix 9 with compressive strength of 46.6 N/mm^2 using the results obtained at 180 days on specimens subjected to polythene curing (P.S.). However, it should be noted the cube strength values relate to 28 day results. Care must therefore be exhibited with curing P.F.A. concretes, particularly with high PFA contents, if the potential benefits are to be fully realised.

The effect of PFA on concrete porosity, as discussed in Section 6.2.3.1 may be attributed to three prime interacting factors:-

a) A reduction in water content and an associated reduction in the number of large pores in well cured concrete.

b) Extension of the cementitious reactions by the presence of long-term pozzolanic reactions.

c) The porosity of the PFA concrete is reduced as pores become blocked by the gel products from both cement hydration and the subsequent pozzolanic reactions.

The abrasion resistance of PFA concretes is controlled by the pore structure of its surface matrix and key factors are the water/cementitious ratio and the PFA content. As an example the total pore volume increases with an increase in the PFA content as shown in Figure 6.2 and 6.3. Furthermore a comparison of these two figures, with due allowance for the different PFA contents, would seem to indicate that higher total pore volumes are associated with a higher water/cementitious ratio and this observation is in broad agreement with the results reported (65) for plain concrete.

Age has also been shown to have an important role in the performance of PFA concrete, this is due to the fact that the continuing hydration of these mixes reduces the porosity, and the permeability of the paste structure through modification of the structure of the cement matrix.

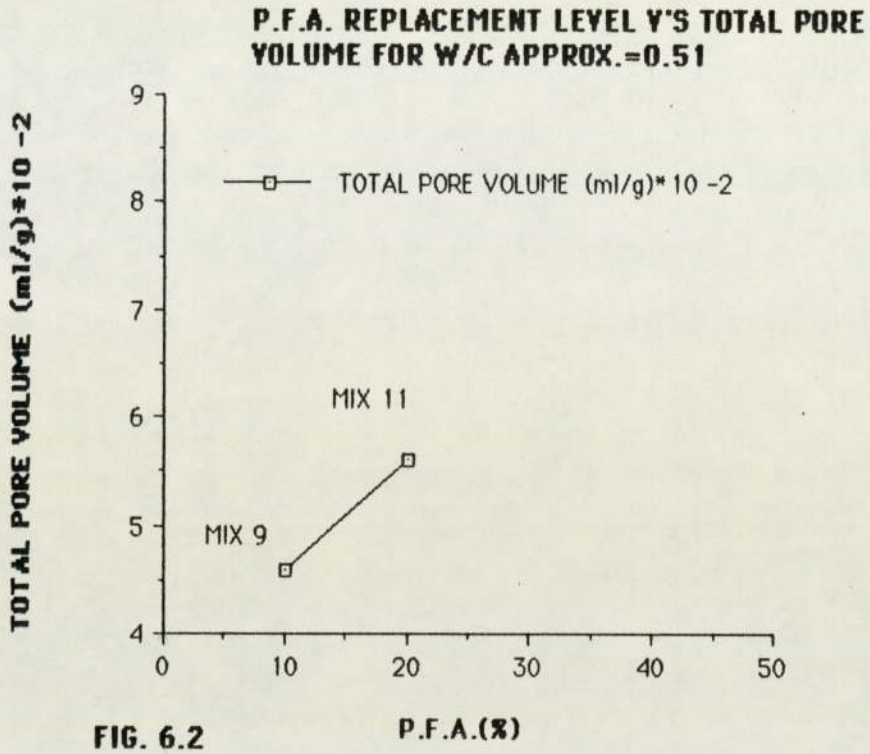

P.F.A. REPLACEMENT LEVEL V'S TOTAL PORE VOLUME FOR W/C APPROX.=0.51
TOTAL PORE VOLUME (ml/g)*10 -2
TOTAL PORE VOLUME (ml/g)*10 -2
MIX 11
MIX 9
9
8
7
6
5
4
0
10
20
30
40
50
P.F.A.(%)

FIG. 6.2

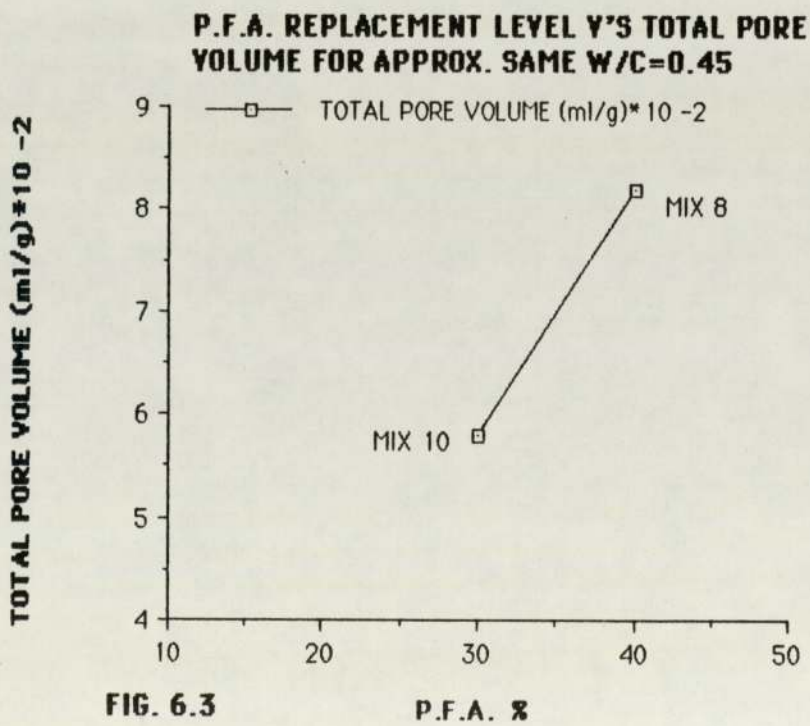

P.F.A. REPLACEMENT LEVEL V'S TOTAL PORE VOLUME FOR APPROX. SAME W/C=0.45
TOTAL PORE VOLUME (ml/g)*10 -2
TOTAL PORE VOLUME (ml/g)*10 -2
MIX 8
MIX 10
9
8
7
6
5
4
10
20
30
40
50
P.F.A. %

FIG. 6.3

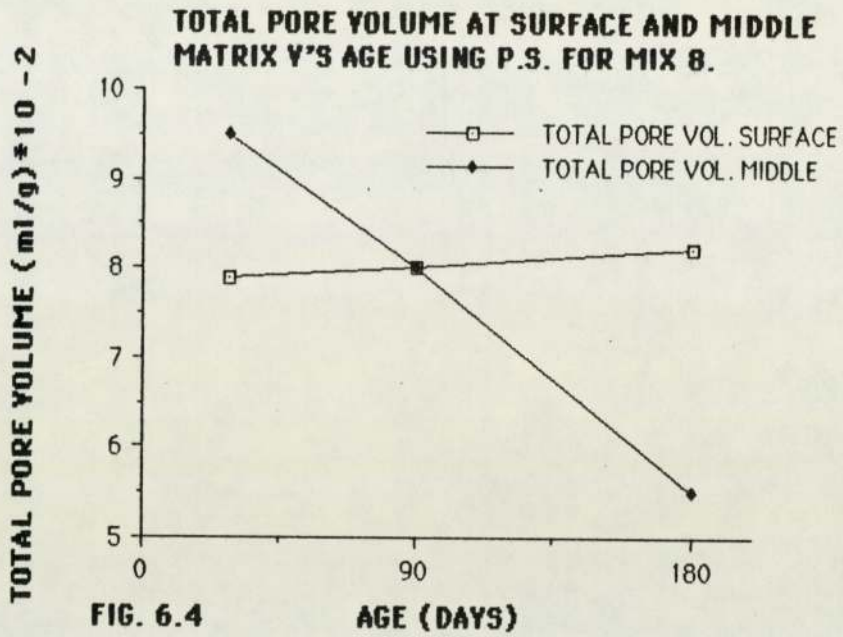

TOTAL PORE VOLUME AT SURFACE AND MIDDLE
MATRIX Y'S AGE USING P.S. FOR MIX 8.
TOTAL PORE VOL. SURFACE
TOTAL PORE VOL. MIDDLE
TOTAL PORE VOLUME (ml/g)*10 -2
10
9
8
7
6
5
0
90
180
AGE (DAYS)

FIG. 6.4

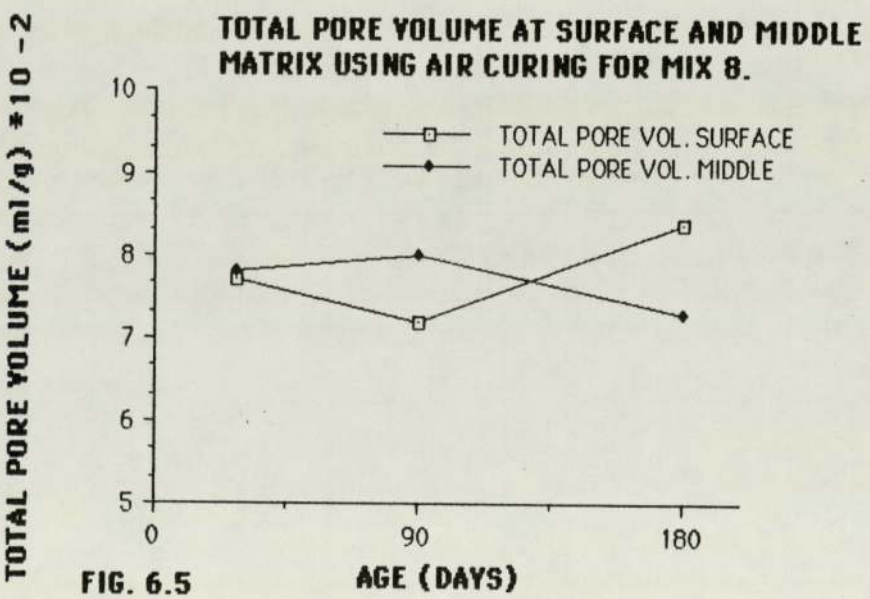

TOTAL PORE VOLUME AT SURFACE AND MIDDLE
MATRIX USING AIR CURING FOR MIX 8.
TOTAL PORE VOL. SURFACE
TOTAL PORE VOL. MIDDLE
TOTAL PORE VOLUME (ml/g) *10 -2
10
9
8
7
6
5
0
90
180
AGE (DAYS)

FIG. 6.5

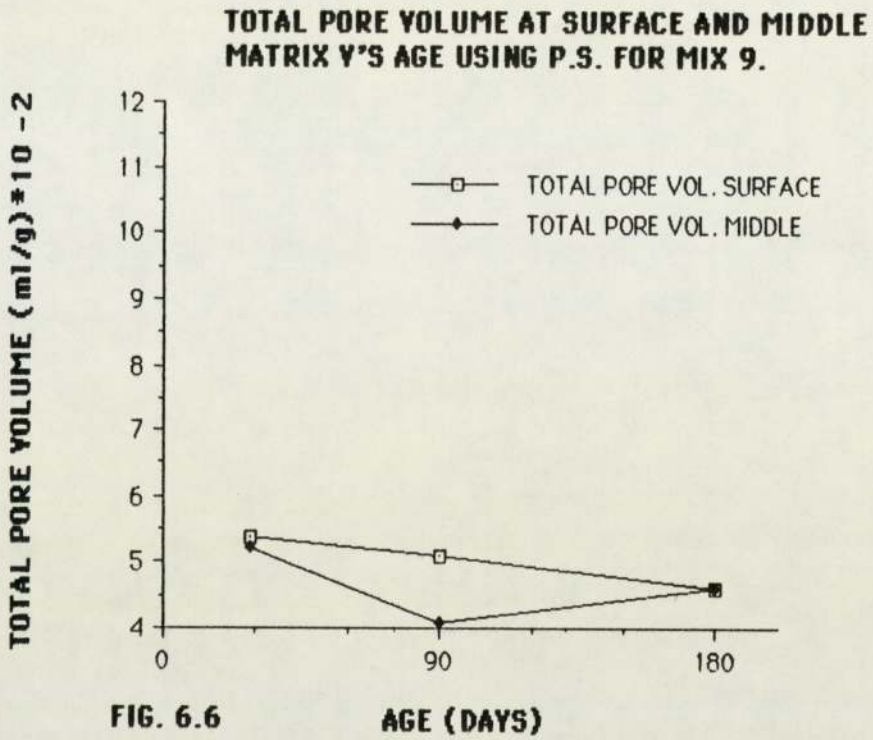

TOTAL PORE VOLUME AT SURFACE AND MIDDLE
MATRIX Y'S AGE USING P.S. FOR MIX 9.
TOTAL PORE VOLUME (ml/g)*10 -2
12
11
10
9
8
7
6
5
4
0
90
180
TOTAL PORE VOL. SURFACE
TOTAL PORE VOL. MIDDLE
AGE (DAYS)

FIG. 6.6

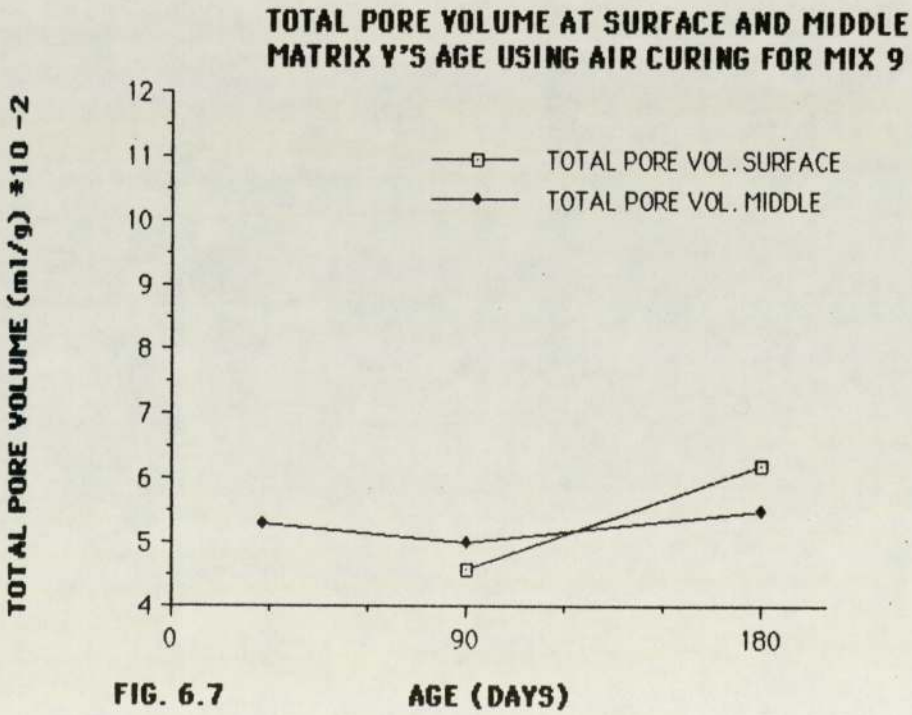

TOTAL PORE VOLUME AT SURFACE AND MIDDLE
MATRIX Y'S AGE USING AIR CURING FOR MIX 9
TOTAL PORE VOLUME (ml/g) *10 -2
12
11
10
9
8
7
6
5
4
0
90
180
TOTAL PORE VOL. SURFACE
TOTAL PORE VOL. MIDDLE
AGE (DAYS)

FIG. 6.7

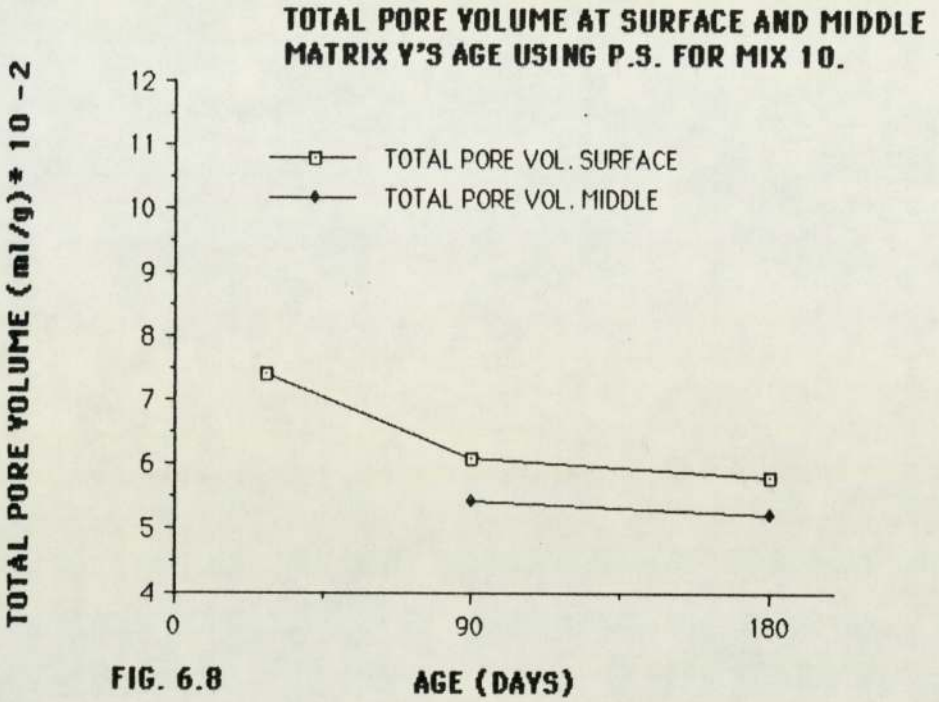

TOTAL PORE VOLUME AT SURFACE AND MIDDLE MATRIX Y'S AGE USING P.S. FOR MIX 10.
TOTAL PORE VOLUME (ml/g)* 10 -2
12
11
10
9
8
7
6
5
4
TOTAL PORE VOL. SURFACE
TOTAL PORE VOL. MIDDLE
0
90
180
AGE (DAYS)

FIG. 6.8

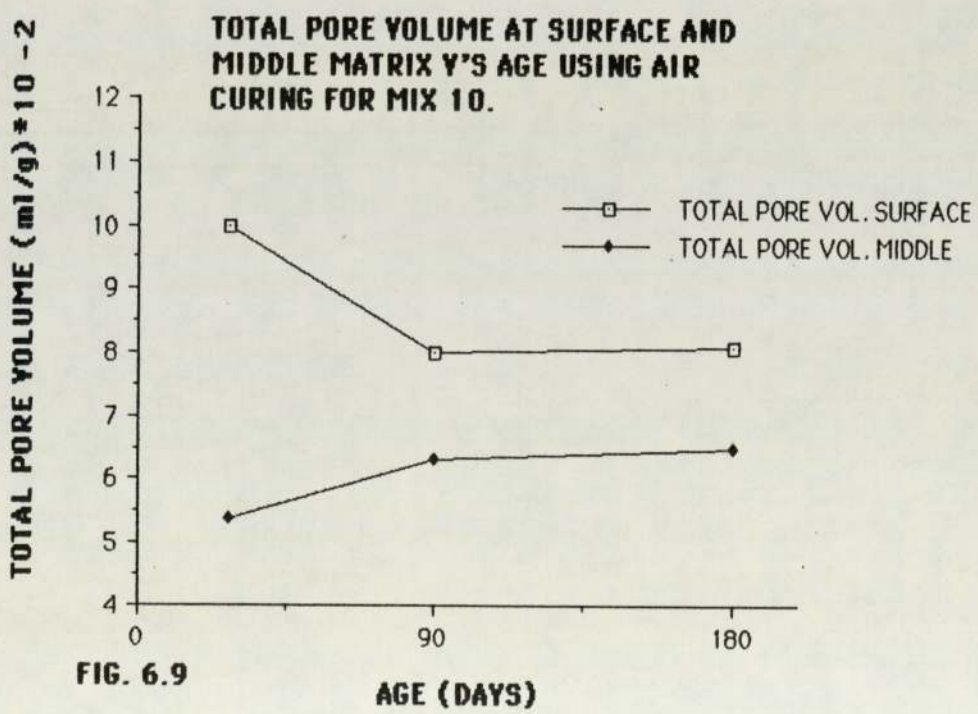

TOTAL PORE VOLUME AT SURFACE AND MIDDLE MATRIX Y'S AGE USING AIR CURING FOR MIX 10.
TOTAL PORE VOLUME (ml/g)*10 -2
12
11
10
9
8
7
6
5
4
TOTAL PORE VOL. SURFACE
TOTAL PORE VOL. MIDDLE
0
90
180
AGE (DAYS)

FIG. 6.9

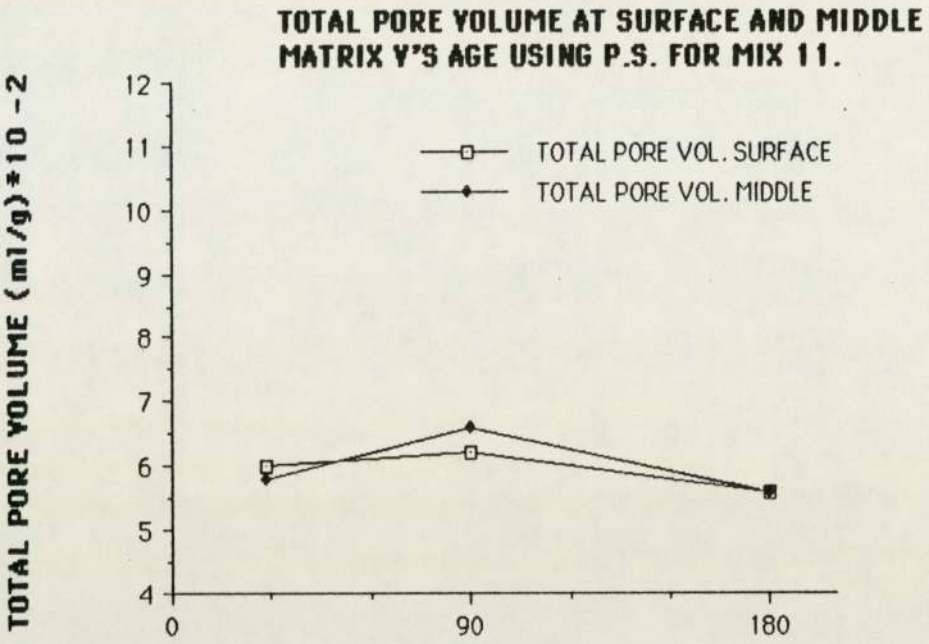


FIG. 6.10

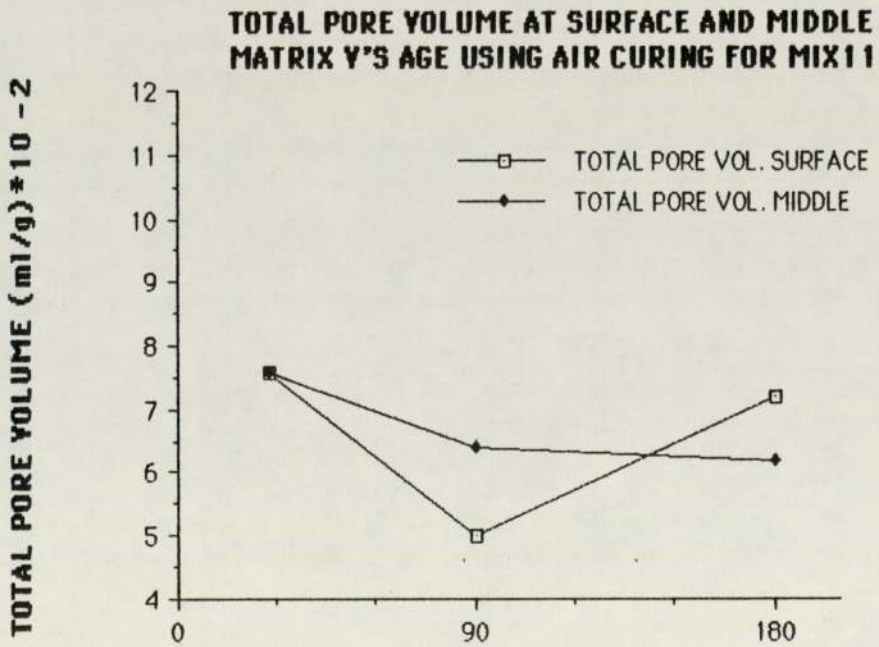


FIG. 6.11

The PSD is a function of the degree of hydration (83) so that variations in the PSD curves can be attributed to the different curing regimes. The total pore volume is given in Table 6.1 for the surface and middle matrix at 28, 90 and 180 days.

These results are plotted in figures 6.4 to 6.11 and show that the porosity is reduced as the hydration of PFA continues from 28 days to 180 days. The hydrated cementitious material formed by the reaction of PFA with $Ca(OH)_2$ fills the capillary structure within the concrete reducing porosity and modifying the P.S.D. If curing is inadequate the water loss from PFA concrete may be rapid, particularly at high levels of PFA (40%) resulting in cessation of hydration leading to increased porosity and lower durability, compared to well-cured concrete.

6.3 MICROHARDNESS TECHNIQUE

This method of investigation was included in the programme, as it was considered that abrasion resistance would be influenced by hardness, since both parameters indicate the resistance to wear. The technique has been used by many investigators both for the study of metals (51) (78) and non metabolic materials (13) (55) (73). The general approach has been to relate microhardness to

various physical properties of the individual materials. In particular, the microhardness of cement paste has been shown to correlate with the strength, the elastic modulus and porosity of hydrated cement. Other investigators (79) (77) have been able to correlate the microhardness with the wear resistance of the aggregates.

In the test a diamond indenter is depressed, under a given load, into the surface of the test material. The size of the resulting indentation is measured and the microhardness is expressed as the ratio of the load to the superficial area of the impression in Kg/mm^2. The particular equipment employed in this investigation was a Vickers M12 microhardness tester, which consisted of a square based pyramid of diamond, the included angle between opposite faces being 136^o. The shape of a perfect Vickers' impression would be that of a square and the superficial area of four faces of the impression being $\frac{d^2}{2}$ sin 68 where

d is the indentation diagonal of the square in microns.

Hardness H = Load/Area.

Vickers microhardness number Hv,

$$Hv = \frac{\sin 68^o \, P}{\frac{d^2}{2}}$$

Where P is the applied load in gm.

The indentation diagonal is measured by means of an

optical system provided within the microhardness instrument. Standard tables, prepared by the manufacturers are used to determine the Vicker's microhardness number.

PFA concrete may be considered as porous and heterogeneous and so the microstructure involves a wide range of particle sizes and pore sizes. Thus, for the microhardness measurement to be representative, it must include a representative number of particles and pores.

Earlier studies (37) have concluded that the error in microhardness values was considerably reduced as the number of indentations was increased. This study indicated that the optimum number of impressions is ten for a non-porous material and so, for each test location, a minimum of thirteen impressions was used to allow for wrong values due to tests performed entirely on embedded aggregate particles. It was, considered that this procedure would provide a reasonably complete range of microhardness values for the location under investigation.

6.3.1 Specimens under investigation

The results of the MIP analysis clearly indicated that the curing regime influenced the PSD of the PFA concrete. It was considered therefore that

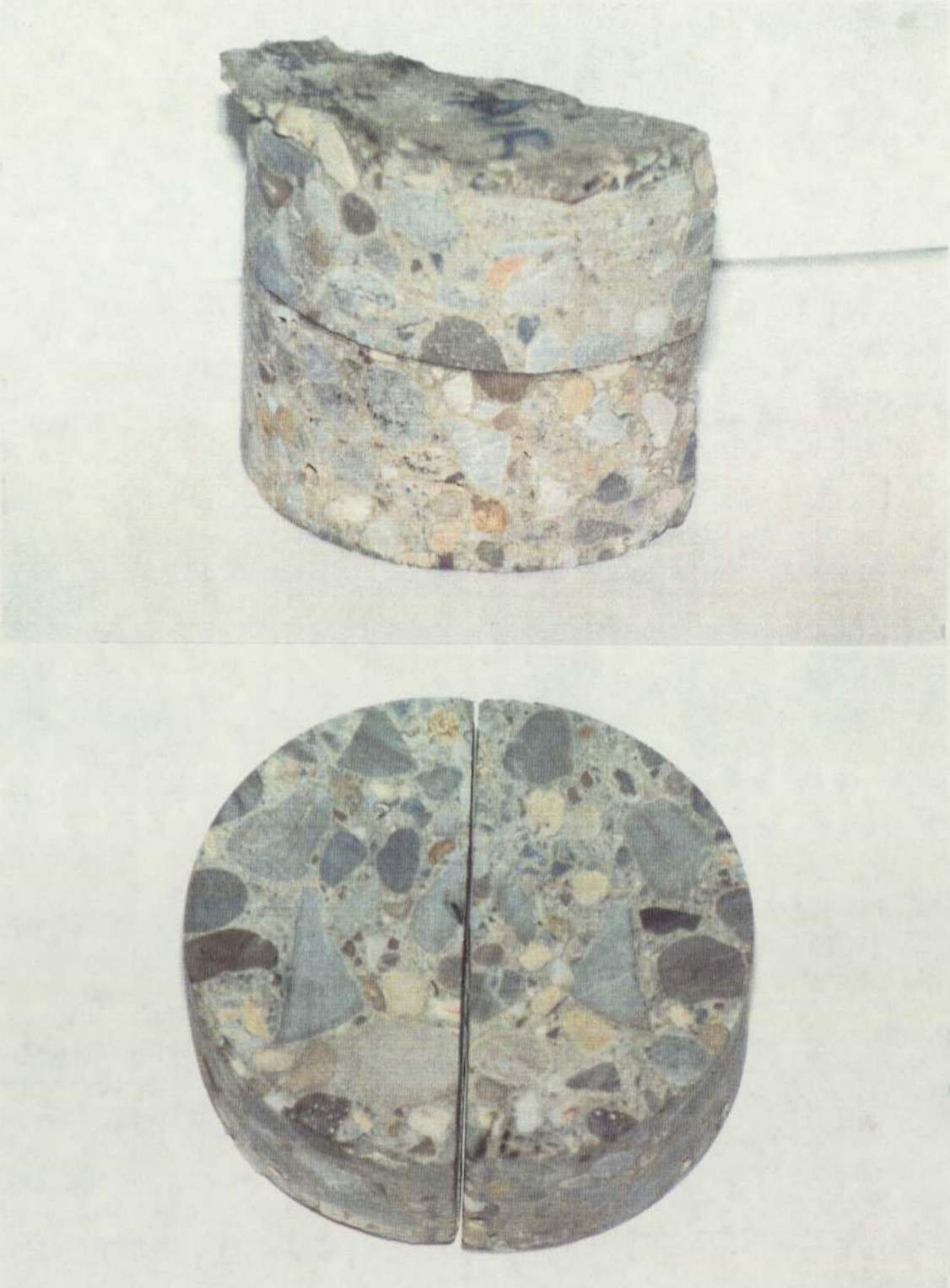


PLATE 6.1 A CONCRETE CORE OF 10MM DIAMETER AND 100MM DEPTH CUT VERTICALLY AND HORIZONTALLY IN THE MIDDLE AS SHOWN

microhardness profiles, from the surface matrix into the core of the concrete specimens, could provide further insight into the mechanism by which the individual curing regimes, PFA content and age influenced the abrasion resistance. A detailed study was therefore undertaken of the microhardness profiles.

Samples were taken from four concrete mixes 8, 9, 10 and 11 all of which had been cured by either plastic sheeting or air. Two core samples, shown in, plate 6.1 were taken from each slab to produce a total of 16 samples to be investigated at 180 days to establish the microhardness at the surface and middle matrix.

To determine the microhardness profiles, indentation readings were recorded at 13 locations below the surface of the samples and three areas were examined in each sample, the top area, middle and bottom with a total of 39 locations for the surface matrix and another 39 locations for the middle matrix. The layout of these test locations is shown in Figure 6.12

6.3.2 Experimental Procedures

The 100mm diameter cores taken from the MIP investigation also provided the samples for this

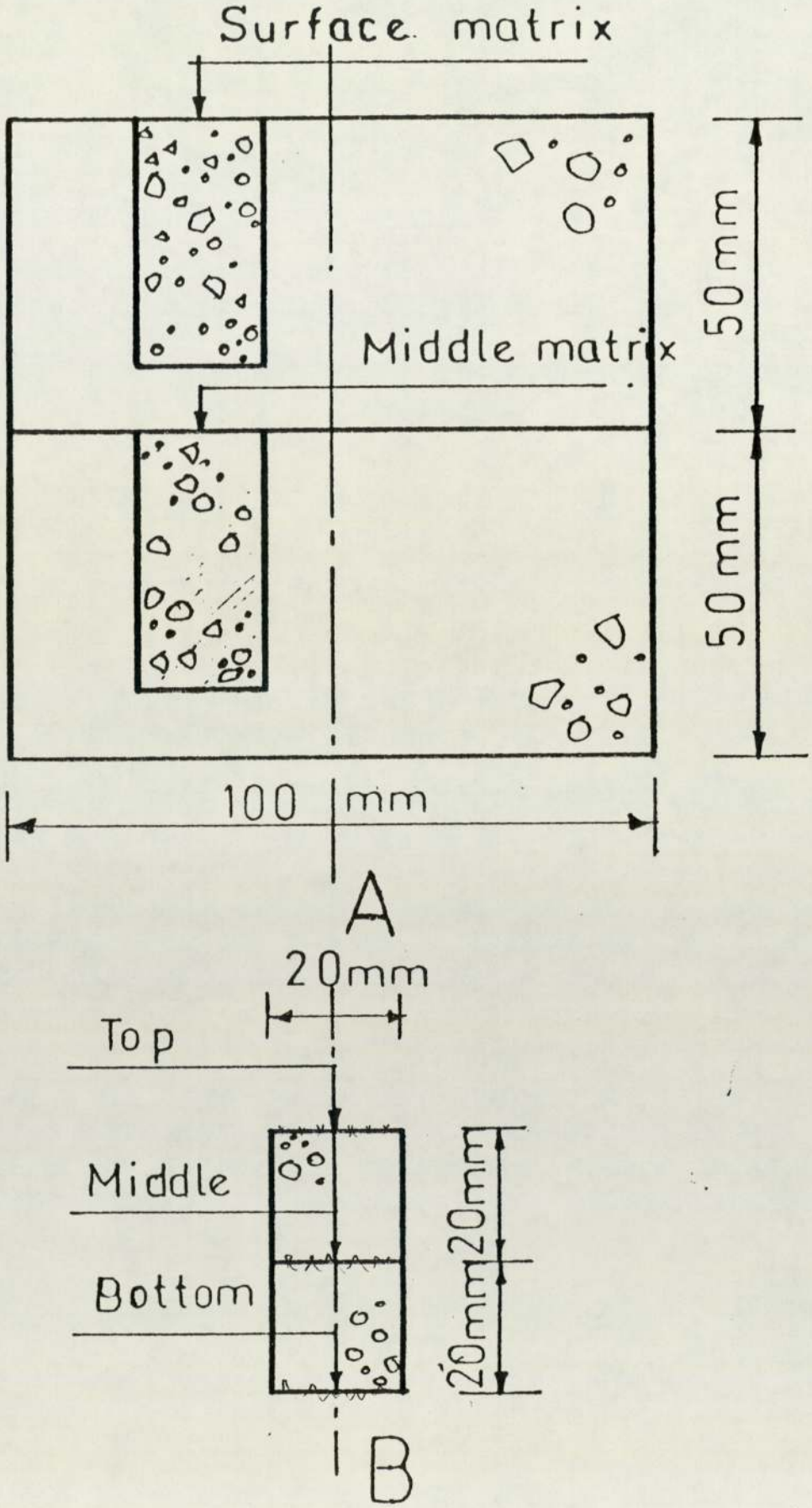


FIGURE 6.12 SECTIONS OF MICROHARDNESS SPECIMENS
(A) CONCRETE CORE SHOWING SURFACE AND MIDDLE MATRIX
(B) MICROHARDNESS SPECIMEN

PLATE 6.2 (a) SURFACE AND MIDDLE MATRIX OF THE CORE

(b) MICROHARDNESS SPECIMENS 20 X 40 X 5MM ATTACHED TO A GLASS PLATE

study. Two samples were cut, using a diamond cutting wheel from each core. Each sample was cut from different locations in the core, these being selected on the basis that they should contain a minimum of exposed aggregate area. These samples were cut parallel to core axis from the top 20mm section of the core. The face area of each sample as approximately 20mm by 40mm and they were 5mm thick.

Each sample was gold plated so the microstructure of the surface layers remain unaltered and then attached to a glass plate to permit for testing, as is illustrated in the Plate 6.2. The mounted specimen was placed on a graduated moveable stage so that, when the stage was moved in the x direction under the objective, the surface moved in parallel with the objective. Two micrometer screws, at right angles to each other, allowed a network pattern of impressions to be conducted.

At each test location across the exposed face thirteen readings were recorded, these being distributed across the width of the sample of the same level. The position of each indentation was selected on the basis that it should not be over an aggregate particle. Initially, the low-power objective was used to select the approximate test

position, with the high-power objective subsequently being used to select the precise point for indentation.

An appropriate load was selected within the range of 50 grams to 200 grams. Small loads produced small indentations with which large optical measuring errors may occur leading to large errors in the microhardness value. The load was, therefore, selected to produce an identation with a minimum diagonal of 100μm. The period of identation was kept constant in all tests, at 15 seconds, for it has been reported (128) that there is a gradual increase in the size of indentation with time. The lengths of the diagonals of the impression were accurately measured, twice, using the optical micrometer eyepiece and the high-power objective. The accuracy of this procedure is ± 1μm.

The readings at the surface level, 0.00mm, were in fact taken 4μm below the surface. This was to ensure that diagonals of the impression were wholly within the sample, and any which were partly located outside the test sample were rejected. The impressions were not made adjacent to any visible voids, and were kept at least 5 diagonal lengths apart to prevent mutual interference. Any impression which developed signs of cracking or

fracturing was rejected for measurement purposes. In a perfectly plastic material the Vicker's indentation should, theoretically, be a perfect square

The three highest readings were rejected, on the assumption that they were probably taken on aggregate particles which had not been detected. The mean Vicker's hardness value for any particular level was, therefore, the average value obtained from the remaining ten indentations, as recommended in earlier studies (49).

6.3.3 Results and Discussion

The microhardness measurements of porous materials have been found by Sereda (73) to provide meaningful information on the mechanical behaviour of the material. Indeed these measurements are as significant for porous material as they are for non-porous materials. It is, therefore, useful to investigate whether links can be found between the microhardness and the abrasion resistance of PFA concrete.

The microhardness profiles for the four mixes that were tested Mix 8 - 11, are shown in Figures 6.13 - 6.28 with data given for both curing regimes,

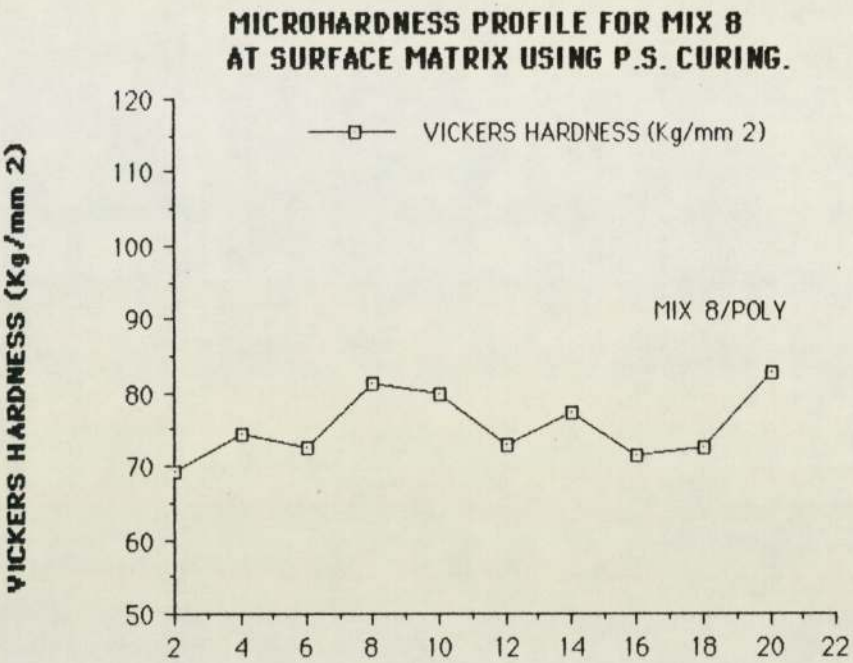


FIG. 6.13

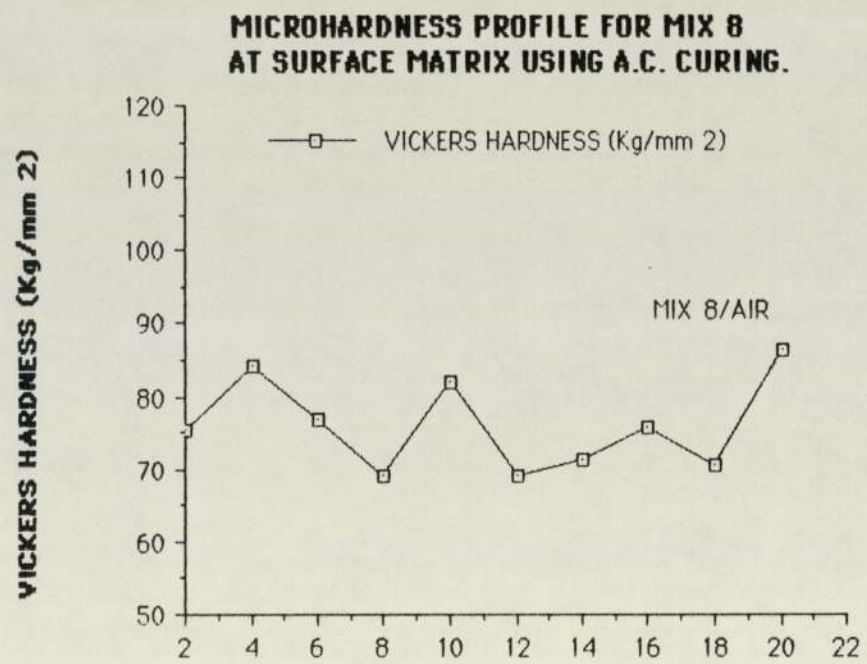


FIG. 6.14

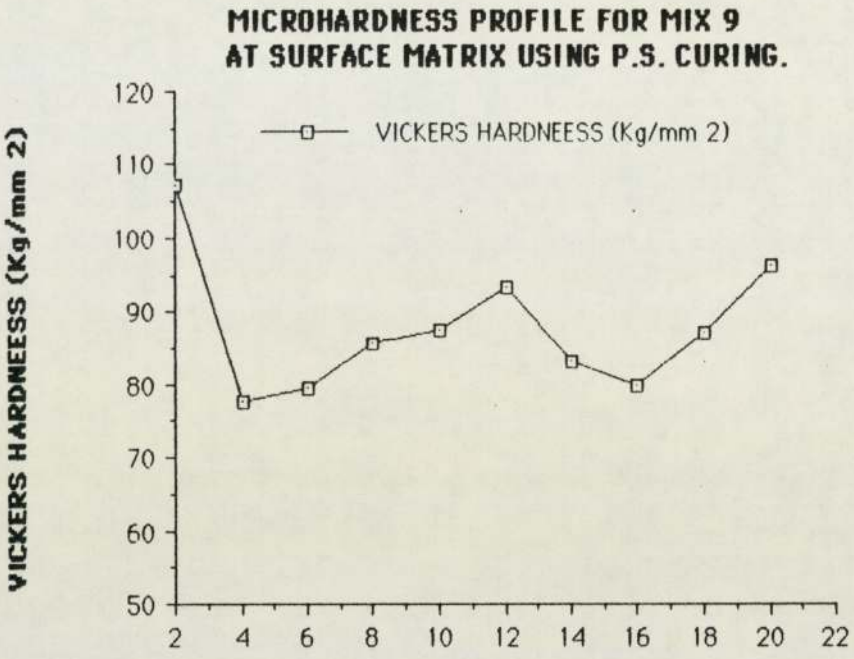


FIG. 6.15

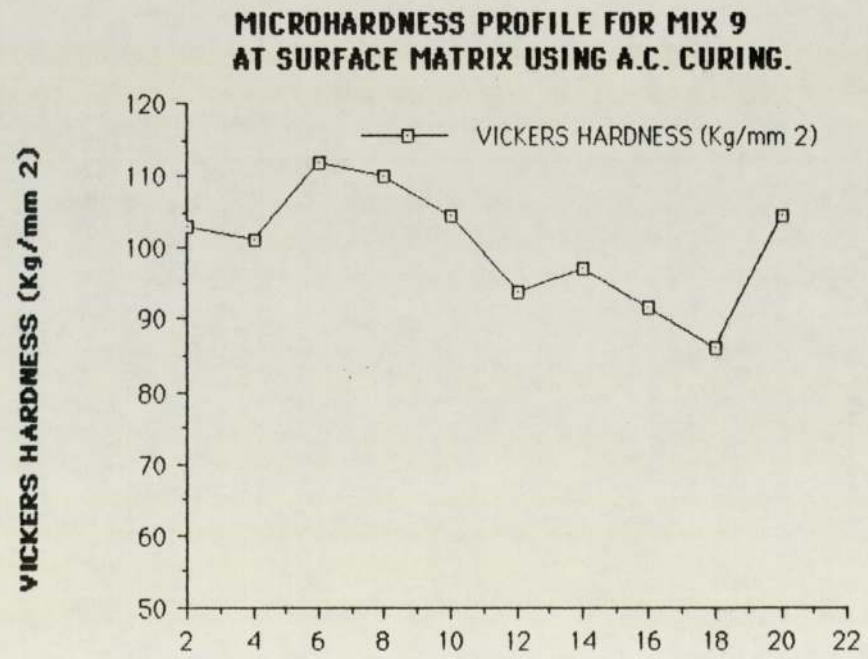


FIG. 6.16

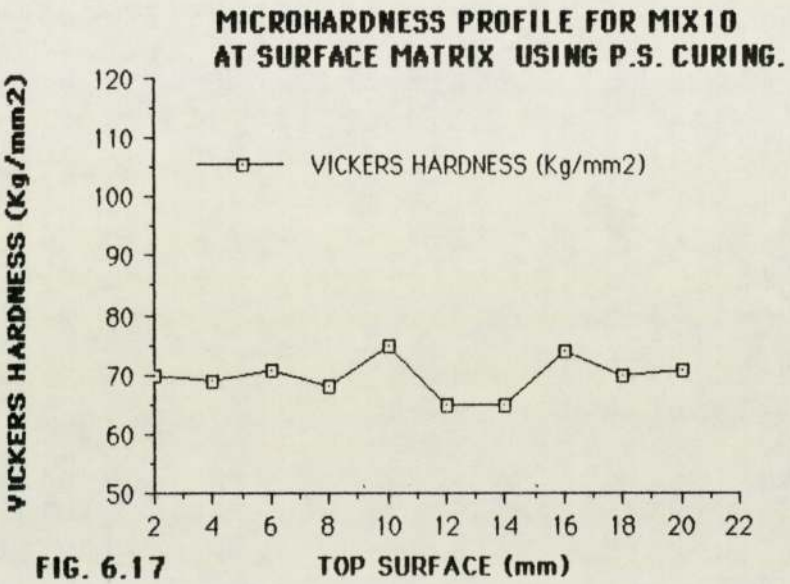


FIG. 6.17

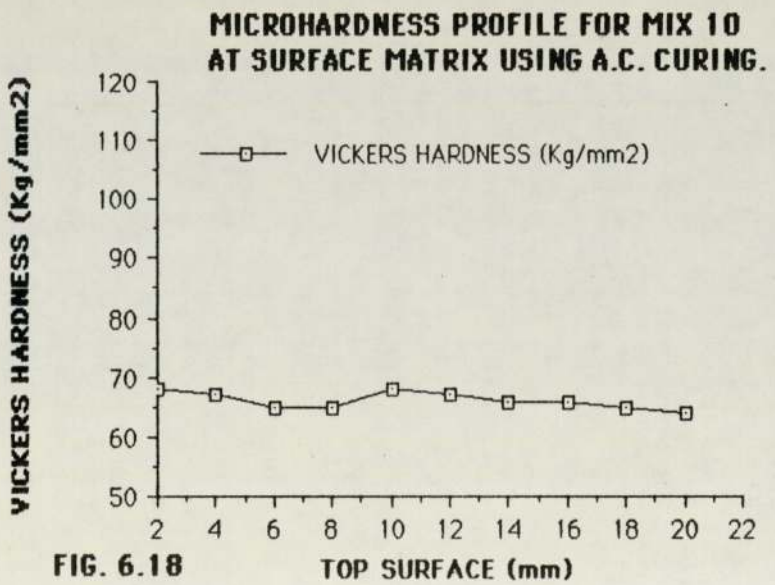


FIG. 6.18

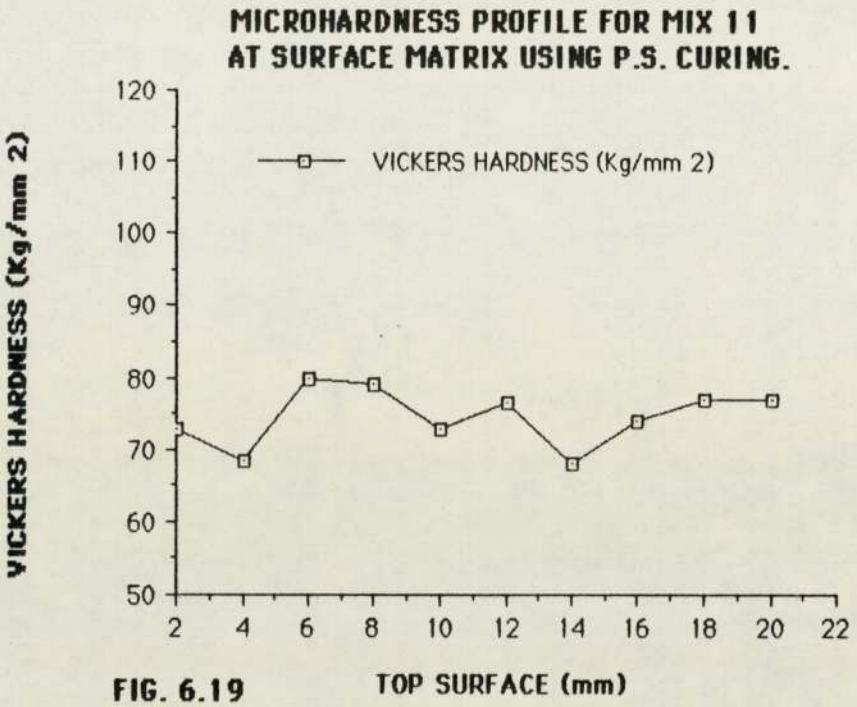


FIG. 6.19

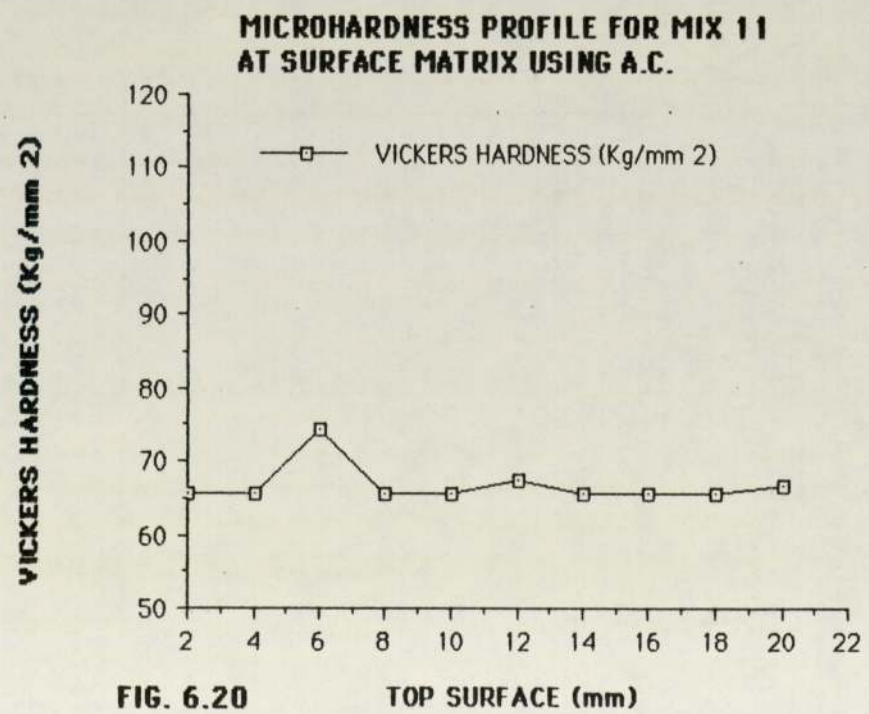


FIG. 6.20

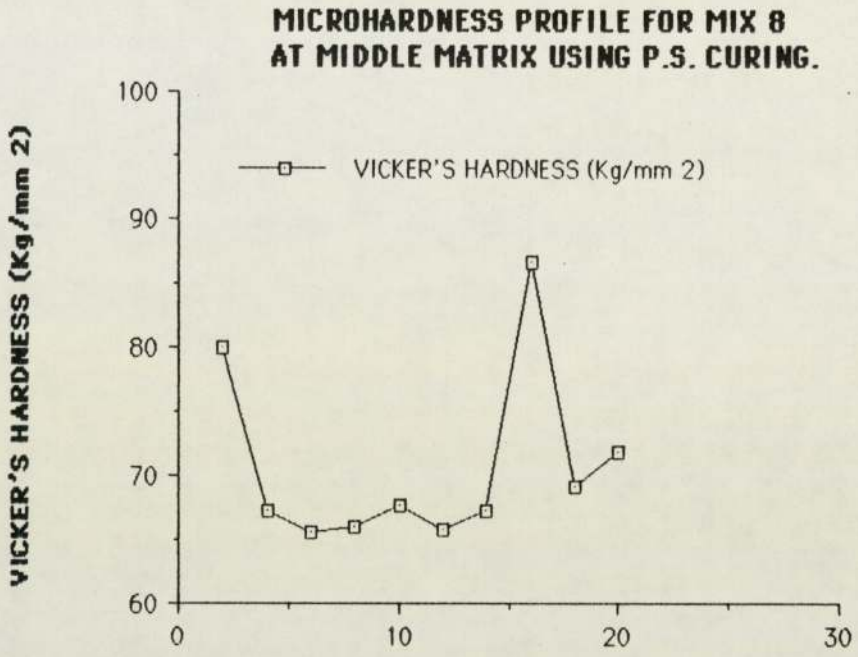


FIG. 6.21

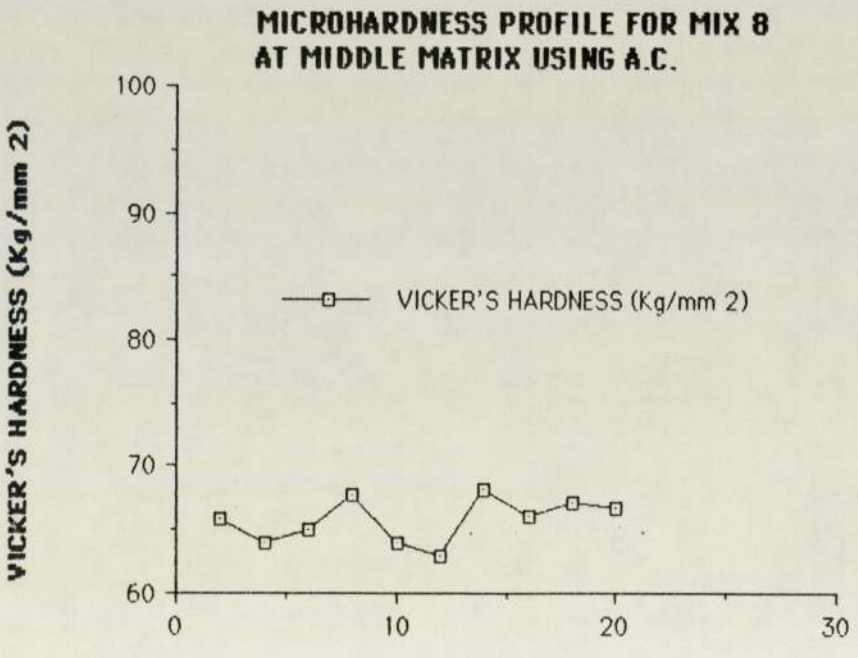


FIG. 6.22

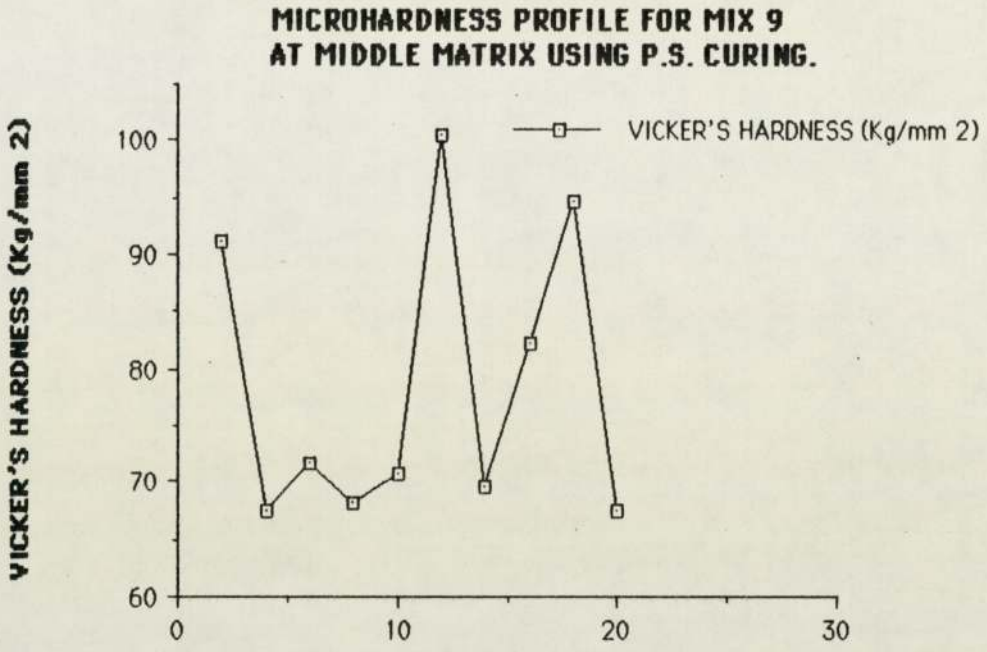


FIG. 6.23

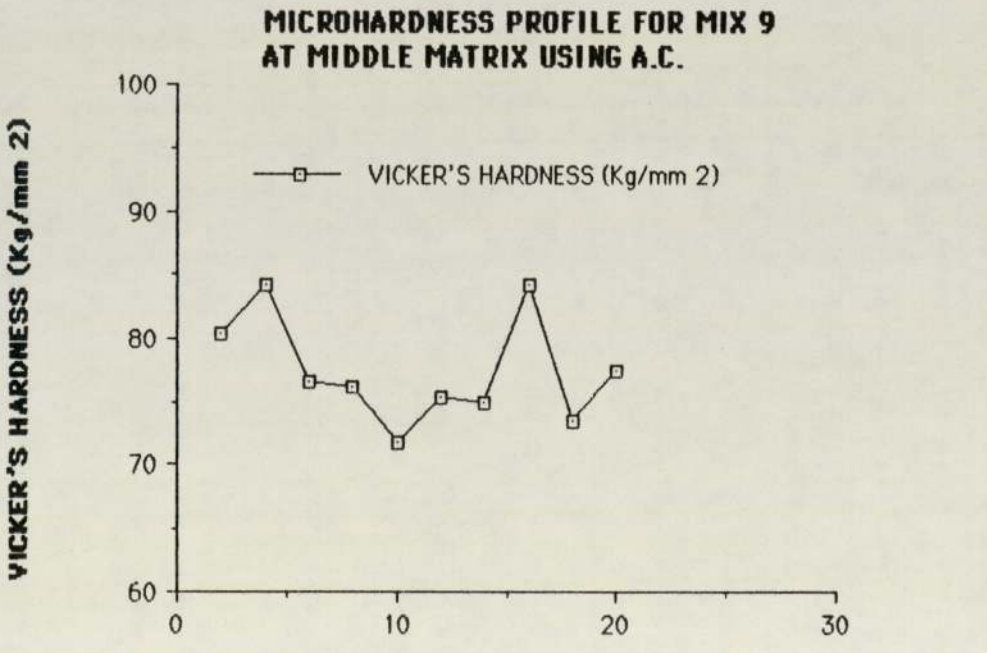


FIG. 6.24

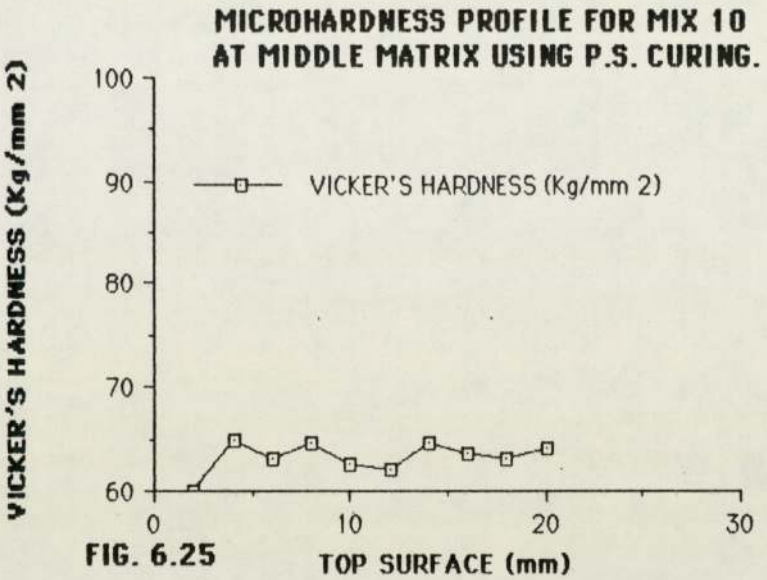


FIG. 6.25

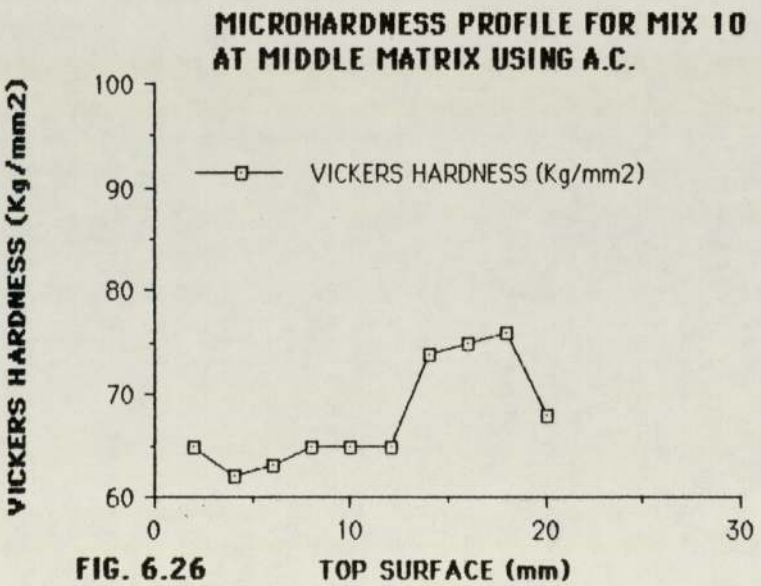


FIG. 6.26

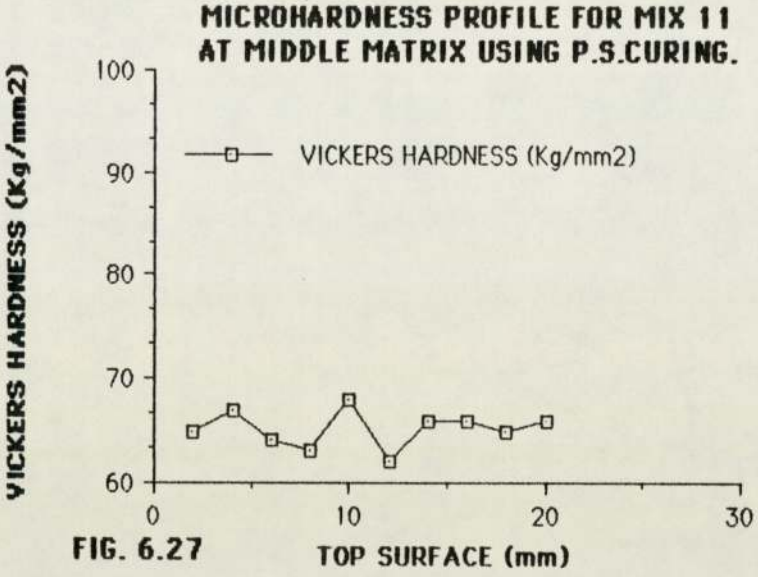


FIG. 6.27

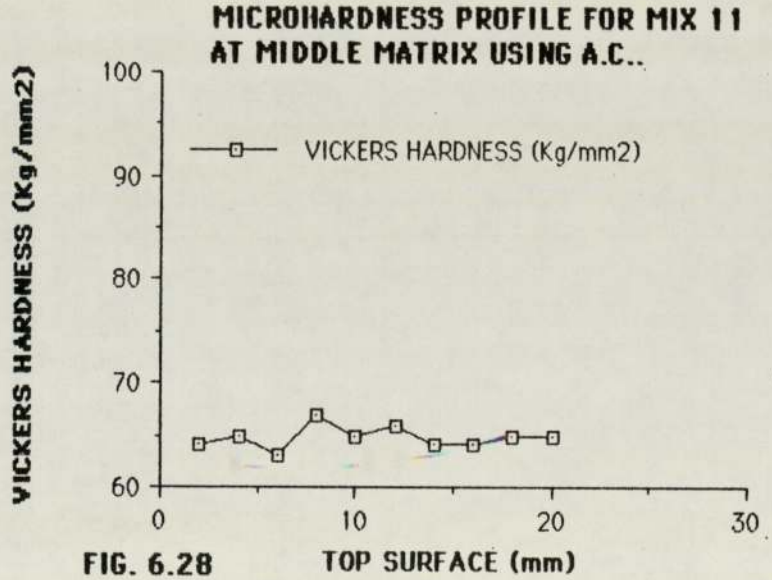


FIG. 6.28

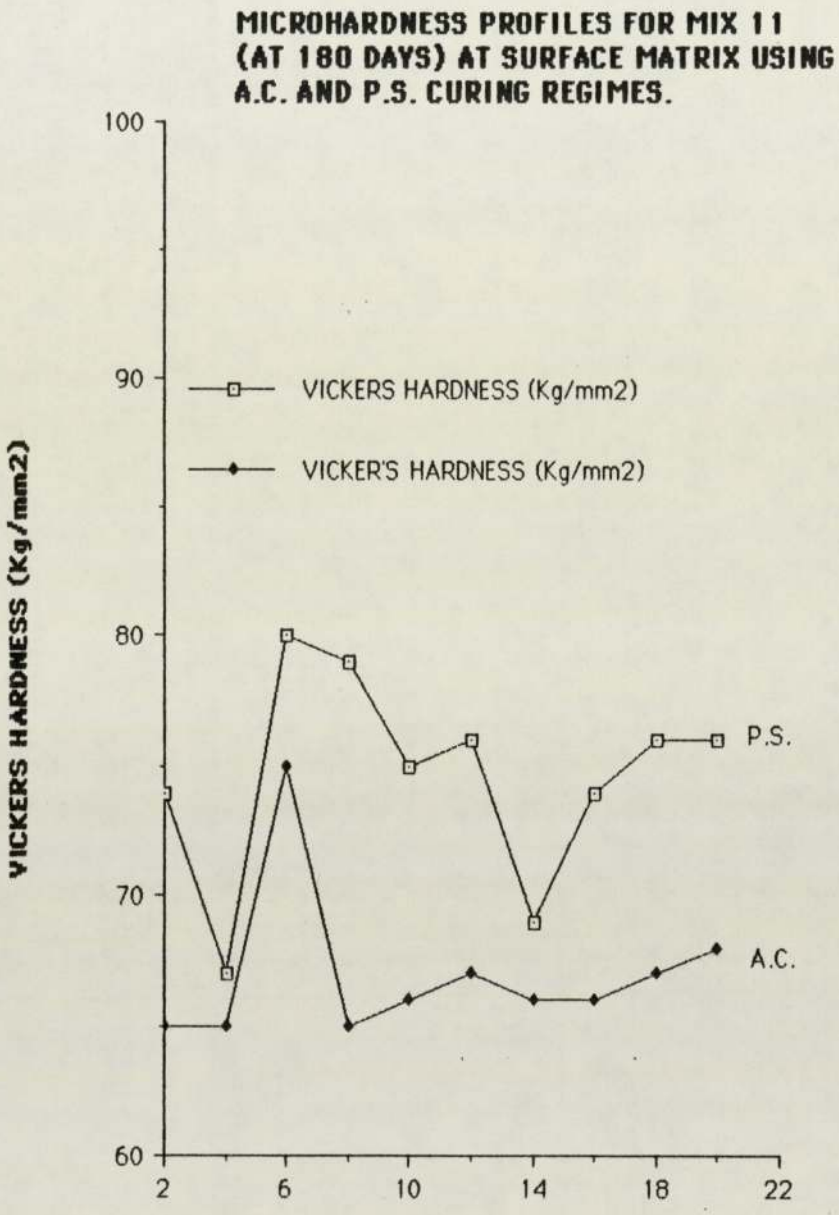

MICROHARDNESS PROFILES FOR MIX 11
(AT 180 DAYS) AT SURFACE MATRIX USING
A.C. AND P.S. CURING REGIMES.
VICKERS HARDNESS (Kg/mm2)
VICKERS HARDNESS (Kg/mm2)
VICKER'S HARDNESS (Kg/mm2)
P.S.
A.C.
100
90
80
70
60
2
6
10
14
18
22
TOP SURFACE (mm)

FIG. 6.29

Polythene and air at the surface and middle matrix. A summary of these profiles for the surface and middle matrix and the two different curing regimes have been plotted to permit comparisons. Data of these microhardness profiles are given in Appendix L. Of particular interest is that these microhardness profiles provide information on the hardness throughout the surface layer, to a depth of 16mm, which may be used to assess the effectiveness of the curing regimes and the influence of PFA in terms of thickness of the affected zone.

From an examination of these hardness profiles several important trends are apparent:-

(1) The hardness values from mix 9 are higher than those from the three other mixes, and so indicate that the hardness increases with the compressive strength of the PFA concrete.

(2) The hardness profiles clearly demonstrate that the P.S. curing regime was able to increase the hardness of the surface matrix for all the PFA concrete mixes. Results for Mix 11 at the surface matrix are shown in Figure 6.29.

(3) As mixes 9, 10 and 11 had very similar water/ cementitious ratios, their results plotted in Figure 6.30 indicate
that the hardness decreased with increasing PFA content in the concrete.

MICROHARDNESS AT 180 DAYS FOR MIXES 8,9,10 AND 11 (WITH W/C OF 0.44, 0.50, 0.46 AND 0.51) AGAINST PFA CONTENT (%) USING A.C. AND P.S. CURING REGIMES.

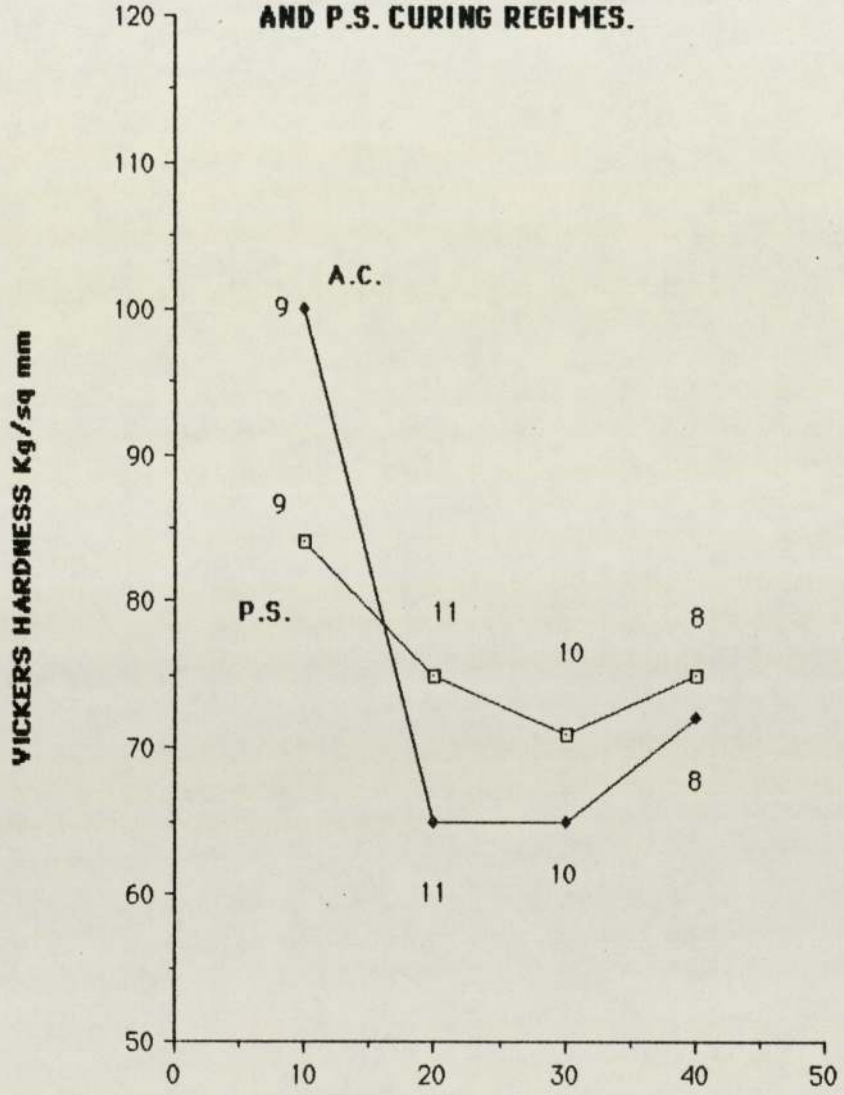


FIG. 6.30 PFA CONTENT (%)

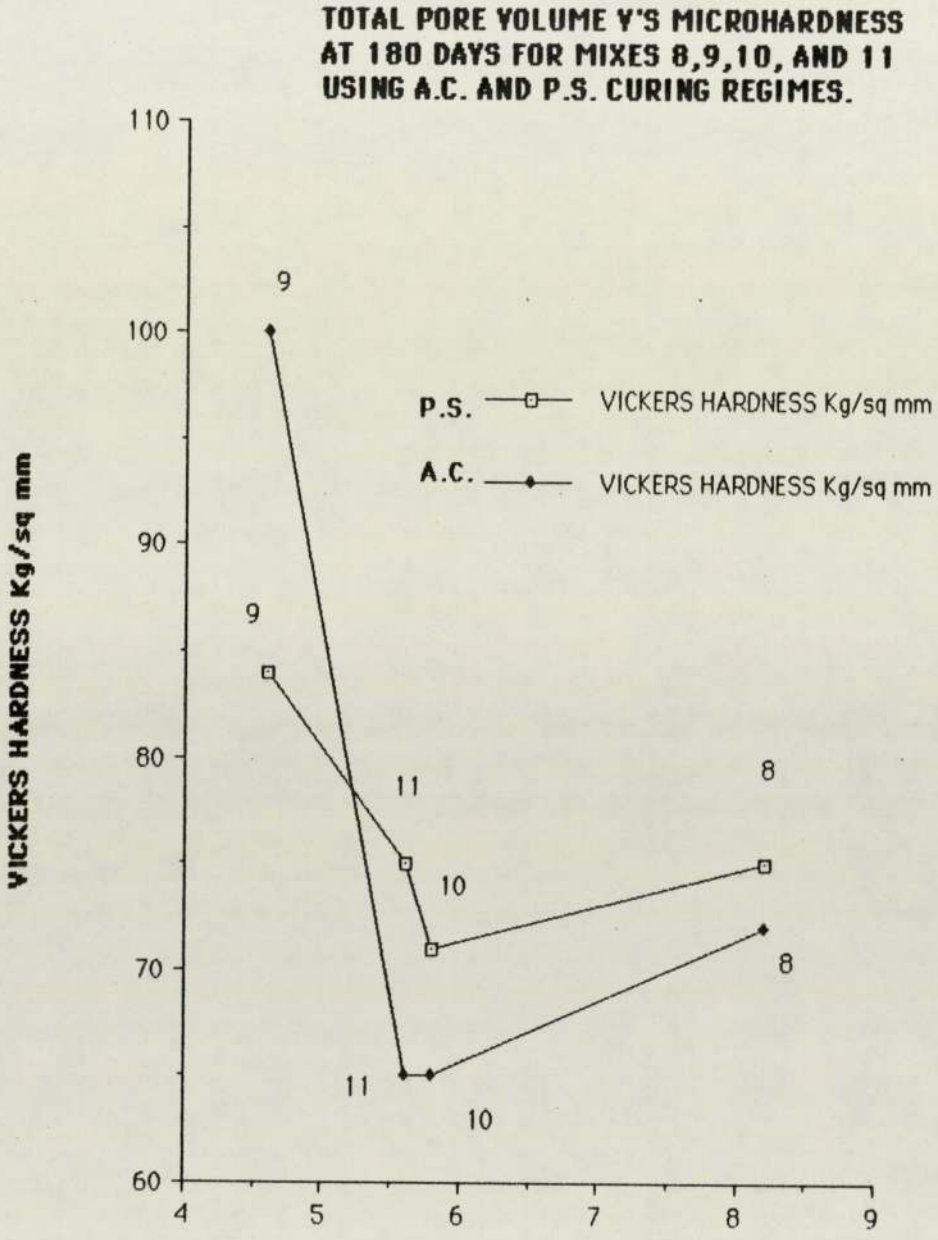

TOTAL PORE VOLUME V'S MICROHARDNESS
AT 180 DAYS FOR MIXES 8,9,10, AND 11
USING A.C. AND P.S. CURING REGIMES.
VICKERS HARDNESS Kg/sq mm
110
100
90
80
70
60
4
5
6
7
8
9
P.S. VICKERS HARDNESS Kg/sq mm
A.C. VICKERS HARDNESS Kg/sq mm
9
9
11
10
8
8
11
10
TOTAL PORE VOLUME (ml/g)•10 -2

FIG. 6.31

6.5 RESULTS OF MICROHARDNESS AND ABRASION DEPTH AT 180 DAYS

Mix No.	w/c/pfa %	Curing	Depth of Abrasion (mm) at 15 min	Vickers Hardness Kg/sq mm					
				Top			Middle		
				0mm	mm	mm	50mm	mm	mm
Mix 8	0.44/40	P.S.	0.30	75	67	64	69	65	67
		A.C.	0.60	72	68	64	65	65	66
Mix 9	0.50/10	P.S.	0.32	84	79	75	77	78	75
		A.C.	0.40	100	86	83	77	77	74
Mix 10	0.46/30	P.S.	0.30	71	65	65	64	64	64
		A.C.	0.80	65	65	65	67	67	65
Mix 11	0.51/20	P.S.	0.30	75	70	69	65	65	64
		A.C.	0.60	65	64	64	64	64	64

(4) Analysis of the results from all four mixes indicates that the hardness values are inversely related to the total pore volume. This is shown in Figure 6.31 for both curing regimes and it can be seen that this behaviour was clearly demonstrated with the polytehene cured samples than with those subjected to air curing.

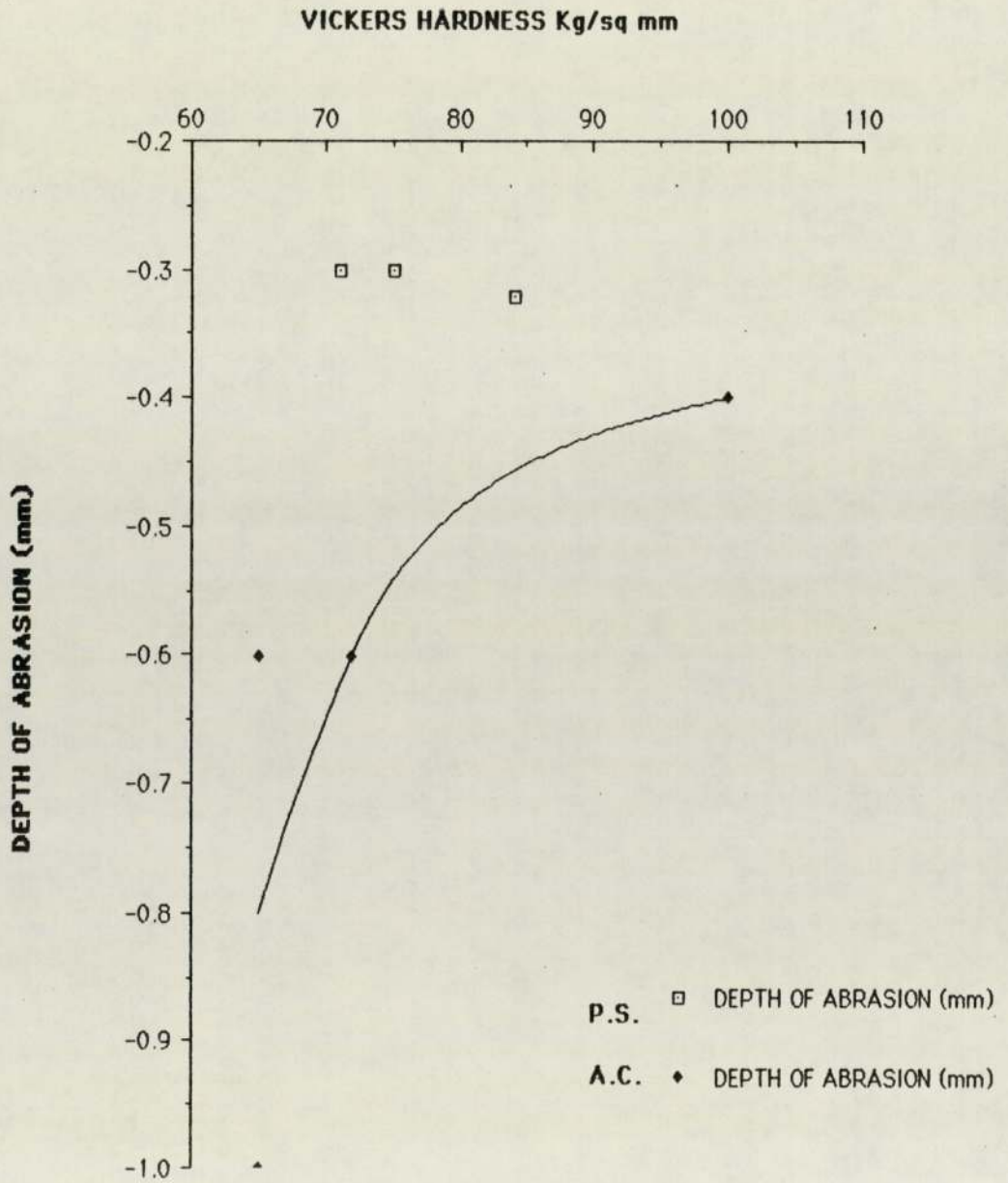
(5) All the specimens of the surface matrix, exhibited their greatest hardness at the top of with hardness being lower both below the top surface and in the middle of the slab and this can be attributed (65) to the power finishing techniques used for the manufacture of all the test slabs.

By comparing the microhardness and the rate of abrasion, as shown in Table 6.5, it is clear that the abrasion resistance is closely related to the hardness of the surface layer, some 200-500 microns in thickness.

These results are summarised in Figure 6.32 where the abrasion depth obtained with the two different curing regimes are plotted against the microhardness values at the surface of each slab. This graph indicated that abrasion resistance is directly related to microhardness of the sample. A surface matrix with high value of hardness leads to a low rate of abrasion as is demonstrated in the graph. Alternatively, where the

FIG. 6.32

ABRASION DEPTH V'S MICROHARDNESS AT 180 DAYS FOR MIXES 8,9,10 AND11, USING A.C. AND P.S. CURING REGIMES.



immediate surface had a low value of hardness, then a high rate of abrasion resulted as was the case with mix 10 subjected to air curing. Once this immediate surface matrix had been penetrated the sample has effectively failed so far as abrasion resistance is concerned, therefore, the main objective in increasing the abrasion resistance of concrete must be to reinforce this top surface matrix which is some 0.5mm in thickness.

It has been found (41) that the microhardness indentation of a non-porous material produces a plastic deformation which has been observed as a barrel-shaped indentation due to the accumulation of debris at the centre of the pyramidal faces. In the case of a porous material this accumulation is not observed, since the disturbed material can be accommodated by the pores (73). For a given porous material the strength is a function of porosity (58) and so a reduction in porosity should produce an increase in the hardness value. On this basis it is suggested that the hardness profiles are consistent with the results of the MIP tests. This is further supported by the relationship shown in Figure 6.32 where the total pore volumes for mixes the four are plotted against the corresponding microhardness values at the surface matrix. The graph shows a direct relationship between porosity and microhardness. This finding is consistent with the conclusion reached by other investigators (76) linking the microhardness and porosity of cement pastes.

The results of the abrasion tests clearly showed that the rate of abrasion was dependent on the curing regime and PFA content for the same water/cementitious ratio. Both MIP and microhardness tests have demonstrated that the individual curing regimes produced significant changes in the quality of the surface matrix of the slab. The MIP results showed that the PSDs were modified by these curing regimes, so that effective curing toughened the surface layer leading to improved abrasion resistance.

The microhardness results also showed that the hardness depended on the PFA content and strength of PFA concrete and these factors also influenced the concrete immediately below the surface layer. This further confirms that the different factors, PFA content, age and curing regime resulted in the production of surface layers with a range of porosity and hardness values. It is suggested that the abrasion resistance of concrete is primarily controlled by the quality of the surface layer, as demonstrated by porosity and microhardness. The microhardness tests were carried out 180 days after the slabs were cast. Unfortunately external factors prevented intermediate testing, at 28 and 90 days, but, since age is an important factor in the performance of PFA concrete, it was considered that 180 day data would be of value to the study. Clearly in future work it would be important to supplement the present data by undertaking microhardness tests on PFA concrete different ages.

CHAPTER SEVEN

GENERAL DISCUSSION

7.1 INTRODUCTION

The long term performance of concrete floors depends on the abrasion resistance of the surface layer. From the data given in the previous two chapters, four main factors have been identified as having considerable influence on the abrasion resistance of concrete containing PFA, primarily due to their effects on the hardness of the surface mortar layer.

These are as follows:-

1) PFA percentage replacement (Fig. 5.7, 5.8 and Fig. 6.30)
2) Water cementitious ratios (His. 5.21 - 5.23)
3) Age (His 5.15 - 5.18)
4) Curing regime (Fig. 5.11 - 5.14)

The quality of the PFA concrete has a major influence on the quality of the surface mortar layer both directly and indirectly as shown in chapters 5 and 6. A factor that should always be considered throughout this research work is the durability of concrete. Potential concrete quality has most commonly been assessed by measuring the compressive or cube strengths and in many past research studies (75) (2) (71) (69) (45) it has been possible to establish a clear correlation between strength and abrasion resistance. With mixes containing PFA the compressive strength is related to the mix design

in terms of the cement/PFA content and the overall water/cementitious ratio. A major constituent of the mortar is the cement and PFA replacement and this type of binder used will have both direct influence on the quality of the mortar and an indirect influence on its tolerance to the curing regime imposed. Therefore the actual quality of the surface concrete has many facets which will influence the abrasion resistance.

The detailed experimental results have been presented in chapters 5 and 6 and the ensuing general discussion is presented in the following paragraphs.

7.2 MACROSTUDY OF ABRASION RESISTANCE WITH PFA

The contribution of PFA percentage replacement to the strength of concrete is a factor that should be considered. In this laboratory work it has been shown that the compressive strength results of mixes containing PFA are influenced by several related factors, with the following trends clearly identified:

a) The higher the PFA percentage, the lower the strengths for a given water/cementitious ratio Figure 5.6.

b) The higher the water cementitious materials ratio, the lower the abrasion resistance (Histograms 5.21 - 5.23). Neither of these findings creates surprises. The contribution of PFA to the quality

of concrete is not a constant value determined solely by the physical and chemical characteristics of PFA but rather it can vary depending on the prevailing circumstances, such as the water cementitious ratio, curing regime and age. Three properties of PFA are mainly responsible for its effects:

a) Ability to combine with free lime (pozzolanic activity)
b) Rounded particle shape
c) Reduced water demand

PFA combines with the free lime released during hydration of Portland cement to form additional cementitious compounds, which would be expected to increase the abrasion resistance. Further benefits accrue from the rounded shape of the PFA particles which can improve the workability of concrete primarily by reducing the demand for water, as compared to plain concrete, at a constant workability. This reduced water content can also help to avoid segregation and bleeding in fresh concrete.

Age is another important factor which should be considered in the abrasion resistance of PFA concrete. As shown in Histograms 5.15, 5.16, 5.17. 5.18 the abrasion depth decreases as the age of PFA concrete increases this is due to the fact that PFA takes longer time to develop its strength and long-term durability

than an OPC concrete Pozolanicity is indicated by how far and how fast the silica in fly ash will combine with calcium hydroxide released by the hydration of Portland cement (27). Fly ash has a slower rate of reaction than most natural pozzolanas and does not contribute significantly to the short-term strength, but at a later stage the abrasion resistance increased with age (Figures 5.11 - 5.14).

To obtain abrasion resistance similar to OPC concretes, PFA concretes should have equivalent strength grade but may need to be cured for longer periods. It is reasonable to assume that the slower the rate of reaction the longer the curing period required to ensure that the potential properties are achieved; hence PFA concretes would be expected to need longer curing periods where durability is recognised as a potential problem. This is taken into account in BS 8110 (48), which recommends longer periods of curing for PFA concretes.

In these sections the quality of the hardened concrete is highly dependent on the curing regime. The durability of the structure may be severely impaired, if curing is not properly applied. Curing influences the surface matrix of PFA concrete and it is this concrete and which must resist abrasion. Polythene has been shown to produce a better abrasion resistance than air curing The use of

curing compounds was found to be, generally, more effective in increasing abrasion resistance, than the plastic sheeting method of curing. This is due mainly to the longer period of controlled curing provided by the curing compound. A resin based 90% efficiency curing compound used.

To obtain good quality concrete, curing in a suitable environment is essential particularly during the early stages of hardening. The object of curing at normal temperature is to keep concrete (PFA) saturated, or as nearly saturated as possible, until the originally water-filled space in the fresh cementitious paste has been occupied to the desired extent by the products of hydration of cement and PFA. The necessity for curing arises from the fact that hydration of cement can take place only in water-filled capillaries. This is why loss of water by evaporation from the capillaries should be prevented. Plastic sheeting prevents evaporation of water from the PFA concrete. Prolonged curing has been shown to improve the abrasion resistance of PFA concrete. In PFA Portland cement blends, some investigators report evidence of early pozzolanic activity, but it is apparent that its contribution to strength does not occur at early ages.

Another factor to consider is the PFA % replacement for a constant water/cementitious ratio in the abrasion

resistance of concrete. For the proportions used in this laboratory work of 0, 10, 20, 30 and 40% of partial replacement of cement with PFA, it has been shown in Figures 5.6 that the compressive strength decreases as the PFA content replacement increases. The abrasion resistance of PFA concrete is higher at longer periods and, when up to 20% replacement of cement with PFA is used, the PFA concrete exhibited greater abrasion resistance than OPC concrete as shown in Figure 5.7-5.8. The abrasion resistance increases with the compressive strength and this has been demonstrated in Chapter 5 (Figures 5.41 and 5.42). This observation that abrasion resistance is primarily a function of compressive strength is consistent with the results shown in Figures 5.41 and 5.42 for the benefits of extended curing or abrasion performance, and certainly further work is necessary to assess the long term benefits of PFA addition to abrasion resistance.

7.3 MICROSTRUCTURAL STUDY OF ABRASION RESISTANCE OF CONCRETE WITH PFA

7.3.1 Introduction

The abrasion resistance of PFA concrete depends on the microstructure of the concrete nearest to the surface. If the microstructure is influenced in any way then abrasion resistance will subsequently be affected.

The present work has adopted two of the many techniques available for the study of the microstructure to examine the role of the surface layer in the abrasion resistance of PFA concrete.

Fresh cement paste is a plastic network of particles of cement in water but, once the paste has set its volume remains approximately constant. Figure 7.1 illustrates the overall changes in structure of the cement paste that accompany hydration. Clearly the structure of the cement paste depends on both the degree of hydration and the age, and water/cementitious ratio. By subjecting the surface to power trowelling and floating, a considerable amount of moisture is lost from this surface layer so that, effectively, it has a lower water/cementitous ratio than the interior leading to a reduced porosity in this layer, particularly when subjected to good curing practice.

For fully hydrated cement, with no excess water above that required for hydration the residual space takes the form of voids of capillary pores which can be empty or full of water. When only partly hydrated, the paste contains an interconnected system of capillary pores. The effect of this is a lower strength and subsequently lower abrasion resistance. This can be avoided if the degree of hydration is sufficiently high for the capillary pore system to become segmented through partial blocking by newly developed cement gel. When this is the

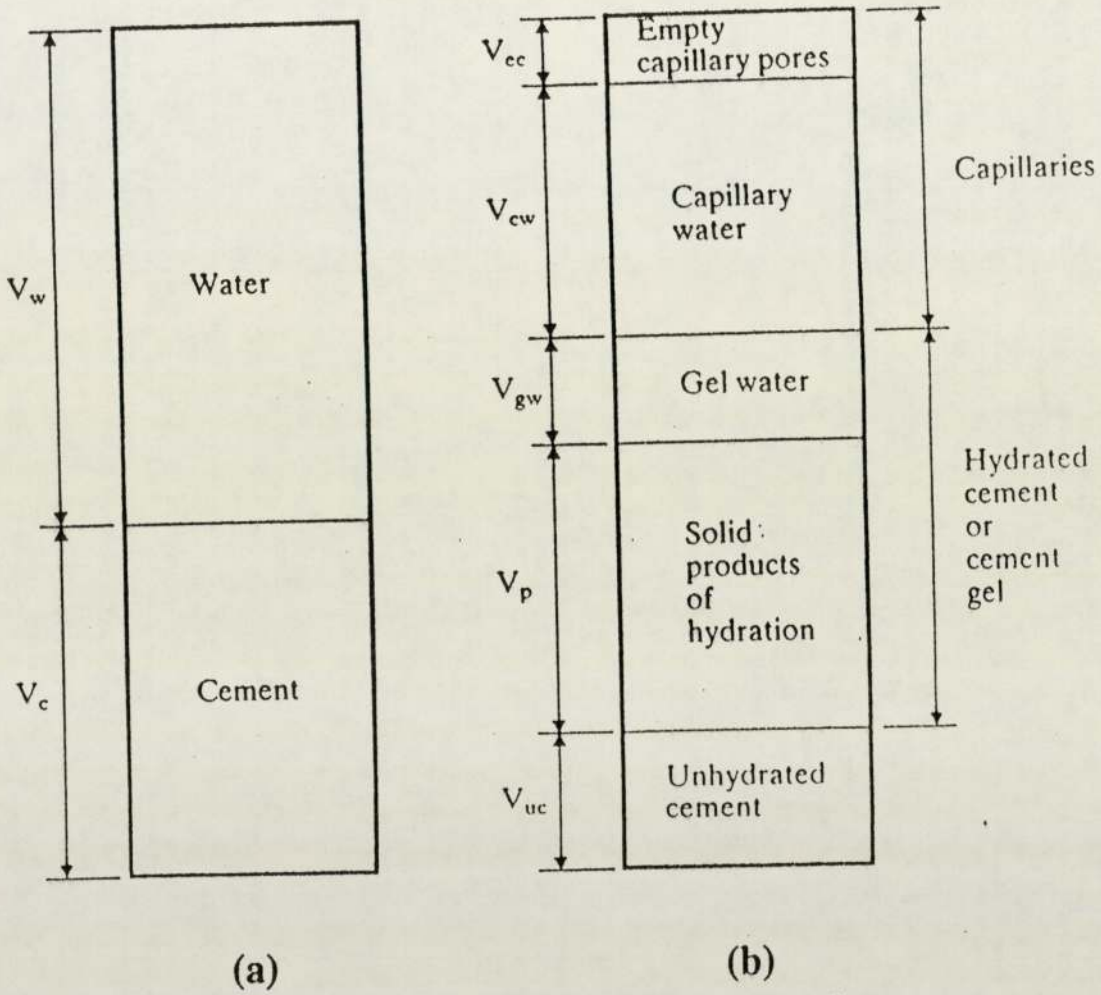


Fig. 7·1 Diagrammatic representation of the volumetric porportions:
(a) before hydration (degree of hydration, $h = 0$), and
(b) during hydration (degree of hydration, h)

case the capillary pores are interconnected only by the much smaller gel pores.

The purpose of this study is to determine the abrasion resistance of PFA concretes with different water/cementitious ratios and PFA percentage replacement.

Clearly this abrasion resistance is expected to be influenced by the porosity and quality of the surface layer and these characteristics were investigated by Mercury Intrusion Porosimetry (MIP) and Microhardness transverse.

7.3.2 Mercury Intrusion Porosimetry

Mercury intrusion porosimetry has been shown to be a sensitive and valuable means of quantitatively investigating the influence of factors which affect the abrasion resistance of PFA concrete. The abrasion resistance of concrete is controlled by the pore structure of the surface matrix. This is influenced by a number of factors which have been the subject of selective examinations in this investigation - PFA content, curing regime, age and water cementitious material ratio - and the MIP technique has been able to detect the influence of these factors on the pore structure.

The results of this particular investigation must be

qualified as the (PSD) pore size distribution curves were only obtained from single samples. Even so, the results demonstrate that the MIP method can be a valuable technique for investigating the abrasion resistance of PFA concrete. The test procedure involved samples taken from two different depths below the surface 10mm and 50mm. The results obtained clearly show that porosity is the major factor in controlling abrasion resistance, and that the abrasion resistance is related to the total porosity.

The polythene sheeting curing regime show better results in porosity i.e. lower porosity than the air curing and this is due to the rate of hydration of PFA cement blends, as shown in Figures 6.8 and 6.9.

Age plays an important role in the abrasion resistance of PFA concrete as demonstrated in the macrostudy. The results in the microstudy also showed that at a later age the PFA concrete developed a lower porosity for both air and polythene curing and so age is a prime factor controlling the performance of PFA concretes. The porosity at the surface matrix appeared to be higher at a later age (180 days) than the porosity of the middle matrix, for both curing regimes air and polythene. This may be attributed to the fact that the degree of hydration in the middle matrix is sufficiently high for the capillary pore system to become segmented through partial blocking by newly developed cement gel.

The PFA percentage replacement is another factor which influence the abrasion resistance of PFA concretes. It has been reported in ACI 201.2R-75 that at equal compressive strengths, properly finished and cured concretes with and without PFA will exhibit essentially equal resistance to abrasion.

The findings of this research work have demonstrated that at equal compressive strengths, properly cured, PFA concretes and properly finished, exhibited almost the same abrasion resistance as shown in Chapter 5 in Figures 5.19 and 5.20.

PFA participates chemically and mineralogically in the internal structure and the hardening of the cement paste and thus of the concrete. As a pozzolanic material the PFA reacts with the cement and becomes a strength forming component of the binder matrix in concrete. In the present work it has been shown that at the age of 28 days to 180 days for Mix 8 as shown in Tables 6.2, 6.3 and 6.4 the total pore volume generally increases for both Polythene sheeting and Air curing.

The rate of abrasion v's total pore volume did not show that the higher the abrasion resistance the lower the total pore volume (see Chapter 6) Table 6 .2, 6.3 and 6.4 although in some cases a correlation between total pore volume and abrasion depth has been shown in Tables 6.2, 6.3 and 6.4.

7.3.3 Microhardness Technique

This method was primarily included in the programme to compare the microstructure of different concrete specimens at 180 days as a later age has been shown to be an important factor in determining the abrasion resistance of PFA concretes. A standard procedure was developed for assessing the microhardness of concrete specimen. The microhardness profiles for specimens slabs subjected to different curing regimes and different PFA percentage replacements and water/cementitious ratios showed considerable variation as shown in Figures 6.13 - 6.28. The different curing regimes resulted in the production of surface layers with different levels of hardness. In all cases curing with the Polythene sheeting produced a harder surface matrix for the PFA concrete than when the same concrete was subjected to air curing.

The abrasion resistance of concrete is directly related to the microhardness of the surface matrix. The hardness of the surface matrix controlled the rate of abrasion as shown in Figure 6.32. The PFA content plays an important role on the microhardness of the surface layer and as shown in Figures 7.4 and 7.5 for the same water/cementitious ratio there is a correlation between abrasion resistance and hardness for PFA % replacement between 30-40%.

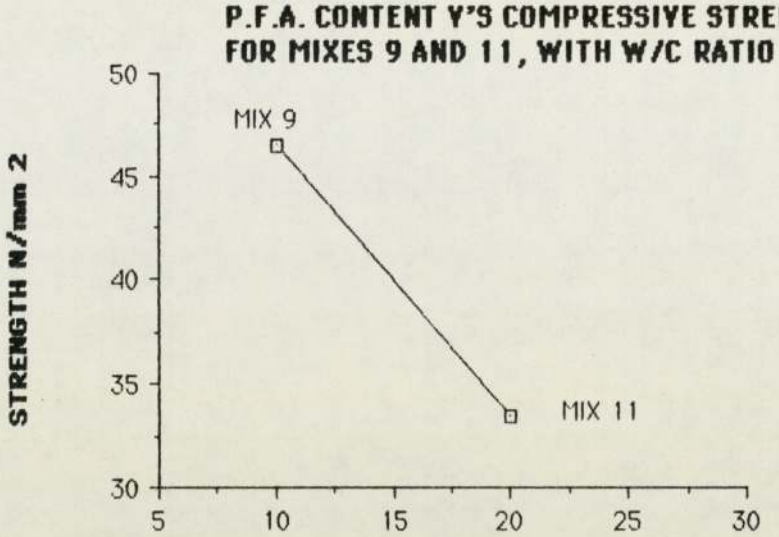

P.F.A. CONTENT Y'S COMPRESSIVE STRENGTH
FOR MIXES 9 AND 11, WITH W/C RATIO (0.50).
STRENGTH N/mm 2
50
45
40
35
30
MIX 9
MIX 11
5
10
15
20
25
30
P.F.A. %

FIG. 7.2

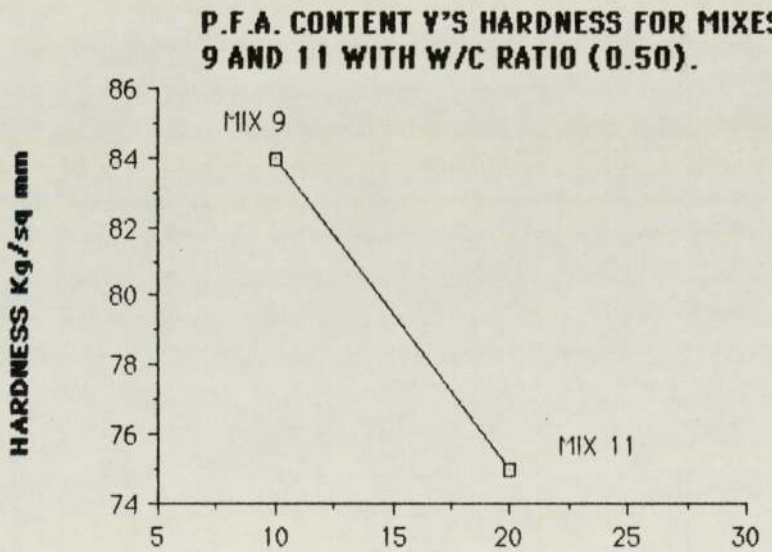

P.F.A. CONTENT Y'S HARDNESS FOR MIXES
9 AND 11 WITH W/C RATIO (0.50).
HARDNESS Kg/sq mm
86
84
82
80
78
76
74
MIX 9
MIX 11
5
10
15
20
25
30
P.F.A. %

FIG. 7.3

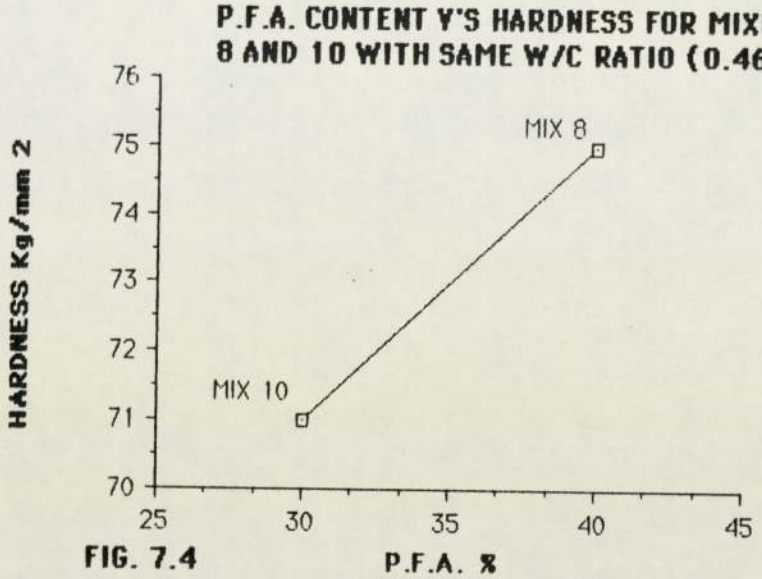

P.F.A. CONTENT V'S HARDNESS FOR MIXES 8 AND 10 WITH SAME W/C RATIO (0.46).
HARDNESS Kg/mm 2
76
75
74
73
72
71
70
MIX 8
MIX 10
25
30
35
40
45
P.F.A. %

FIG. 7.4

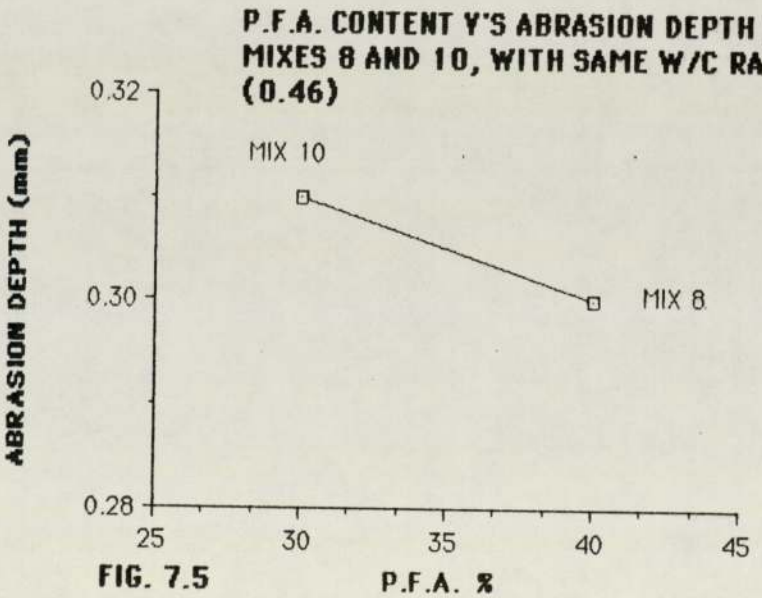

P.F.A. CONTENT V'S ABRASION DEPTH FOR MIXES 8 AND 10, WITH SAME W/C RATIO (0.46)
ABRASION DEPTH (mm)
0.32
0.30
0.28
MIX 10
MIX 8
25
30
35
40
45
P.F.A. %

FIG. 7.5

The microhardness of the surface matrix of the specimen slabs was directly related to the corresponding total pore volume as shown in Figure 6.31. Although not in the same manner for specimens cured with polythene and specimens cured in air and these lead directly to the improved abarasion resistance associated with the harder surface layer. The higher the porosity, the lower the hardness. In this connection the role of the replacement was not as influential as the curing regime where, for the same mix it was shown that Polythene sheeting gave better results than Air curing regime as shown in Figures 6.30 and 6.31. The microhardness profiles clearly demonstrated the depth to which each curing regime influenced the structure of the surface and middle layers. Results are shown in the Figures 6.13 to 6.29.

Generally it has been shown (Figure 6.29) that the specimens which were cured with polythene gave higher values of hardness than the spcimens which were under air curing regime.

Considering Figures 6.31 and 6.32 a correlation between porosity hardness and abarsion resistance can be seen.

7.4 LINKS BETWEEN THE MACROSTUDY AND THE MICROSTUDY

The results of the abrasion tests in the macrostudy clearly showed that the rate of abrasion was dependent on

the curing regime and age, thus a comparison of the macrostudy and microstudy can be achieved by considering the results from mixes 8-11. These four mixes were subjected to two curing regimes - polythene sheeting and air curing up to the age of 180 days. Details of the mixes are given in Table 4.4. It is clear that they cover four replacement levels - 10, 20, 30, 40 percent and two very similar water/cementitious material ratios 0.50 (Mixes 9 and 11) and 0.46 (mixes 8 and 10).

In considering their behaviour four factors have been selected:-

(1) Compressive strength

(2) Total pore volume

(3) Microhardness

(4) Abrasion resistance

so that the macrostudy (strength and abrasion resistance) can be related to the microstudy (porosity and microhardness).

For a given porous material the strength is a function of the porosity and so a reduction in the porosity should produce an increase in the hardness value. This is supported by the relationships shown in Figures 7.6 and 7.7 where the total pore volume is plotted against strength from mixes 8, 9, 10 and 11 and again the total pore vlume is plotted against hardness. These data relate to specimens tested at 180 days and subjected to polythene curing. From these graphs it is clearly

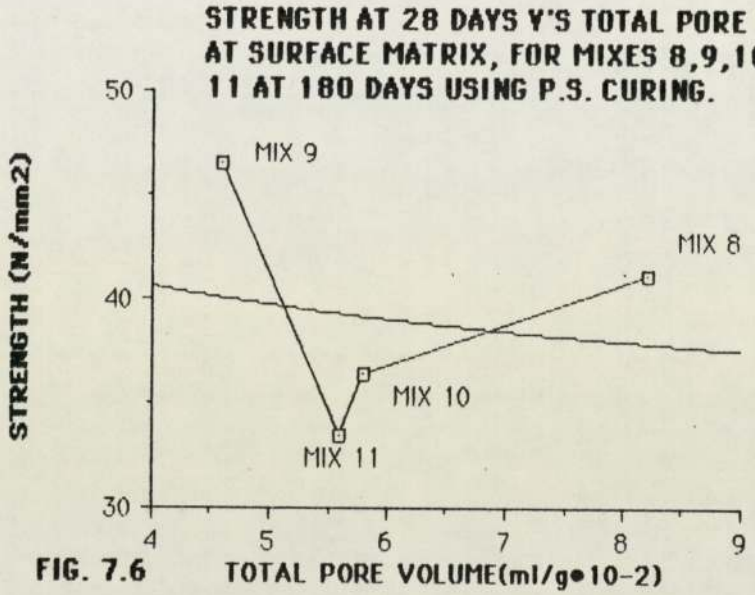

STRENGTH AT 28 DAYS Y'S TOTAL PORE VOLUME
AT SURFACE MATRIX, FOR MIXES 8,9,10 AND
11 AT 180 DAYS USING P.S. CURING.
STRENGTH (N/mm2)
50
40
30
MIX 9
MIX 8
MIX 10
MIX 11
4
5
6
7
8
9
TOTAL PORE VOLUME(ml/g•10-2)

FIG. 7.6

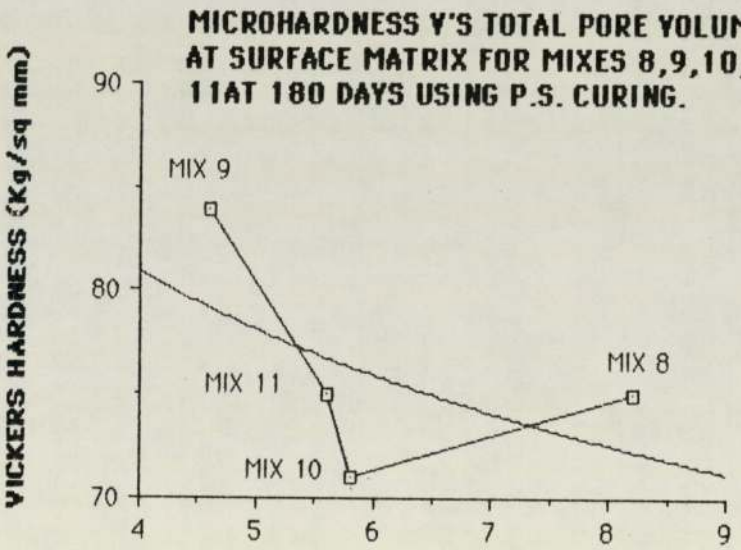

MICROHARDNESS Y'S TOTAL PORE VOLUME
AT SURFACE MATRIX FOR MIXES 8,9,10,AND
11AT 180 DAYS USING P.S. CURING.
VICKERS HARDNESS (Kg/sq mm)
90
80
70
MIX 9
MIX 11
MIX 10
MIX 8
4
5
6
7
8
9
TOTAL PORE VOLUME(ml/g•10-2)

FIG. 7.7

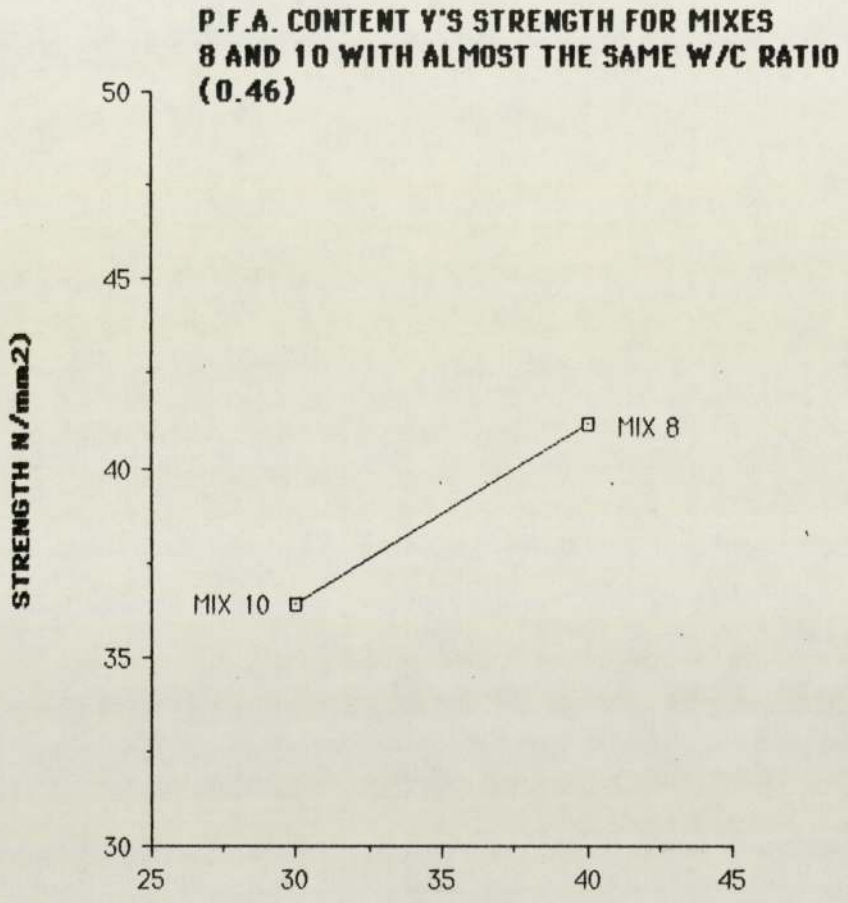

P.F.A. CONTENT V'S STRENGTH FOR MIXES
8 AND 10 WITH ALMOST THE SAME W/C RATIO
(0.46)
STRENGTH N/mm2)
50
45
40
35
30
25
30
35
40
45
MIX 8
MIX 10
P.F.A. (%)

FIG. 7.8

demonstrated that an increase in the total volume produce a decrease in hardness.

Relating Figure 7.2 with Figure 7.3 it is shown that there is a direct relationship between strength and the hardness of the surface matrix. The same correlation between strength and microhardness can be seen in figures 7.4 and 7.8 for mixes 8 and 10. For the same mixes (8 and 10) the abrasion resistance increases as the strength increases as shown in Figures 7.5 and 7.8. Therefore we can conclude that the strength is a function of porosity and also, when there is a reduction in porosity there is an increase in hardness and subsequently an increase in abrasion resistance. Mix 9, with the highest compressive strength, showed lower porosity and higher microhardness and as well low abrasion depth when cured with PS at 180 days.

A relationship between abrasion and PFA concrete exists; as shown in Figure 7.5, for the same water/cementition ratio and adequate curing at later ages the abrasion resistance increases with an increase in the PFA content between 30-40%.

CHAPTER EIGHT

CONCLUSIONS

8.1 INTRODUCTION

This study has developed test procedures for assessing the abrasion resistance of PFA concrete. Through the laboratory programme, it is possible to establish conclusions related to the effects, on abrasion resistance, of the following factors:

1. PFA replacement level
2. Curing regime
3. Age
4. Water/cementitious ratio

The abrasion resistance of concrete is primarily dependent on the microstructure of the concrete nearest to the surface and, by the use of microtechniques, it has been possible to assess the various mechanisms by which the addition of PFA has modified the abrasion resistance of concrete.

8.2 MACROSTUDY OF ABRASION RESISTANCE

(1) The abrasion resistance of PFA concrete is significantly influenced by the curing regime.

(2) Polythene sheeting of PFA concrete slabs, significantly increased the abrasion resistance, especially with PFA concrete mixes of lower water/cementitious ratios.

(3) The use of curing compounds was found to be generally more effective in increasing abrasion resistance, than the plastic sheeting method of curing. This is mainly due to the longer period of controlled curing that can be achieved with these spray techniques.

(4) The rate of abrasion is dependent on the structure of the surface matrix of the specimen under investigation.

(5) Compressive strength at 28 days is affected by the level of PFA replacement, the cement content and water/cementitious ratio of the concrete.

(6) For the same water cementitious ratio an increase in the PFA content in the cement PFA blend causes a decrease in the 28 day compressive strength.

(7) Lower water/cementitious ratios exhibit higher compressive strengths and subsequently lower abrasion depths at later ages.

(8) At equal compressive strengths, properly cured PFA concretes will exhibit essentially equal resistance to abrasion, irrespective of the replacement level or water/cementitious ratio.

(9) Abrasion resistance is influenced by age in PFA concretes. This has been attributed to the fact that after the initial strength contribution due to the hydration of the Portland cement, the continued pozzolanic activity of the PFA contributes to increased strength gain at later ages. This

requires the concrete to be subjected to extended curing so that PFA concrete, with equivalent or lower strength at early ages, may have equivalent or higher strength at later ages than a plain similar concrete.

(10) Positive curing has a major influence on the abrasion resistance of PFA concretes both at 28 days and greater ages. Whilst polythene sheeting and curing membrane can produce PFA concrete slabs with good abrasion performance, air curing seriously impairs the performance of these slabs.

(11) With PFA concretes, further improvements in abrasion resistance were detected in mixes tested at 90 and 180 days. This has important benefits for practical concreting where a curing membrane is employed since improvement in abrasion resistance could be expected until the membrane is removed in service.

(12) With a given water/cementitious ratio the abrasion resistance is influenced by the combined effects of PFA content and curing regime. Well cured concrete appeared to be relatively independently of PFA content, up to 40 percent, but the performance of air cured slabs appears to be inversely proportioned to PFA content.

8.3 MICROSTUDY OF ABRASION RESISTANCE

(1) Mercury intrusion porosimetry method is a valuable means of quantitatively investigating the influence

of factors which affect the abrasion resistance of PFA concrete such as curing, age, PFA content replacement.

(2) The abrasion resistance of concrete is controlled by the pore structure of the surface matrix. Curing regimes influenced the pore size distribution and total pore volume of the surface matrix, so that polythene sheeting reduced the porosity of the surface layer leading to improved abrasion resistance.

(3) Age decreased the total pore volume and increase the abrasion resistance of PFA concretes.

(4) The total pore volume increased as the PFA content replacement increased for the same water/cementititious ratio.

(5) At later ages the total pore volume at the middle matrix was less than the total pore volume of the surface matrix for both the PS and AC regimes.

(6) The abrasion resistance of PFA concrete at the surface matrix varies directly with the total pore volume of its surface matrix.

(7) A standard procedure for assessing the microhardness of PFA concrete specimens was developed. The microhardness profiles for specimen slabs at 180 days were clearly influenced by the nature of the individual curing regimes PS and AC.

(8) The abrasion resistance of concrete was directly related to the microhardness of the surface matrix. The hardness of the surface matrix controlled the

rate of abrasion. The ability of a PFA concrete surface to resist abrasion forces in primarily controlled by the top 1mm of the surface matrix.

(9) The microhardness of the surface matrix of the PFA concrete slabs was directly related to the corresponding total pore volume.

(10) The microhardness profiles clearly demonstrated the depth to which each curing regime influenced the structure of the surface layer.

CHAPTER NINE

FUTURE WORK

9.1 INTRODUCTION

The work undertaken has been designed to assess abrasion resistance of concrete containing PFA percentage replacement. With the completion of this particular study, a number of recommendations are proposed regarding the need for further work. These are summarised below:

9.2 MACROSTUDY OF ABRASION RESISTANCE OF PFA CONCRETE

(1) PFA's from different sources in the UK should be used in a number of standard concrete mixes to investigate the influence of the source on the abrasion resistance.

(2) A related issue concerns the links between porosity and permeability for a durable concrete, thus the use of PFA in concrete should be investigated with reference to the initial surface absorption test and air permeability test before the PFA concrete undergoes abrasion test.

(3) The effect of PFA on the carbonation of concrete should be investigated and linked to the influence of surface carbonation on the abrasion resistance of these concretes.

(4) Temperature control during the time of curing and its influence on the abrasion resistance of PFA concrete could be as well investigated in the future.

(5) The influence of different aggregate/cementitious ratios on the abrasion resistance of PFA concrete.

(6) The improvements in abrasion resistance with prolonged curing have been demonstrated and it would be valuable to link these more closely to strength development. This should include testing standard cubes and cores removed from the slabs after various time intervals.

(7) Where floor slabs are to be in a cold environments, they would need to be air entrained for frost resistance and since this technique influences porosity, it would be useful to examine the links between air entrainment porosity and abrasion resistance.

9.3 MICROSTUDY OF THE ABRASION RESISTANCE OF PFA CONCRETE

(1) The MIP method can be used to monitor the pore size distribution of the cement paste for a direct evaluation of the pozzolanic activity, of different PFA/OPC material ratios, and different sources of PFA.

(2) Microhardness tests at 28 days and 90 days should be considered for comparison with data obtained at 180 days. Indeed it would be useful to carry out both MIP and Microhardness tests at selected intervals, on slabs subjected to prolonged (1 year) curing and storage. This would permit an evaluation of the influence of the pozzolanic reactions on both the

porosity and quality of the hardened materials.

(3) The microhardness technique should be used on the surface of the specimens subjected to liquid surface treatment so that comparisons can be made with specimens subjected to the PS and AC regimes.

LIST OF REFERENCES

1. ABDUN-NUR E.A. "Fly ash in concrete - An evaluation." Highways Res. Bull 284, National Research Council,138.

2. ABRAMS,D.A. "Wear tests of concrete." Proceedings of the American Society for testing materials Vol. 21. Part 2, 1921, pp 1013-1038.

3. ABRAMS, D.A., "A method of making wear tests of concrete". Proceedings of the AMERICAN SOCIETY OF TESTING MATERIALS, Vol. 16, Part 2, 1916 pp 194-208.

4. ABRAMS, D.A. "Effect of curing condition on the wear and strength of concrete", Proceedings, Vol. 20, 1919.

5. ALFORD, N.M. and RAHMAN, A.A. "An Assessment of Porosity and Pore sizes in Hardened Cement Pastes", Journal of Materials Science, Vol. 16, 1981, pp 3105-3114.

6. AMERICAN CONCRETE INSTITUTE, "Recommended Practice for Concrete floor and slab construction," (ACI (302-369)), Chicago, April 1969.

7. AMERICAN CONCRETE INSTITUTE, COMMITTEE 116 "Cement and Concrete Terminology" SP19, ACI, Detroit, 1967.

8. ASTM Standards (C-779) Assessing the abrasion resistance of a horizontal concrete surface.

9. ASTM Standards G.40 "Definitions of terms relating to erosion by cavitation and impengement.

10. AUSKERN, A. and HORN, W. "Capillary Porosity in Hardened Cement Paste," Journal of Testing and Evaluation, JTEVA, Vol. 1, 1975, pp 74-79.

11. BAMFORTH, P.B., "Insitu measurement of the effect of partial Portland cement replacement using either fly ash or GGBS on the performance of mass concrete. Proceedings Institution of Civil Engineers Part 2, Vol 69, September 1980.

12. BISSELL, T.B. and WALLIS, D.M. "The handling and disposal of ash from CEGB power stations" Ash Tech 1984, Second International Conference on ash technology and marketing. London September 1984, CEGB London.

13. BRACE, W.F. "Behaviour of rock salt, limestone and anhydrite during indentation", J. Geophys. Res., Vol. 64, No. 6, 1960, pp 1773-1788.

14. BRAGER, D.H. and SELLEVOLD, E.J. "Mercury Porosimetry of Hardened Cement Paste: The Influence of Particle Size", Cement and Concrete Research, Vol. 5, 1975, pp 171-178.

15. BROWNE, R.D. "Surface Finishes advances in Concrete Slab Technology," Pergoman, 1980, pp 497-504.

16. BS 3892, Part 1 1982. "Specification for PFA for use as a cementitious component in structural concrete". British Standards Institution, London, 1982.

17. B.S.I. In-situ floorings. Part 1: Code of Practice for concrete bases and screeds to receive in-situ floorings. London BS8204, 1987.

18. B.S.I. In-situ floorings. Part 2: Code of Practice for concrete wearing surfaces. London: BS8204, 1987.

19. CABRERA, J.G., HOPKINS, C.J., WOOLEY, G.R., LEE, R.E., SHAW, J., PLOWMAN, C., FOX, H.
Ash Tech. '84, London 1984 pp 437-443.

20. CEBECI, O. "Pore Structure of Air-entrained Hardened Cement Paste", Cement and Concrete Research, Vol.11, 1981, pp 257-265.

21. CEMENT AND CONCRETE ASSOCIATION Report for the fly ash 1979.

22. CHAPLIN, R.G. The influence of cement replacement materials and other factors on the abrasion resistance of industrial concrete floors. Technical report, Cement and Concrete Association, Slough, England, 1986 pp 361-362,468.

23. CHAPLIN, R.G. "The abrasion resistance of concrete floors" Technical Report 42.471 Cement and Concrete Association, London 1972.

24. CHAPLIN, R.G., "The influence of cement replacement materials - fine aggregate and curing on the abrasion resistance of concrete floor slabs". International colloquium, Industrial floors Suttgart, West Germany, 13-15 January 1987.

25. CONCRETE SOCIETY, The use of ggbs and PFA in concrete, Technical Report 1987, pp 76-78.

26. COULOMB,C. "Theorie des Machines Simples" Mem Math Phys. 10 (1785), p 161.

27. DALZIEL, J.A. and GUTTERRIDGE, W.A. "The influence of PFA upon the hydration characteristics and certain physical properties of a Portland cement paste. C & CA Technical report 560. January 1986.

28. DEPARTMENT OF THE ENVIRONMENT
Design of normal concrete mixes. Joint publication produced by the Building Research establishment, Transport and Road Research Laboratory and the Cement and Concrete Association.

29. DHIR, R.K., MUNDAY, J.G.L. and ONG L.T., "Strength variability of OPC/PFA concrete. Concrete, V15, No.6, 1981, pp 33-37.

30. DIAMOND, S. "A Critical Comparison of Mercury Porosimetry and Capillary Condensation Pore Size Distributions of Portland Cement Pastes", Cement and Concrete Research, Vol. 1, 1971, pp 531-545.

31. DOKOS, J.J. "Sliding friction under extreme pressures". J.Appl. Mechanics Vol. 13, 1946, pp. A148-A156.

32. DUNSTAN, M.R.H. "Fly ash as the fourth ingredient in concrete mixtures". SP 91-7 Ash Tech 84, London 1984.

33. FENTRESS, B. "Slab Construction practices compared by wear test". A.C.I. Journal, July 1973.

34. FITZMAURICE, R. & LEA, F.M. "Floors for Industrial Purposes", Inst. Chem. Eng. Trans., 1939, 17,30.

35. GOPOLAN, M.K. and HAQUE, M.N. "Effect of curing regime on two properties of fly ash concrete." American Concrete Institute Materials Journal Vol. 84, No. 1, pp 14-19. January 1987.

36. GRAHAM, J. and BRINKWORTH, D.C. "Characteristics of PFA from different power stations and dust collection points. Ash Tech 1984, September 1984, CEGB, London.

37. HENRIQUES, A. "The Vickers Hardness of zinc blende". Ark. Miner. Geol. Vol. 2, No. 3, 1957, pp 283-287.

38. IDORN, G.M. 1983 "30 years with alkalis in concrete" Proceedings, 6th International Conference on alkalis in concrete, Danish Concrete Society, Copenghagen 1983 pp 21-38.

39. KENNEDY, H.L. "Homogencity of air entraining concrete". Proceedings Am. Con. Inst. Vol.42 1946 pp 557-563.

40. KETTLE, R.J. and SADEGZADEH, M. "Development of an accelerated abrasion test apparatus with a standardised testing procedure". Aston University Dept of Civil Eng. Materials and Structures, 1988, 21, pp 47-56.

41. KING, R.F. and TABOR, D. "The strength properties and frictional behaviour of brittle solids". Proceedings, Royal Society London, Series A, Vol. 223, 1954, pp 225-238.

42. KRAGELSKI, I.V. "Friction and Wear". Butterworth, London, 1965.

43. LANE, R.O. and BEST, J.F. 1982. "Properties and use of fly ash in Portland cement concrete". Concrete International Design and Construction Vol. 4 No. 7, July 1982 pp 81-92.

44. LEWANDOWSKI, R. "Effect of different fly ash quanlities on the properties of concrete" Betonwert and Fertigteil - Technik.

45. LI, SHU-T'IEN Wear resistant concrete construction. Journal of the American Concrete Institute. Proceedings Vol. 55, February 1959, pp 879-892.

46. LIU, T.C. (1980) "Maintenance and preservation of concrete structures, Report 3: Abrasion- Erosion resistance of concrete, Tech report C78-4, US Army waterways Experiment Station, 129.

47. MICROMETRICS INSTRUMENT CORPORATION, Instruction Manual, Model 900/910 Series Mercury Penetration Porosimeter.

48. MILLS, R.H. "Curing of concrete at various depths from an exposed surface. Civil Engineering in S. Africa, Dec 1965, pp 322-326.

49. MITSCHE, R. and ONITSCH, E.M. "Mikroharte and bindungsart", Miktrochim, Acta, Vol 36, 1951, pp 841-862.

50. MORIN, A. "Nouvelles Experiences sur le frottement, faites a Metzen 1831-32-33," Mem, pres. Acad. Scien.Paris 4 (1835) 1, 591, 641.

51. MOTT, B.W. "Micro-indentation hardness testing" London, Butterworths, 1956.

52. MUNDAM, J.G.L., ONG, L.T. and DHIR, R.K. "Mix proportioning of concrete with PFA: A critical review. ACI publication SP 79, 1983, pp 267-288.

53. NEVILLE, A.M., "Properties of concrete" Appendix 1 pp 714 Year 1981-82.

54. ORR, C. "Application of Mercury penetration to materials analysis" Powder Technology, Vol. 3, 1969, pp 117-123.

55. PINCHIN, D.J. "The cement-steel interface: Friction and adhesion", PhD Thesis, University of Cambridge, 1977.

56. PLOWMAN, J.M. "Maturity and strength of concrete" Magazine of concrete research Vol. 8. No. 22 March 1956 pp 15-22.

57. PRIOR, M.E., "Abrasion resistance" significance of tests and properties of concrete and concrete making materials, ASTM, STP, No.169-A, 1966, pp 246-260.

58. RAMACHANDRAN, V.A. and FELDMAN, R.F. "Hydration characteristics of monocalcium, aluminate at a low water-cement ratio," Cement and Concrete Research, Vol.3, 1973, pp 729-750.

59. RAVINDRA, K.DHIR, Pulverised fuel ash. pp 227-230.

60. REGOURD, M. 1983. "Technology in the 1990's development in hydraulic cements." Proceedings A310, 5 Phylosophical transactions, Royal Society of London pp 85-91.

61. RENNIE, G. "Experiments on the friction and abrasion of the surfaces of solids. Phil. Trans. (1829).

62. ROBERTS, N.K. "The surface tension of mercury and adsorption of water vapour and some saturated hydrocarbons on mercury". Journal Chem. Soc. 1964, pp 1907-1915.

63. ROOTARE, H.M. "Advanced Experimental Techniques in Powder Metallurgy, VS: Perspectives in Power Metallurgy" Plenum Press NY pp 225-254.

64. RUSHING, H.B. "Concrete wear study" Report PB 183410 Louisiana Department of Highway, June 1968.

65 SADEGZADEH, M. "Abrasion resistance of Concrete." PhD Thesis, Department of Civil Engineering and Construction, University of Aston, 1984.

66. SADEGZADEH, M. and KETTLE, R.J. "Abrasion resistance of polymer impregnated concrete". CONCRETE May 1987, pp 32-34.

67. SAHLMAN, L. "Nya Provnings - metoder for betonggolr",Husbyggaren No.1 (1970) pp 40-41.

68. SAMARIN, A.M., MUNN, R.L. and ASHBY, J.B. (1983) "The use of fly ash in concrete - Australian experience", Proc. 1st Int. Conf. on the use of fly ash, Siliciefume, Slag and other mineral by-products in concrete, ed. V.M. Malhotra,Montebello, August 1983. ACI Spec Pub SP-79,143-172.

69. SAWYER, J.L. "Wear tests on concrete using the German Standard method of test and machine". Proceedings American Society Test. Mats. Volume 57, 1957, pp 1143-1153.

70. SCHUMAN, L. and TUCKER, J., "A portable appartus for determining the relative wear resistance of concrete floors". Journal of Research, National Bureau of Standards, Vol. 23, No.5 Pr. 1252. November 1939, pp 549-570.

71. SCRIPTURE, E.W., BENEDICT, S.W. and BRYANT, D.E. "Floor aggregates". Journal of the American Concrete Institute. Proceedings Vol. 50, December 1953, pp 305-316.

72. SELLEVOLD, E.J. "Mercury Porosimetry of Hardened Cement Paste Cured or Stored at 7°C, Cement and Concrete Research, Vol. 4, 1974, pp 399-404.

73. SEREDA, P.J. "Significance of microhardness of porous inorganic materials, Cement and Concrete Research, Vol.2, 1972, pp 717-729.

74. SHAW, J.D.N. "Special finishes for concrete floors", in advances in concrete slab technology, Pergamon Press, 1980.

75. SMITH, F.L. "The effect of aggregate quality on the resistance of concrete to abrasion". Cement and Concrete, STP No. 205 ASTM, 1958,pp 91-106.

76. SOROKA, I. and SEREDA, P.J. "The structure of cement-stone and the rise of compacts as structural models". Proceedings 5th Int. Symp. on the chemistry of cement, Tokyo, Vol. 3, 1968 pp 67-73.

77. STIFFLER, K. "Relations between wear and physical properties of roadstones", HRB special report 101, Highway Research Board, 1969.

78. TABOR, D. "The hardness of metals", Oxford, Clarendon Press, 1951.

79. TOGNON, G.P. et al. "Resistance to wear in relationship to certain other mechanical properties of natural stone and of concrete." IL CEMEENTO, October 1970, pp 165-176.

80. VINCE, S. "The motion of bodies affected by friction" Phil. Trans. (1785).

81. WASHBURN, E.W., "Note of a method of determining the distribution of pore sizes in a porous material." Proceedings, National Academy of Sciences, PNASA, Vol. 7, 1921, pp 112-116.

82. WATT, J.D. and THORNE, D.J. "Composition and pozzolanic properties of PFA as Chem 15, 585 Year 1965.

83. WINSLOW, N.M. and DIAMOND, S. "A Mercury Porosimetry Study of the Evolution of Porosity in Portland Cement." Journal of Materials JMLSA, Vol. 5, No. 3, 1970, pp 564-585.

84. WINSLOW, N.M. and SHAPIRO, J.J."Instrument for the Measurement of Pore-Size Distribution by Mercury Penetration", ASTM Bulletin, February 1959, pp 39-44.

85. WILBURN, I. LUKE 1961
"Nature and distribution of particles of various sizes in fly ash".
Technical Report No. 6-583 US Army Engineer Waterways experiment station Vicksburg Nov. 1961 pp 21.

A P P E N D I X A

TABLE A1

Specifications and properties for PFA (3892/1)

Property	Requirement in BS 3892 Part 1 1982	Requirement in BBA Certificate 85/1504	Typical Properties
Loss-on-ignition	7.0% (max)	6.5% (max)	3.0%
Colour index	not specified	Shade 7 (max)	Shade 3
Fineness (retention on 45 micron sieve)	12.5% (max)	12.5% (max)	6.0%
Relative density	not specified	2000kg/m^3 (min)	350kg/m^3
Sulphuric anhydride (as SO_3)	2.5% (max)	2.5% (max)	0.8%
Magnesia (as MgO)	4.0% (max)	not specified	1.25%
Moisture content	0.5% (max)	0.5% (max)	0.1%
Water requirement	not exceeding 95% of ordinary Portland cement	not specified	2%
Pozzolanic activity index	85% (min) recommendation only	not specified	-
Concrete workability and strength requirement	not specified but See Footnote 1	When tested to BS4550 and BS1881, at 0.6 w/c. a 35/65 PFA/OPC mixture shall (i) provide workability greater than concrete made with 100% OPC (ii) shall comply with the strength requirement of BS 6588, ie at 3 days not less than 8N/mm^2 at 28 days higher than the compressive strength at 3 days and not less than 22N/mm^2	13N/mm^2 at 3 days 29N/mm^2 at 28 days
Standard	not specified	See Footnote 2	

Footnote 1 - Refer to 1.5 for details of testing regime for compliance with BS 6588: 1985 Portland PFA Cement

Footnote 2 - In order to meet the compliance limits of this BSA Specification. the statistical analysis shall be on the above characteristic levels outside which not more than 1% of the test results may be expected to fall (i.e. confidence limits, controlling variability within the specification).

TABLE A2 **CENTRAL ELECTRICITY GENERATING BOARD**

North Western Region

P.F.A. LABORATORY, CARRINGTON

Client/Scheme:- Pozzolanic Lytag

Material: P.F.A. Source: Fiddlers Ferry

Reference	0.59
Silica * (% as Slo_2)	47.2
Aluminium * (% as Al_2O_3)	29.6
Iron * (% as Fe_2O_3)	13.2
Calcium (% as CaO)	1.6
Magnesium * (% as MgO)	1.5
Sodium (% as Na_2O)	1.1
Potassium * (% as K_2O)	4.7
Titanium * (% as TiO_2)	1.0
Loss on Ignition (%)	5.4
Total Sulphate (% as SO_3)	0.67
2:1 Water Soluble Sulphate g/l as SO_3)	

* On Combustible free basis

Signed R Coombs Date 22.08.86

TABLE A3 ORDINARY TYPICAL CEMENT CHEMICAL ANALYSIS

Chemical Name	% Present
SiO_2	20.2
I.R.	0.62
Al_2O_3	4.8
Fe_2O_3	3.4
Mn_2O_3	0.07
P_2O_5	0.09
TiO_2	0.27
CaO	64.6
MgO	1.4
SO_3	2.9
Ignition Loss	0.8
K_2O	0.66
Na_2O	0.11

GRADING CURVES FOR FINE AGGREGATES.

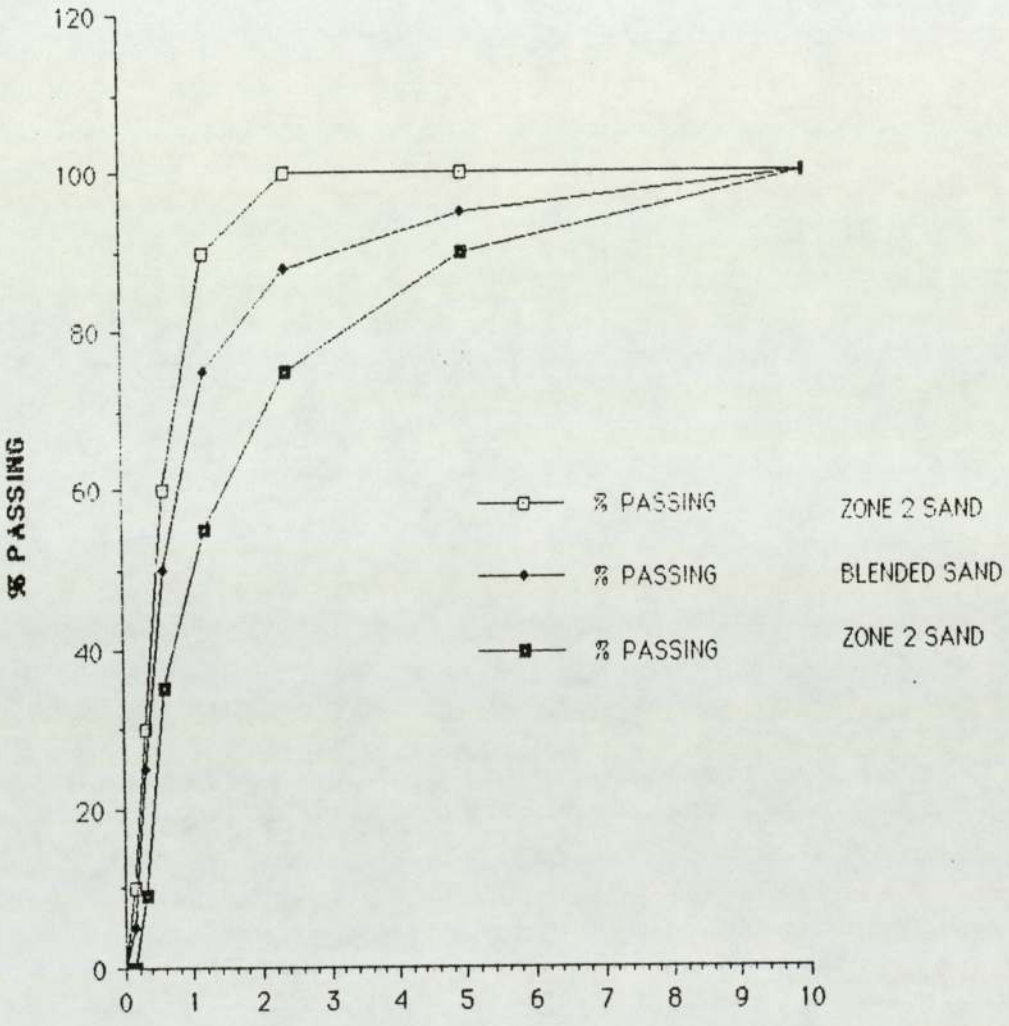


FIG. A1

A P P E N D I X B

APPENDIX B

Mix Details

Mix 1 (0.65/30)	Dry weights per m3
Cement	210 kg
PFA	90 kg
20-10 mm Aggregate	770 kg
10-5 mm Aggregate	255 kg
Fine Aggregate	840 kg
Water	195 kg
Free Water - Cementitious ratio	0.65

Mix 2 (0.37/30)	Dry weights per m3
Cement	301 kg
PFA	129 kg
20-10 mm Aggregate	935 kg
10-5 mm Aggregate	310 kg
Fine Aggregate	560 kg
Water	159.6 kg
Free Water - Cementitious ratio	0.37

Mix 3 (0.65/40)	Dry weights per m3
Cement	180 kg
PFA	120 kg
20-10 mm Aggregate	770 kg
10-5 mm Aggregate	255 kg
Fine Aggregate	840 kg
Water	195 kg
Free Water - Cementitious ratio	0.65

Mix 4 (0.65/0)	Dry weights per m3
Cement	300 kg
20-10 mm Aggregate	770 kg
10-5 mm Aggregate	255 kg
Fine Aggregate	840 kg
Water	195 kg
Free Water - Cement ratio	0.65

Mix 5 (0.56/0)	Dry weights per m3
Cement	280 kg
20-10 mm Aggregate	900 kg
10-5 mm Aggregate	410 kg
Fine Aggregate	640 kg
Water	156.8 kg
Free Water - Cement ratio	0.56

Mix 6 (0.65/10)	Dry weights per m3
Cement	270 kg
PFA	30 kg
20-10 mm Aggregate	770 kg
10-5 mm Aggregate	255 kg
Fine Aggregate	840 kg
Water	195 kg
Free Water - Cementitious ratio	0.65

Mix 7 (0.65/20)	Dry weights per m3
Cement	240 kg
PFA	60 kg
20-10 mm Aggregate	770 kg
10-5 mm Aggregate	255 kg
Fine Aggregate	840 kg
Water	195 kg

Mix 8 (0.44/40)	Dry weights per m3
Cement	219 kg
PFA	146 kg
20-10 mm Aggregate	940 kg
10-5 mm Aggregate	315 kg
Fine Aggregate	620 kg
Water	160.6 kg
Free Water - Cementitious ratio	0.44

Mix 9 (0.56/10)	Dry weights per m3
Cement	252 kg
PFA	28 kg
20-10 mm Aggregate	900 kg
10-5 mm Aggregate	410 kg
Fine Aggregate	645 kg
Water	141 kg
Free Water - Cementitious ratio	0.56

Mix 10 (0.46/30)	Dry weights per m3
Cement	243.6 kg
PFA	104.4 kg
20-10 mm Aggregate	858 kg
10-5 mm Aggregate	429 kg
Fine Aggregate	605 kg
Water	160 kg
Free Water - Cementitious ratio	0.46

Mix 11 (0.51/20)	Dry weights per m3
Cement	250.4 kg
PFA	62.6 kg
20-10 mm Aggregate	834 kg
10-5 mm Aggregate	418 kg
Fine Aggregate	675 kg
Water	160 kg
Free Water - Cementitious ratio	0.51

A P P E N D I X C

Fosroc®

CONCURE® WB

Water based concrete curing compound

USES

Provides a spray-on temporary membrane to retain moisture in concrete for effective curing. Used for concreting generally but especially useful for large areas of concrete construction such as runways, motorways or bridgeworks.

ADVANTAGES

Reduces surface shrinkage and cracking by eliminating moisture loss from exposed surfaces.

Enables cement to hydrate more efficiently.

Provides hard wearing surface and prevents dusting.

No surface wetting required prior to application to vertical surfaces.

Easy application reduces labour costs.

Non toxic and non flammable. Can be used safely.

Eliminates need for damp hessian, sand or polyethylene.

DESCRIPTION

CONCURE WB is a white, low viscosity wax emulsion which incorporates a special alkali reactive emulsion breaking system. This system ensures that the emulsion breaks down to form a non penetrating continuous film immediately upon contact with a cementitious surface. This impervious film prevents excessive water evaporation which in turn permits more efficient cement hydration thus reducing shrinkage and increasing durability. The membrane once formed is designed to degrade (via a photo initiator in the clear formulation) when exposed to ultra violet light over a period of time dependent of conditions of exposure.

CONCURE WB is available in two grades CLEAR and WHITE PIGMENTED.

CLEAR (ASTM C 309-74 Type 1) grade is for all normal temperate climate applications.

WHITE PIGMENTED (ASTM C 309-74 Type 2) grade contains white pigments to give light reflectance thus minimizing solar heat gain and is particularly suitable for use in hot climates.

STANDARDS

UK Department of Transport Specification for Road and Bridge Works Clause 2709 (modified to remove surface water prior to application) ASTM C 309-74

US Federal Specification TT-C-800A (water loss requirement)

CP 110 1972 Part 1 Clause 6.16.2

PROPERTIES

Colour:

	CLEAR	WHITE PIGMENTED
Bulk Liquid	White	White
Dry film	Clear	White

Specific gravity at 20°C: 0.98 1.00

Viscosity: Brookfield Model RVF N1/S10 at 20°C Both grades 8-15 cP

Minimum application temperature: 5°C

Curing efficiency: (applicable to both grades) Water loss 0.17 kg/m² applied at 245 ml/m² which is considerably more efficient than the maximum permissable water loss of 0.55 kg/m² in ASTM C309-74 and 0.39 kg/m² in U.S. Federal Specification TT-C-800A

86% when applied at 270 ml/m². Modified Department of Transport Specification for Road and Bridge Works Clause 2709

Membrane break down: (applicable to both grades) After a period of approximately 28 days, the film formed on the concrete surface will begin to degrade. The rate of degradation will depend upon initial membrane thickness and the degree of exposure to ultra violet light.

Light reflectance: 62% for white pigmented (must be more than 60%) ASTM C 309-74

Fosroc®

CONCURE®

CONCRETE CURING COMPOUNDS

USES

To provide a resin membrane on the surface of newly placed concrete to retain moisture for effective curing to take place.

Concrete runways, motorways, roadworks, bridgeworks, hardstandings and concrete generally.

ADVANTAGES

Reduces surface shrinkage and cracking

Enables concrete to hydrate more efficiently

Ease of application

No waiting - apply as soon as possible after placing concrete

Eliminates the need for damp hessian, sand or polythene

Reduces labour costs

DESCRIPTION

CONCURE is the name given to a range of resin based curing compounds for spraying onto the surface of concrete to provide an effective and economical method of curing.

CONCURE is available in several grades to meet specific requirements.

CONCURE 75 Standard, 90 Clear and 90 Aluminised.

CONCURE 75 Standard

General-purpose curing compound. Contains a fugitive green dye to assist in application. Curing efficiency in excess of 85% tested in accordance with DOT specification for Road and Bridge Works 1976 Clause 2709. Water loss 0.029 g/cm^2: complies with ASTM C309 Type 1.

Can be used where concrete will be in direct contact with potable water e.g. Reservoirs, Water Towers etc.

CONCURE 90 Aluminised

For high efficiency curing and where light reflectance is required to keep the temperature of the concrete to a minimum, particularly for Roadways, Runways etc. Curing efficiency in excess of 92% complies with DOT Specification for Road and Bridge Works 1976, Clause 2603 and with DOE Specification for Aircraft Pavements 1972, Clause 810.

CONCURE 90 Clear

Unpigmented version. Curing efficiency in excess of 92% when tested in accordance with DOT Specification for Road and Bridge Works 1976, Clause 2709.

PROPERTIES

CONCURE forms a tough resin film on the surface of freshly placed concrete or render. This enables the cement to hydrate more efficiently, eliminates the causes of shrinkage cracking and produces high compressive strengths with a harder wearing surface to the concrete.

The CONCURE Aluminised grade has the ability to reflect the rays of the sun, thereby keeping the temperature of the concrete to a minimum, which helps to prevent thermal stresses. All CONCURE films have a built in breakdown system causing the resin film to disintegrate by the action of ultra-violet light over a period of two to three months, depending on weather conditions, except CONCURE 90 Aluminised which breaks down by physical abrasion

INSTRUCTIONS FOR USE

CONCURE is spray applied to the surface of the newly placed concrete, care being taken to ensure complete coverage

CONCURE should be applied as soon as possible after the concrete has been surface finished, i.e. trowelled tamped or textured as required, but generally within 30 minutes or earlier if in conditions of hot sun or strong dry winds. The nozzle of the spray should be held approximately 450mm from the surface and passed back and forth to effect complete coverage. The pressure on the pump must be maintained at all times to produce a fine spray.

Immediately after use, the spraying equipment should be cleaned out, especially the line and nozzle, with FOSROC SOLVENT 103 or White Spirit.

NOTE: On vertical surfaces or soffit of concrete which may have partially dried out by being retained in shuttering, it is imperative that the concrete be well wetted down before applying the CONCURE. If this is not done permanent staining will result.

Do not apply CONCURE to dry or semi dry concrete. To ensure the breakdown of the CONCURE film, heavier coating must be avoided.

For the application of CONCURE, various types of spraying equipment can be supplied, i.e. Knapsack or motorised sprayers.

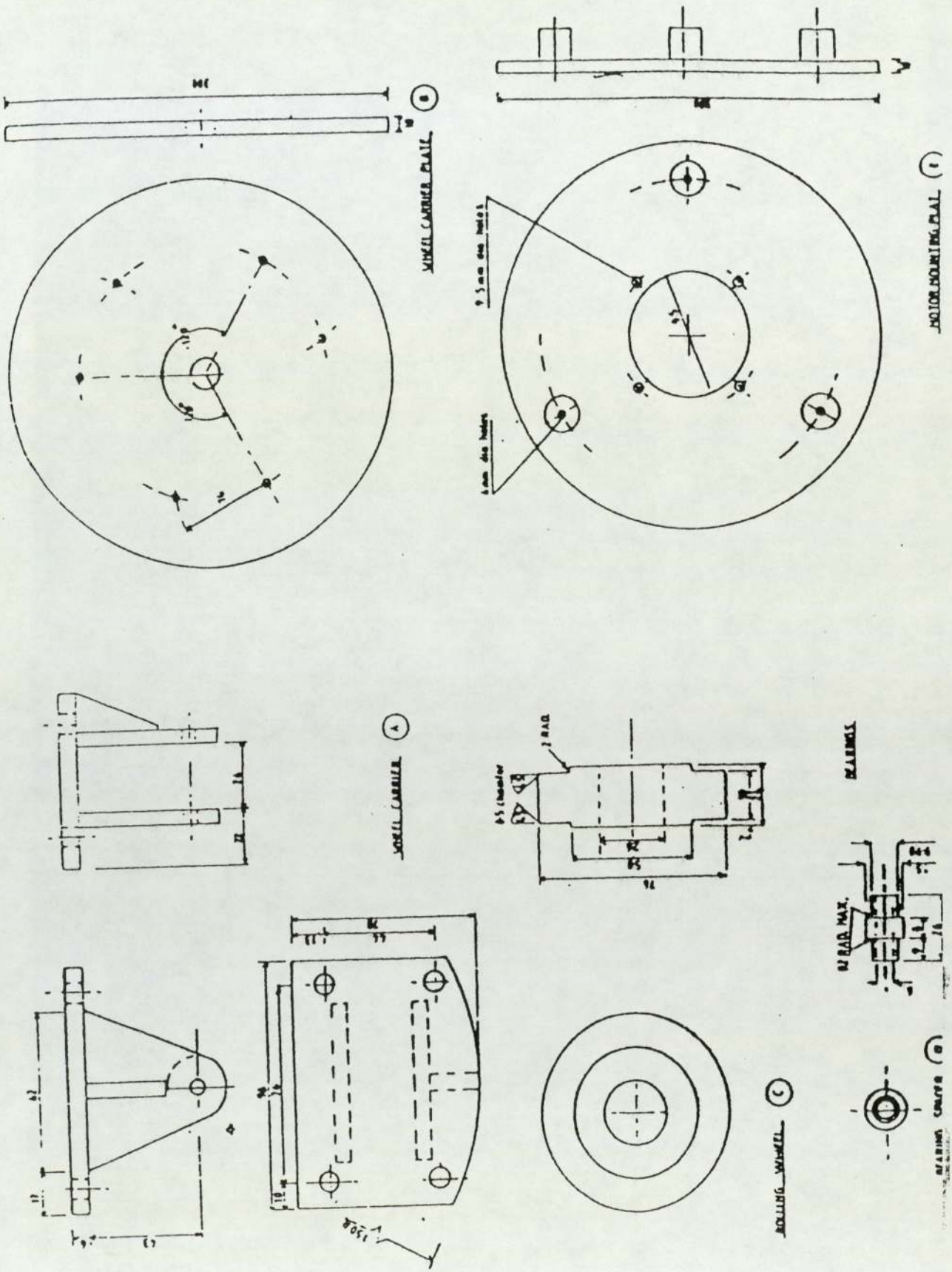
PRECAUTIONS

Health & Safety

If contact with the resin occurs, the skin should be washed with soap and water - NOT SOLVENT. A resin removing cream such as KEROCLEANSE 22 should preferably be used. Goggles should be worn when spraying with a short lance. Any eye contamination should be washed with plenty of water and medical treatment sought. When used in enclosed areas, good ventilation must be provided.

CBP

A P P E N D I X D



Accelerated Abrasion Tests
Apparatus and Three Types of Abrasive Heads

FIGURE D1

ACCELERATED Abrasion Tests
Apparatus and Three Types of Abrasive Heads

A P P E N D I X E

TABLE E1

MIX: 8	W/C : 0.44	PFA: 40%	CURING: PS	AGE OF TESTING: 28 DAYS

CIRCULAR PATH C1

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1535	1539	1546	1558	1538	1540	1547	1556	1545	0.00
5 Min	1499	1525	1526	1528	1506	1513	1508	1495	1513	0.32
10 Min	1489	1450	1455	1500	1495	1492	1458	1495	1479	0.66
15 Min	1479	1450	1440	1500	1480	1490	1440	1490	1471	0.74

CIRCULAR PATH C2

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1540	1525	1555	1537	1544	1510	1497	1543	1531	0.00
5 Min	1495	1505	1530	1510	1512	1508	1495	1530	1510	0.21
10 Min	1494	1505	1470	1500	1450	1465	1460	1507	1581	0.50
15 Min	1493	1504	1470	1500	1440	1460	1450	1495	1477	0.54

CIRCULAR PATH C3

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1519	1510	1490	1480	1511	1546	1553	1530	1517	0.00
5 Min	1519	1490	1475	1480	1507	1493	1546	1500	1501	0.16
10 Min	1504	1430	1450	1480	1505	1480	1545	1500	1487	0.30
15 Min	1500	1420	1440	1470	1500	1470	1540	1500	1480	0.37

TABLE E2

MIX: 8	W/C : 0.44	PFA: 40%	CURING: AC	AGE OF TESTING: 28 DAYS

CIRCULAR PATH C1

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1520	1545	1520	1548	1541	1492	1528	1510	1526	0.00
5 Min	1490	1520	1482	1513	1480	1456	1519	1470	1491	0.35
10 Min	1480	1497	1470	1460	1470	1425	1470	1450	1465	0.61
15 Min	1470	1470	1460	1460	1460	1420	1420	1440	1450	0.76

CIRCULAR PATH C2

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1525	1525	1500	1497	1538	1525	1525	1525	1520	0.00
5 Min	1520	1525	1500	1490	1535	1502	1528	1520	1515	0.05
10 Min	1500	1450	1500	1483	1435	1455	1520	1499	1480	0.40
15 Min	1495	1450	1495	1470	1430	1440	1510	1480	1471	0.49

CIRCULAR PATH C3

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1498	1513	1532	1540	1480	1538	1515	1510	1516	0.00
5 Min	1475	1481	1498	1515	1525	1496	1496	1510	1500	0.16
10 Min	1467	1480	1478	1485	1517	1470	1452	1492	1480	0.36
15 Min	1460	1470	1470	1480	1500	1460	1450	1470	1470	0.46

TABLE E3

MIX: 8	W/C : 0.44	PFA: 40%	CURING: PS	AGE OF TESTING: 3 MONTHS

CIRCULAR PATH C1

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1494	1524	1514	1515	1560	1515	1560	1540	1528	0.00
5 Min	1492	1478	1480	1506	1530	1567	1520	1490	1495	0.33
10 Min	1490	1460	1465	1495	1500	1430	1514	1490	1481	0.47
15 Min	1488	1460	1460	1490	1495	1430	1510	1485	1477	0.51

CIRCULAR PATH C2

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1526	1520	1460	1525	1542	1518	1505	1508	1513	0.00
5 Min	1525	1510	1460	1482	1460	1467	1495	1500	1487	0.26
10 Min	1497	1498	1440	1473	1445	1465	1488	1480	1473	0.40
15 Min	1490	1490	1440	1470	1445	1460	1480	1480	1469	0.44

CIRCULAR PATH C3

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1560	1517	1455	1535	1533	1515	1550	1495	1519	0.00
5 Min	1540	1511	1455	1497	1502	1490	1525	1485	1501	0.18
10 Min	1494	1502	1455	1477	1502	1478	1525	1470	1488	0.31
15 Min	1490	1498	1450	1470	1495	1470	1505	1469	1481	0.38

TABLE E4

MIX: 8	W/C : 0.44	PFA: 40%	CURING: AC	AGE OF TESTING: 3 MONTHS

CIRCULAR PATH C1

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1515	1530	1548	1547	1566	1577	1482	1528	1537	0.00
5 Min	1460	1519	1455	1480	1503	1507	1450	1510	1486	0.51
10 Min	1460	1515	1450	1480	1475	1499	1448	1455	1473	0.64
15 Min	1455	1500	1445	1470	1460	1470	1440	1445	1461	0.76

CIRCULAR PATH C2

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1525	1519	1500	1508	1540	1565	1506	1522	1523	0.00
5 Min	1492	1465	1470	1463	1505	1478	1470	1478	1478	0.45
10 Min	1472	1460	1462	1460	1461	1438	1465	1465	1460	0.63
15 Min	1460	1450	1450	1458	1460	1435	1450	1450	1452	0.71

CIRCULAR PATH C3

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1519	1523	1544	1470	1553	1535	1470	1504	1515	0.00
5 Min	1472	1475	1473	1463	1458	1455	1470	1455	1465	0.50
10 Min	1472	1440	1470	1440	1450	1400	1470	1435	1450	0.65
15 Min	1462	1432	1460	1438	1442	1400	1460	1430	1441	0.74

TABLE E5

MIX: 8	W/C : 0.44	PFA: 40%	CURING: PS	AGE OF TESTING: 6/12 MONTHS

CIRCULAR PATH C1

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1532	1538	1534	1542	1515	1505	1533	1540	1530	0.00
5 Min	1491	1514	1496	1520	1500	1505	1519	1526	1509	0.21
10 Min	1490	1509	1495	1510	1499	1500	1510	1515	1508	0.22
15 Min	1489	1500	1490	1505	1498	1499	1505	1510	1500	0.30

CIRCULAR PATH C2

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1511	1554	1523	1541	1522	1532	1500	1513	1524	0.00
5 Min	1510	1529	1487	1516	1479	1514	1500	1503	1504	0.20
10 Min	1499	1498	1486	1510	1475	1510	1499	1499	1499	0.35
15 Min	1493	1495	1483	1505	1470	1508	1498	1494	1494	0.30

CIRCULAR PATH C3

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1528	1535	1520	1553	1486	1545	1520	1554	1530	0.00
5 Min	1527	1512	1520	1540	1475	1505	1500	1505	1510	0.20
10 Min	1520	1510	1505	1510	1465	1500	1499	1501	1501	0.29
15 Min	1519	1505	1500	1505	1464	1500	1498	1500	1500	0.30

TABLE E6

MIX: 8	W/C : 0.44	PFA: 40%	CURING: AC	AGE OF TESTING: 6/12 MONTHS

CIRCULAR PATH C1

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1522	1512	1552	1516	1512	1498	1495	1596	1512	0.00
5 Min	1470	1490	1470	1470	1455	1495	1460	1455	1470	0.42
10 Min	1465	1468	1465	1462	1450	1480	1455	1445	1462	0.50
15 Min	1455	1458	1460	1458	1449	1460	1450	1440	1452	0.60

CIRCULAR PATH C2

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1538	1525	1528	1480	1518	1551	1523	1505	1521	0.00
5 Min	1445	1520	1485	1465	1455	1510	1490	1460	1466	0.55
10 Min	1440	1510	1468	1461	1451	1501	1460	1458	1461	0.60
15 Min	1435	1501	1451	1460	1450	1500	1450	1450	1451	0.70

CIRCULAR PATH C3

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1508	1522	1525	1535	1515	1491	1525	1514	1516	0.00
5 Min	1508	1475	1520	1530	1450	1490	1490	1490	1494	0.22
10 Min	1490	1470	1499	1520	1440	1480	1481	1486	1486	0.30
15 Min	1480	1460	1479	1510	1439	1470	1471	1476	1476	0.40

TABLE E7

MIX: 9	W/C : 0.5		PFA: 10%		CURING: PS			AGE OF TESTING: 28 DAYS		
CIRCULAR PATH C1										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1518	1543	1545	1544	1538	1528	1543	1544	1538	0.00
5 Min	1485	1530	1490	1508	1505	1490	1513	1490	1501	0.37
10 Min	1480	1520	1480	1500	1482	1450	1460	1480	1482	0.56
15 Min	1470	1510	1470	1500	1480	1445	1455	1470	1475	0.63
CIRCULAR PATH C2										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1510	1547	1534	1537	1542	1533	1545	1511	1532	0.00
5 Min	1495	1509	1485	1505	1507	1490	1508	1496	1499	0.32
10 Min	1490	1500	1480	1489	1495	1465	1595	1488	1488	0.44
15 Min	1480	1499	1475	1480	1490	1460	1490	1480	1482	0.50
CIRCULAR PATH C3										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1537	1535	1534	1534	1534	1544	1532	1545	1537	0.00
5 Min	1510	1492	1495	1485	1496	1499	1490	1480	1493	0.44
10 Min	1450	1481	1490	1480	1495	1499	1484	1460	1480	0.57
15 Min	1456	1470	1490	1480	1490	1490	1480	1460	1476	0.61

TABLE E8

MIX: 9	W/C : 0.5		PFA: 10%		CURING: AC			AGE OF TESTING: 28 DAYS		
CIRCULAR PATH C1										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1537	1538	1537	1537	1518	1535	1538	1532	1534	0.00
5 Min	1505	1493	1480	1470	1460	1490	1510	1495	1488	0.46
10 Min	1499	1462	1453	1470	1460	1472	1450	1495	1470	0.64
15 Min	1475	1460	1450	1460	1453	1470	1480	1480	1462	0.72
CIRCULAR PATH C2										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1530	1531	1533	1533	1537	1534	1536	1532	1533	0.00
5 Min	1492	1480	1480	1490	1490	1499	1490	1501	1490	0.43
10 Min	1475	1480	1480	1490	1465	1498	1480	1475	1480	0.53
15 Min	1470	1468	1456	1475	1452	1490	1440	1470	1465	0.68
CIRCULAR PATH C3										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V										
5 Min										
10 Min										
15 Min										

TABLE E9

MIX: 9A	W/C : 0.5	PFA: 10%	CURING: PS	AGE OF TESTING: 3 MONTHS

CIRCULAR PATH C1

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1499	1495	1498	1504	1505	1504	1510	1505	1503	0.00
5 Min	1485	1490	1498	1500	1500	1589	1501	1498	1495	0.08
10 Min	1475	1485	1470	1465	1475	1473	1473	1473	1473	0.30
15 Min	1472	1475	1470	1463	1472	1472	1473	1472	1472	0.31

CIRCULAR PATH C2

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1512	1500	1495	1520	1498	1506	1512	1505	1506	0.00
5 Min	1495	1500	1495	1495	1487	1495	1495	1496	1495	0.11
10 Min	1494	1501	1494	1495	1486	1495	1494	1495	1495	0.11
15 Min	1486	1496	1488	1486	1480	1485	1480	1490	1486	0.20

CIRCULAR PATH C3

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1475	1505	1509	1492	1510	1504	1503	1502	1500	0.00
5 Min	1465	1501	1475	1490	1504	1484	1502	1501	1490	0.10
10 Min	1465	1475	1465	1470	1480	1470	1472	1475	1470	0.30
15 Min	1460	1470	1460	1470	1475	1465	1470	1475	1470	0.30

TABLE E10

MIX: 9A	W/C : 0.5	PFA: 10%	CURING: AIR	AGE OF TESTING: 3 MONTHS

CIRCULAR PATH C1

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1495	1502	1498	1509	1502	1501	1505	1495	1501	0.00
5 Min	1489	1502	1463	1482	1495	1488	1502	1495	1490	0.11
10 Min	1481	1491	1463	1481	1481	1485	1481	1481	1481	0.20
15 Min	1470	1472	1462	1475	1475	1471	1471	1471	1471	0.30

CIRCULAR PATH C2

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1494	1495	1507	1502	1499	1499	1492	1502	1499	0.00
5 Min	1481	1477	1473	1499	1483	1498	1492	1485	1486	0.12
10 Min	1470	1470	1470	1469	1469	1470	1468	1465	1469	0.30
15 Min	1460	1460	1459	1459	1459	1459	1459	1459	1459	0.40

CIRCULAR PATH C3

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1501	1477	1499	1506	1503	1506	1504	1495	1499	0.00
5 Min	1501	1470	1476	1485	1485	1480	1504	1495	1487	0.12
10 Min	1458	1459	1460	1461	1458	1458	1458	1459	1459	0.40
15 Min	1457	1458	1458	1458	1459	1457	1456	1458	1458	0.41

TABLE E11

MIX: 9	W/C : 0.50		PFA: 10%		CURING: PS			AGE OF TESTING: 6/12 MONTHS		
CIRCULAR PATH C1										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1520	1540	1520	1543	1460	-	1530	1540	1521	0.00
5 Min	1515	1525	1500	1513	1460	-	1510	1525	1506	0.15
10 Min	1504	1502	1509	1494	1492	-	1501	1493	1499	0.27
15 Min	1500	1502	1500	1424	1492		1501	1492	1497	0.24
CIRCULAR PATH C2										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1514	1525	1523	1535	1532	1545	1535	1529	1529	0.00
5 Min	1516	1516	1516	1518	1518	1525	1520	1513	1517	0.12
10 Min	1495	1496	1501	1493	1436	1500	1502	1501	1497	0.32
15 Min	1495	1496	1501	1493	1486	1500	1500	1500	1496	0.33
CIRCULAR PATH C3										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1514	1540	1530	1536	1535	1542	1527	1533	1535	0.00
5 Min	1525	1525	1523	1519	1529	1533	1517	1519	1523	0.12
10 Min	1490	1500	1514	1508	1495	1487	1488	1491	1497	0.38
15 Min	1490	1500	1512	1508	1495	1486	1487	1490	1496	0.39

TABLE E12.

MIX: 9	W/C : 0.50		PFA: 10%		CURING: AIR			AGE OF TESTING: 6/12 MONTHS		
CIRCULAR PATH C1										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1530	1529	1530	1531	1524	1533	1533	1540	1531	0.00
5 Min	1509	1512	1513	1498	1487	1512	1510	1499	1505	0.26
10 Min	1504	1514	1500	1505	1503	1503	1503	1493	1503	0.28
15 Min	1500	1506	1500	1494	1430	1498	1503	1493	1490	0.41
CIRCULAR PATH C2										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1530	1545	1530	1531	1532	1531	1530	1528	1532	0.00
5 Min	1510	1499	1500	1505	1516	1513	1504	1501	1506	0.26
10 Min	1510	1500	1500	1508	1511	1502	1507	1501	1504	0.28
15 Min	1489	1490	1500	1489	1489	1502	1499	1497	1495	0.37
CIRCULAR PATH C3										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1520	1530	1525	1532	1533	1531	1528	1533	1529	0.00
5 Min	1494	1500	1508	1514	1508	1500	1510	1502	1504	0.25
10 Min	1494	1500	1508	1514	1508	1489	1500	1500	1502	0.27
15 Min	1490	1496	1508	1510	1497	1491	1494	1485	1496	0.33

TABLE E13

MIX: M0	W/C : 0.46	PFA: 30%	CURING: PS	AGE OF TESTING: 28 DAYS

CIRCULAR PATH C1

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1496	1510	1511	1512	1502	1502	1515	1500	1506	0.00
5 Min	1490	1478	1475	1459	1500	1485	1500	1500	1486	0.20
10 Min	1446	1478	1475	1430	1470	1450	1478	1475	1465	0.41
15 Min	1415	1435	1445	1430	1470	1420	1430	1470	1439	0.67

CIRCULAR PATH C2

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1494	1490	1525	1472	1496	1485	1485	1498	1493	0.00
5 Min	1455	1490	1456	1472	1496	1470	1460	1458	1470	0.23
10 Min	1440	1488	1455	1452	1466	1440	1458	1430	1453	0.40
15 Min	1420	1448	1440	1450	1460	1410	1420	1425	1434	0.59

CIRCULAR PATH C3

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1523	1507	1528	1487	1550	1511	1530	1499	1517	0.00
5 Min	1463	1503	1510	1450	1475	1484	1508	1488	1485	0.32
10 Min	1450	1500	1509	1430	1445	1454	1505	1468	1470	0.47
15 Min	1448	1470	1480	1430	1445	1425	1475	1460	1454	0.63

TABLE E14

MIX: 10	W/C : 0.46		PFA: 30%		CURING: AIR			AGE OF TESTING: 28 DAYS		
CIRCULAR PATH C1										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1530	1525	1514	1538	1524	1515	1516	1515	1522	0.00
5 Min	1480	1495	1452	1448	1467	1465	1448	1515	1471	0.51
10 Min	1420	1458	1450	1440	1450	1435	1440	1485	1447	0.75
15 Min	1400	1445	1438	1410	1440	1390	1425	1480	1429	0.93
CIRCULAR PATH C2										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1505	1503	1500	1535	1522	1518	1502	1520	1513	0.0
5 Min	1460	1462	1440	1462	1468	1450	1400	1466	1451	0.62
10 Min	1440	1450	1438	1450	1450	1430	1400	1436	1437	0.76
15 Min	1430	1440	1430	1430	1440	1400	1400	1430	1424	0.89
CIRCULAR PATH C3										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1508	1499	1500	1495	1505	1528	1508	1505	1506	0.00
5 Min	1455	1495	1492	1468	1505	1443	1487	1490	1479	0.27
10 Min	1440	1480	1488	1450	1490	1430	1480	1470	1466	0.40
15 Min	1430	1470	1460	1440	1480	1429	1465	1465	1455	0.51

TABLE E15

MIX: 10	W/C : 0.46		PFA: 30%		CURING: AC			AGE OF TESTING: 3 MONTHS		
CIRCULAR PATH C1										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1528	1520	1525	1528	1509	1543	1548	1536	1530	0.00
5 Min	1523	1502	1504	1504	1498	1522	1498	1505	1507	0.23
10 Min	1520	1500	1500	1501	1495	1510	1495	1504	1500	0.30
15 Min	1499	1480	1495	1480	1475	1480	1481	1482	1480	0.50
CIRCULAR PATH C2										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1537	1532	1526	1527	1530	1538	1527	1530	1531	0.00
5 Min	1497	1499	1498	1491	1512	1487	1527	1518	1504	0.27
10 Min	1480	1490	1495	1490	1498	1480	1510	1496	1492	0.39
15 Min	1480	1481	1482	1485	1485	1480	1470	1480	1481	0.50
CIRCULAR PATH C3										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1525	1532	1555	1537	1540	1537	1538	1540	1538	0.00
5 Min	1480	1495	1525	1490	1507	1533	1535	1510	1509	0.29
10 Min	1479	1490	1509	1489	1506	1520	1515	1508	1508	0.30
15 Min	1470	1488	1489	1488	1501	1500	1503	1489	1488	0.50

TABLE E16

MIX: 10	W/C : 0.46		PFA: 30%		CURING: PS			AGE OF TESTING: 6/12 MONTHS		
CIRCULAR PATH C1										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1527	1525	1532	1533	1523	1500	1540	1528	1526	0.00
5 Min	1513	1507	1512	1517	1490	1498	1510	1510	1507	0.19
10 Min	1507	1503	1506	1508	1489	1502	1512	1507	1504	0.22
15 Min	1502	1491	1503	1498	1507	1499	1502	1502	1500	0.26
CIRCULAR PATH C2										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1525	1541	1539	1540	1531	1527	1498	1542	1530	0.00
5 Min	1502	1510	1502	1507	1531	1508	1498	1519	1509	0.21
10 Min	1497	1507	1492	1494	1525	1503	1481	1504	1500	0.30
15 Min	1494	1507	1472	1494	1513	1482	1481	1504	1493	0.37
CIRCULAR PATH C3										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1527	1537	1535	1532	1525	1539	1521	1519	1529	0.00
5 Min	1507	1517	1514	1510	1512	1521	1512	1508	1512	0.17
10 Min	1504	1506	1502	1500	1490	1507	1499	1502	1501	0.28
15 Min	1501	1505	1502	1499	1490	1507	1494	1502	1500	0.29

TABLE E17

MIX: 10	W/C : 0.46		PFA: 30%		CURING: AC			AGE OF TESTING: 6/12 MONTHS		
CIRCULAR PATH C1										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1537	1542	1520	1546	1546	1532	1535	1535	1533	0.00
5 Min	1495	1454	1463	1479	1483	1469	1475	1471	1473	0.54
10 Min	1479	1453	1461	1469	1481	1452	1475	1452	1465	0.64
15 Min	1479	1438	1450	1469	1450	1451	1452	1422	1451	0.82
CIRCULAR PATH C2										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1534	1540	1528	1530	1548	1530	1519	1542	1533	0.00
5 Min	1475	1516	1484	1452	1472	1477	1476	1484	1479	0.54
10 Min	1462	1507	1454	1446	1437	1455	1471	1460	1461	0.72
15 Min	1429	1497	1453	1446	1437	1426	1459	1448	1449	0.84
CIRCULAR PATH C3										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1535	1530	1533	1528	1546	1538	1517	1520	1530	0.00
5 Min	1475	1510	1474	1482	1491	1483	1470	1452	1479	0.51
10 Min	1445	1470	1451	1466	1473	1456	1434	1439	1455	0.75
15 Min	1444	1470	1431	1458	1473	1437	1434	1439	1446	0.84

TABLE E18

MIX: 11	W/C : 0.51	PFA: 20%	CURING: PS	AGE OF TESTING: 28 DAYS

CIRCULAR PATH C1

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1528	1511	1515	1519	1515	1519	1515	1519	1518	0.00
5 Min	1491	1497	1505	1508	1515	1497	1515	1519	1508	0.10
10 Min	1490	1495	1495	1494	1485	1490	1515	1519	1498	0.20
15 Min	1488	1488	1488	1489	1485	1485	1489	1488	1488	0.30

CIRCULAR PATH C2

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1516	1520	1520	1522	1518	1525	1515	1525	1520	0.00
5 Min	1516	1475	1500	1437	1500	1502	1560	1510	1500	0.20
10 Min	1470	1468	1500	1495	1495	1488	1485	1490	1486	0.34
15 Min	1470	1470	1476	1476	1476	1480	1480	1480	1476	0.44

CIRCULAR PATH C3

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1515	1510	1520	1518	1520	1511	1518	1513	1516	0.00
5 Min	1505	1495	1520	1512	1520	1505	1480	1513	1506	0.10
10 Min	1505	1485	1514	1509	1514	1502	1480	1490	1500	0.16
15 Min	1499	1485	1490	1499	1495	1490	1480	1490	1490	0.26

TABLE E19

MIX: 11	W/C : 0.51	PFA: 20%	CURING: PS	AGE OF TESTING: 28 DAYS

CIRCULAR PATH C1

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1528	1511	1515	1519	1515	1519	1515	1519	1518	0.00
5 Min	1491	1497	1505	1508	1515	1497	1515	1519	1508	0.10
10 Min	1490	1495	1495	1494	1485	1490	1515	1519	1498	0.20
15 Min	1488	1488	1488	1489	1485	1485	1489	1488	1488	0.30

CIRCULAR PATH C2

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1516	1520	1520	1522	1518	1525	1515	1525	1520	0.00
5 Min	1516	1475	1500	1437	1500	1502	1560	1510	1500	0.20
10 Min	1470	1468	1500	1495	1495	1488	1485	1490	1486	0.34
15 Min	1470	1470	1476	1476	1476	1480	1480	1480	1476	0.44

CIRCULAR PATH C3

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1515	1510	1520	1518	1520	1511	1518	1513	1516	0.00
5 Min	1505	1495	1520	1512	1520	1505	1480	1513	1506	0.10
10 Min	1505	1485	1514	1509	1514	1502	1480	1490	1500	0.16
15 Min	1499	1485	1490	1499	1495	1490	1480	1490	1490	0.26

TABLE E20

MIX: 11	W/C : 0.51		PFA: 20%		CURING: A.C.			AGE OF TESTING: 28 DAYS		
CIRCULAR PATH C1										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1507	1515	1513	1510	1510	1529	1525	1515	1516	0.00
5 Min	1455	1480	1475	1462	1510	1515	1499	1485	1485	0.31
10 Min	1440	1462	1445	1460	1458	1490	1495	1485	1467	0.49
15 Min	1440	1460	1445	1457	1457	1457	1495	1485	1457	0.59
CIRCULAR PATH C2										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1525	1507	1520	1521	1503	1517	1518	1516	1516	0.00
5 Min	1493	1475	1485	1495	1503	1463	1480	1476	1484	0.32
10 Min	1493	1460	1460	1460	1453	1463	1462	1472	1465	0.51
15 Min	1440	1460	1445	1457	1453	1457	1456	1456	1456	0.60
CIRCULAR PATH C3										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1517	1510	1526	1516	1525	1525	1515	1517	1518	0.00
5 Min	1517	1485	1492	1481	1499	1475	1480	1476	1488	0.30
10 Min	1475	1458	1490	1470	1499	1472	1479	1476	1477	0.41
15 Min	1467	1458	1480	1467	1467	1470	1475	1467	1467	0.51

TABLE E21

MIX: 0.51	W/C : 20%		PFA:		CURING: AC			AGE OF TESTING: 3 MONTHS		
CIRCULAR PATH C1										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1535	1535	1540	1549	1535	1532	1530	1539	1537	0.00
5 Min	1500	1520	1535	1526	1511	1519	1525	1520	1520	0.17
10 Min	1499	1498	1497	1495	1493	1499	1501	1501	1497	0.40
15 Min	1487	1485	1488	1490	1495	1483	1489	1483	1487	0.50
CIRCULAR PATH C2										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1537	1530	1532	1540	1538	1543	1533	1533	1536	0.00
5 Min	1530	1530	1480	1518	1525	1514	1518	1520	1517	0.19
10 Min	1494	1505	1480	1512	1520	1506	1505	1502	1503	0.33
15 Min	1490	1499	1480	1496	1499	1498	1500	1493	1496	0.40
CIRCULAR PATH C3										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1530	1528	1535	1539	1535	1530	1550	1550	1537	0.00
5 Min	1530	1525	1515	1498	1515	1500	1510	1515	1514	0.23
10 Min	1499	1498	1497	1468	1500	1499	1500	1509	1497	0.40
15 Min	1489	1488	1487	1458	1495	1489	1490	1485	1487	0.50

TABLE E22

MIX: 11	W/C : 0.51		PFA: 20%		CURING: AC		AGE OF TESTING: 6/12 MONTHS			
CIRCULAR PATH C1										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1532	1538	1528	1531	1538	1533	1530	1528	1532	0.00
5 Min	1500	1501	1502	1500	1508	1500	1500	1501	1501	0.31
10 Min	1474	1482	1494	1491	1507	1452	1471	1479	1481	0.51
15 Min	1457	1482	1476	1486	1493	1440	1456	1469	1470	0.62
CIRCULAR PATH C2										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1531	1529	1532	1535	1531	1535	1536	1536	1533	0.00
5 Min	1501	1509	1520	1516	1510	1510	1510	1511	1511	0.22
10 Min	1472	1501	1486	1481	1485	1483	1483	1474	1483	0.50
15 Min	1462	1484	1472	1470	1477	1483	1477	1473	1474	0.59
CIRCULAR PATH C3										
POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1533	1535	1533	1538	1538	1530	1528	1530	1533	0.00
5 Min	1463	1499	1491	1486	1484	1489	1492	1502	1505	0.28
10 Min	1463	1499	1491	1486	1484	1489	1492	1502	1488	0.45
15 Min	1463	1485	1482	1459	1472	1472	1490	1502	1478	0.55

TABLE E23

MIX: 11	W/C : 0.51	PFA: 20%	CURING: AC	AGE OF TESTING: 6/12 MONTHS

CIRCULAR PATH C1

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1535	1532	1533	1530	1525	1530	1540	1535	1532	0.00
5 Min	1524	1520	1519	1520	1520	1525	1530	1515	1521	0.11
10 Min	1514	1503	1512	1504	1506	1507	1514	1501	1507	0.35
15 Min	1500	1503	1512	1504	1506	1505	1503	1501	1504	0.28

CIRCULAR PATH C2

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1538	1530	1525	1526	1534	1530	1532	1531	1530	0.00
5 Min	1515	1514	1519	1520	1524	1517	1520	1515	1518	0.12
10 Min	1507	1509	1512	1517	1511	1505	1508	1503	1509	0.21
15 Min	1504	1509	1512	1516	1509	1505	1508	1498	1507	0.23

CIRCULAR PATH C3

POINTS	1	2	3	4	5	6	7	8	M.VALUE	M.DEPTH(mm)
Initial V	1529	1537	1543	1530	1538	1525	1530	1530	1532	0.00
5 Min	1500	1515	1515	1520	1515	1520	1519	1520	1515	0.17
10 Min	1490	1509	1513	1509	1507	1493	1512	1514	1505	0.27
15 Min	1490	1509	1508	1508	1507	1493	1512	1497	1503	0.29

A P P E N D I X F

APPENDIX F
ABRASION TEST - DETAILED RESULTS

TABLE F1 MIX 1

DETAILED RESULTS OF ABRASION DEPTH									
MIX No.	TYPE OF CURING	AGE (days)	TIME (min)	DEPTH OF WEAR (mm)			MEAN VALUE (mm)	COMMENTS	
				1	2	3			
1. 0.65 /30	PS	28	5 10 15	0.19 0.47 -	0.21 0.41 -	0.32 0.45 -	0.240 0.443 -	Time (min)	Depth (mm)
								5 10 15	0.46 1.04
		28	5 10 15	0.68 1.69 -	0.56 1.72 -	0.80 1.47 -	0.68 1.63 -		
		90	5 10 15	0.31 0.73 1.13	0.37 0.73 0.97	0.34 0.72 0.92	0.34 0.73 1.01	5 10 15	0.32 0.72 1.01
		90	5 10 15	0.19 0.67 1.20	0.25 0.60 1.04	0.46 0.84 1.29	0.30 0.70 1.18		
	AC	28	5 10 15	0.67 0.71 1.35	0.78 2.60 2.70	0.67 0.80 1.24	0.71 1.37 1.76	5 10 15	0.81 1.32 1.60
		28	5 10 15	0.74 1.18 1.49	0.85 1.25 1.37	1.11 1.38 1.45	0.90 1.27 1.44		
		90	5 10 15	2.08 - -	2.15 - -	1.60 - -	1.94 - -	5 10 15	1.79 - -
		90	5 10 15	1.81 - -	1.44 - -	1.65 - -	1.63 - -		
	CC	28	5 10 15	1.76 - -	2.16 - -	1.60 - -	1.84 - -	5 10 15	1.92 - -
		28	5 10 15	2.51 - -	2.01 - -	1.49 - -	2.00 - -		
		90	5 10 15	2.46 - -	2.06 - -	2.06 - -	2.19 - -	5 10 15	2.20 - -
		90	5 10 15	2.20 -	- -	- -	2.20 -		

TABLE F2 MIX 2

DETAILED RESULTS OF ABRASION DEPTH									
MIX No.	TYPE OF CURING	AGE (days)	TIME (min)	DEPTH OF WEAR (mm)			MEAN VALUE (mm)	COMMENTS	
				1	2	3			
2. 0.37 /30	PS	28	5	0.23	0.12	0.05	0.13	Time	Depth
			10	0.26	0.21	0.16	0.21		
			15	0.45	0.52	0.23	0.42	5	0.14
								10	0.25
		28	5	0.24	0.15	0.07	0.15	15	
			10	0.41	0.26	0.19	0.29		
			15	0.56	0.39	0.36	0.44		
		90	5	0.19	0.28	0.48	0.32		
			10	0.30	0.46	0.61	0.46		
			15	0.36	0.52	0.73	0.54		
		180	5	0.03	0.01	0.06	0.03		
			10	0.08	0.12	0.07	0.09		
			15	0.14	0.13	0.07	0.11		
	AC	28	5	0.13	0.24	0.29	0.22		
			10	0.25	0.49	0.39	0.38		
			15	0.40	0.81	0.58	0.60	5	0.25
								10	0.43
		28	5	0.31	0.27	0.27	0.28	15	0.65
			10	0.52	0.40	0.52	0.48		
			15	0.83	0.61	0.67	0.70		
		90	5	0.15	0.20	0.11	0.15		
			10	0.34	0.41	0.26	0.34		
			15	0.42	0.95	0.72	0.69		
		180	5	0.06	0.06	0.12	0.08		
			10	0.19	0.22	0.26	0.22		
			15	0.26	0.30	0.44	0.33		
	CC	28	5	0.12	0.06	0.02	0.06		
			10	0.22	0.11	0.09	0.14		
			15	0.28	0.15	0.12	0.18	5	0.08
								10	0.14
		28	5	0.07	0.05	0.16	0.09	15	0.18
			10	0.09	0.09	0.20	0.13		
			15	0.14	0.14	0.26	0.18		
		90	5	0.28	0.24	0.20	0.24		
			10	0.47	0.34	0.26	0.36		
			15	0.51	0.47	0.43	0.47		
		180	5	0.08	0.01	0.05	0.05		
			10	0.08	0.07	0.05	0.06		
				0.09	0.08	0.07	0.08		

TABLE F3 MIX 3

DETAILED RESULTS OF ABRASION DEPTH

MIX No.	TYPE OF CURING	AGE (days)	TIME (min)	DEPTH OF WEAR (mm) 1	2	3	MEAN VALUE (mm)	COMMENTS Time	Depth
3. 0.65 /40	PS	28	5	0.41	0.47	0.89	0.59	Time	Depth
			10	-	-	-	-		
			15	-	-	-	-	5	0.07
								10	0.19
		28	5	0.08	0.07	0.05	0.07	15	0.54
			10	0.10	0.24	0.24	0.19		
			15	0.42	0.66	0.54	0.54		
		90	5	0.10	0.10	slab	0.10		
			10	0.32	0.17	was	0.25		
			15	0.38	0.35	broken	0.37		
		180	5	0.50	0.36	0.25	0.37		
			10	0.65	0.48	0.32	0.48		
			15	0.69	0.54	0.41	0.55		
	AC	28	5	0.96	1.17	0.70	0.94		
			10	-	-	-	-		
			15	-	-	-	-	5	0.28
								10	0.92
		28	5	0.18	0.50	0.16	0.28	15	-
			10	0.84	1.40	0.66	0.97		
			15	-	-	-	-		
		90	5	0.66	0.54	0.68	0.63		
			10	1.54	0.98	1.40	1.31		
			15	-	-	-	-		
		180	5	1.27	1.38	1.43	1.36		
			10	-	-	-	-		
			15	-	-	-	-		
	CC	28	5	0.68	0.99	0.63	0.77		
			10	-	-	-	-		
			15	-	-	-	-	5	0.18
								10	0.65
		28	5	0.20	0.18	0.16	0.18	15	1.48
			10	0.61	0.68	0.66	0.65		
			15	1.58	1.57	1.30	1.48		
		90	5	0.09	0.11	0.17	0.12		
			10	0.20	0.15	0.19	0.18		
			15	0.28	0.24	0.22	0.25		
		90	5	1.03	0.72	0.54	0.76		
			10	-	-	-	-		
			15	-	-	-	-		

TABLE F4 MIX 4

DETAILED RESULTS OF ABRASION DEPTH

MIX No.	TYPE OF CURING	AGE (days)	TIME (min)	DEPTH OF WEAR (mm) 1	2	3	MEAN VALUE (mm)	COMMENTS Time	Depth
4. 0.65/0	PS	28	5	0.29	0.16	0.15	0.20		
			10	0.58	0.29	0.28	0.38		
			15	0.76	0.74	0.63	0.71	5	0.30
								10	0.64
		28	5	0.54	0.34	0.30	0.39	15	1.0
			10	1.28	0.70	0.71	0.90		
			15	1.56	1.20	-	1.38		
		90	5	0.09	0.10	0.18	0.12		
			10	0.17	0.25	0.39	0.27		
			15	0.37	0.40	0.57	0.45		
		180	5	0.18	0.22	0.24	0.21		
			10	0.32	0.28	0.30	0.30		
			15	0.42	0.33	0.34	0.36		
	AC	28	5	0.25	0.58	0.37	0.40		
			10	0.46	1.13	0.62	0.74		
			15	0.95	1.38	0.85	1.06	5	0.37
								10	0.62
		28	5	0.32	0.24	0.47	0.34	15	1.05
			10	0.49	0.45	0.56	0.50		
			15	0.94	1.04	1.12	1.03		
		90	5	0.26	0.39	0.27	0.31		
			10	0.45	0.68	0.43	0.52		
			15	0.77	0.97	0.97	0.90		
		180	5	0.38	0.34	0.34	0.35		
			10	0.51	0.48	0.50	0.50		
			15	0.58	0.55	0.59	0.57		
	CC	28	5	0.51	0.27	0.32	0.37		
			10	1.04	0.69	0.74	0.82		
			15	1.69	1.48	1.18	1.45	5	0.35
								10	0.99
		28	5	0.31	0.43	0.25	0.33	15	1.45
			10	0.64	1.22	0.63	1.16		
			15	-	-	-	-		
		90	5	0.18	0.20	0.29	0.22		
			10	0.50	0.28	0.36	0.38		
			15	1.20	0.70	0.65	0.85		
		90	5	0.19	0.14	0.26	0.20		
			10	0.20	0.18	0.26	0.21		
			15	0.21	0.21	0.38	0.26		

TABLE F5 MIX 5

DETAILED RESULTS OF ABRASION DEPTH								
MIX No.	TYPE OF CURING	AGE (days)	TIME (min)	DEPTH OF WEAR (mm)			MEAN VALUE (mm)	COMMENTS
				1	2	3		
5. 0.56 /0	PS	28	5	0.08	0.09	0.21	0.13	
			10	0.27	0.22	0.28	0.26	
			15	0.43	0.42	0.39	0.41	
		90	5	0.01	0.01	0.34	0.12	
			10	0.01	0.05	0.37	0.14	
			15	0.01	0.05	0.40	0.15	
	AC	28	5	0.22	0.13	0.21	0.19	
			10	0.55	0.51	0.38	0.48	
			15	0.65	0.64	0.71	0.67	
		90	5	0.61	0.47	0.40	0.49	
			10	0.73	0.65	0.55	0.64	
			15	0.79	0.88	0.83	0.83	
	CC	28	5	0.11	0.02	0.06	0.06	
			10	0.14	0.05	0.11	0.10	
			15	0.25	0.12	0.11	0.16	
		90	5	0.20	0.29	0.05	0.18	
			10	0.36	0.45	0.20	0.34	
			15	0.46	0.50	0.20	0.39	

TABLE F6 MIX 6

DETAILED RESULTS OF ABRASION DEPTH								
MIX No.	TYPE OF CURING	AGE (days)	TIME (min)	DEPTH OF WEAR (mm)			MEAN VALUE (mm)	COMMENTS
				1	2	3		
6. 0.65 /10	PS	28	5	0.22	0.18	0.20	0.20	
			10	0.27	0.21	0.27	0.25	
			15	0.30	0.28	0.29	0.29	
		90	5	0.13	0.13	0.09	0.12	
			10	0.17	0.18	0.15	0.17	
			15	0.21	0.19	0.18	0.19	
	AC	28	5	0.55	0.41	0.56	0.51	
			10	0.64	0.63	0.84	0.70	
			15	0.67	0.67	0.89	0.74	
		90	5	0.23	0.24	0.22	0.23	
			10	0.31	0.38	0.34	0.34	
			15	0.34	0.43	0.39	0.39	
	CC	28	5	0.33	0.33	0.32	0.33	
			10	0.41	0.33	0.35	0.36	
			15	0.48	0.41	0.37	0.42	
		90	5	0.11	0.08	0.10	0.01	
			10	0.12	0.09	0.13	0.11	
			15	0.14	0.11	0.17	0.14	

TABLE F7 MIX 7

DETAILED RESULTS OF ABRASION DEPTH								
MIX No.	TYPE OF CURING	AGE (days)	TIME (min)	DEPTH OF WEAR (mm)			MEAN VALUE (mm)	COMMENTS
				1	2	3		
7. 0.65 /20	PS	28	5	0.20	0.14	0.10	0.15	
			10	0.39	0.29	0.20	0.29	
			15	0.46	0.35	0.27	0.36	
		90	5	0.37	0.34	0.17	0.29	
			10	0.46	0.42	0.33	0.40	
			15	0.51	0.46	0.43	0.47	
	AC	28	5	0.31	0.29	0.41	0.34	
			10	0.49	0.48	0.59	0.52	
			15	0.70	0.74	0.67	0.70	
		90	5	0.19	0.29	0.24	0.24	
			10	0.33	0.45	0.47	0.42	
			15	0.49	0.51	0.58	0.53	
	CC	28	5	0.24	0.17	0.21	0.21	
			10	0.32	0.24	0.32	0.29	
			15	0.35	0.32	0.53	0.40	
		90	5	0.15	0.16	0.27	0.19	
			10	0.20	0.19	0.36	0.25	
			15	0.28	0.28	0.40	0.32	

TABLE F8 MIX 8

DETAILED RESULTS OF ABRASION DEPTH								
MIX No.	TYPE OF CURING	AGE (days)	TIME (min)	DEPTH OF WEAR (mm)			MEAN VALUE (mm)	COMMENTS
				1	2	3		
8. 0.44 /40	PS	28	5	0.32	0.21	0.16	0.23	
			10	0.66	0.50	0.30	0.49	
			15	0.74	0.54	0.37	0.55	
		90	5	0.33	0.26	0.18	0.26	
			10	0.47	0.40	0.31	0.39	
			05	1.51	0.44	0.38	0.44	
		180	5	0.21	0.20	0.20	0.20	
			10	0.22	0.25	0.29	0.25	
			15	0.30	0.30	0.30	0.30	
	AC	28	5	0.35	0.05	0.16	0.19	
			10	0.61	0.40	0.36	0.46	
			15	0.76	0.49	0.46	0.57	
		90	5	0.51	0.45	0.50	0.49	
			10	0.64	0.63	0.65	0.64	
			15	0.76	0.71	0.74	0.74	
		180	5	0.42	0.55	0.22	0.40	
			10	0.50	0.60	0.30	0.46	
			15	0.60	0.70	0.40	0.57	

TABLE F9 MIX 9

DETAILED RESULTS OF ABRSION DEPTH								
MIX No.	TYPE OF CURING	AGE (days)	TIME (min)	DEPTH OF WEAR (mm)			MEAN VALUE (mm)	COMMENTS
				1	2	3		
9. 0.50 /10	PS	28	5	0.37	0.33	0.44	0.38	
			10	0.56	0.44	0.57	0.52	
			15	0.63	0.50	0.61	0.58	
		90	5	0.08	0.11	0.10	0.01	
			10	0.30	0.11	0.30	0.24	
			15	0.31	0.20	0.30	0.27	
		180	5	0.15	0.12	0.12	0.13	
			10	0.22	0.32	0.38	0.31	
			15	0.24	0.33	0.39	0.32	
	AC	28	5	0.46	0.43	-	0.45	
			10	0.64	0.53	-	0.59	
			15	0.72	0.68	-	0.70	
		90	5	0.11	0.13	0.12	0.12	
			10	0.20	0.30	0.40	0.30	
			15	0.30	0.40	0.41	0.37	
		180	5	0.26	0.26	0.25	0.26	
			10	0.28	0.28	0.27	0.28	
			15	0.41	0.37	0.33	0.37	

TABLE F10 MIX 10

DETAILED RESULTS OF ABRASION DEPTH								
MIX No.	TYPE OF CURING	AGE (days)	TIME (min)	DEPTH OF WEAR (mm)			MEAN VALUE (mm)	COMMENTS
				1	2	3		
10. 0.46 /10	PS	28	5	0.20	0.23	0.32	0.25	
			10	0.41	0.40	0.47	0.43	
			15	0.67	0.59	0.63	0.63	
		90	5	0.08	0.08	0.24	0.13	
			10	0.20	0.21	0.30	0.24	
			15	0.50	0.40	0.50	0.47	
		180	5	0.19	0.21	0.17	0.19	
			10	0.22	0.30	0.28	0.27	
			15	0.26	0.37	0.29	0.31	
	AC	28	5	0.51	0.62	0.27	0.47	
			10	0.75	0.76	0.40	0.64	
			15	0.93	0.89	0.51	0.78	
		90	5	0.23	0.27	0.29	0.26	
			10	0.30	1.39	0.30	0.33	
			15	0.50	0.50	0.50	0.50	
		180	5	0.54	0.54	0.51	0.53	
			10	0.64	0.72	0.75	0.70	
			15	0.82	0.84	0.84	0.83	

TABLE F11 MIX 11

DETAILED RESULTS OF ABRASION DEPTH								
MIX No.	TYPE OF CURING	AGE (days)	TIME (min)	DEPTH OF WEAR (mm)			MEAN VALUE (mm)	COMMENTS
				1	2	3		
11. 0.51 /20	PS	28	5	0.10	0.20	0.10	0.13	
			10	0.20	0.34	0.16	0.23	
			15	0.30	0.44	0.26	0.33	
		90	5	0.11	0.11	0.06	0.09	
			10	0.25	0.40	0.40	0.35	
			15	1.40	0.41	0.41	0.41	
		180	5	0.11	0.12	0.17	0.13	
			10	0.25	0.21	0.27	0.24	
			15	0.28	0.23	0.29	0.27	
	AC	28	5	0.31	0.32	0.30	0.31	
			10	0.49	0.51	0.41	0.47	
			15	0.59	0.60	0.51	0.56	
		90	5	0.17	0.19	0.23	0.20	
			10	0.40	0.33	0.40	0.38	
			15	0.50	0.40	0.50	0.47	
		180	5	0.31	0.22	0.28	0.27	
			10	0.51	0.50	0.45	0.49	
			15	0.62	0.59	0.55	0.59	

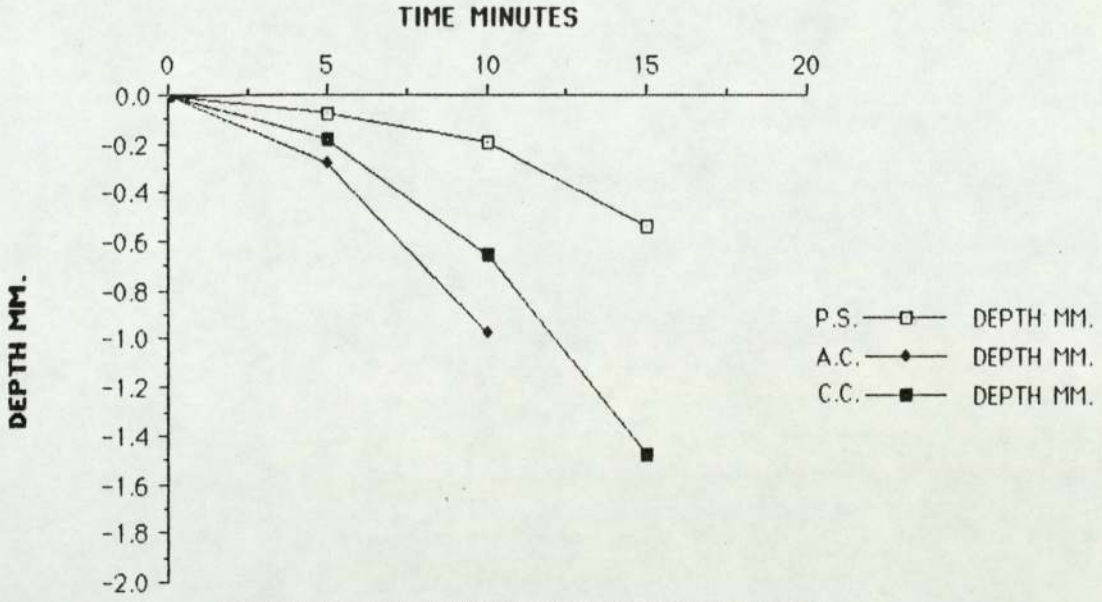


FIG. F1 RATE OF ABRASION RESISTANCE OF MIX 3 AT 28 DAYS FOR DIFFERENT CURING REGIMES.

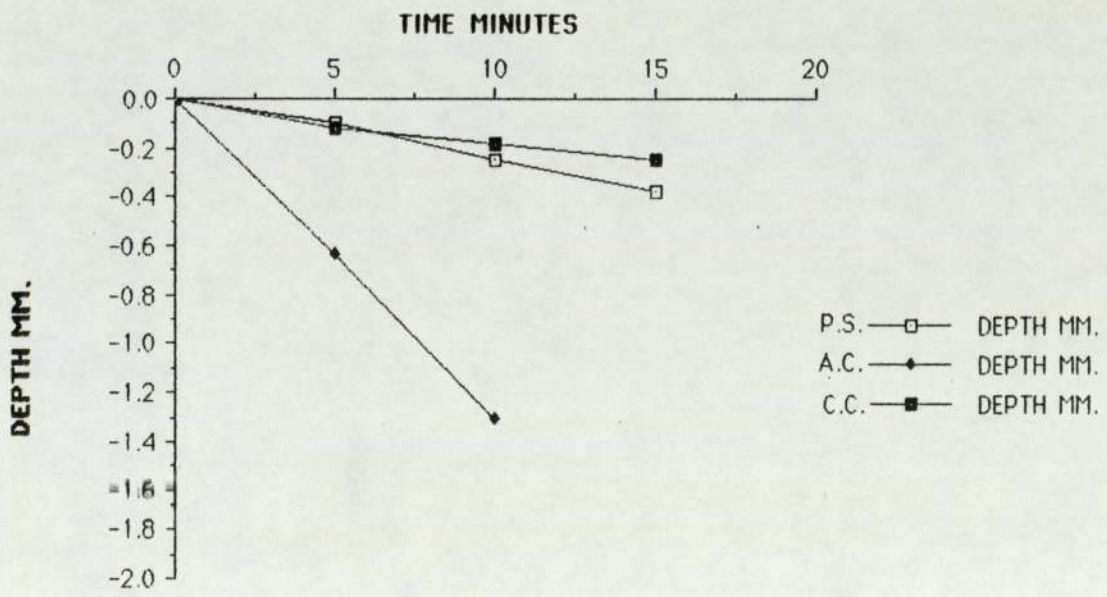


FIG. F2 RATE OF ABRASION RESISTANCE OF MIX 3 AT 90 DAYS FOR DIFFERENT CURING REGIMES.

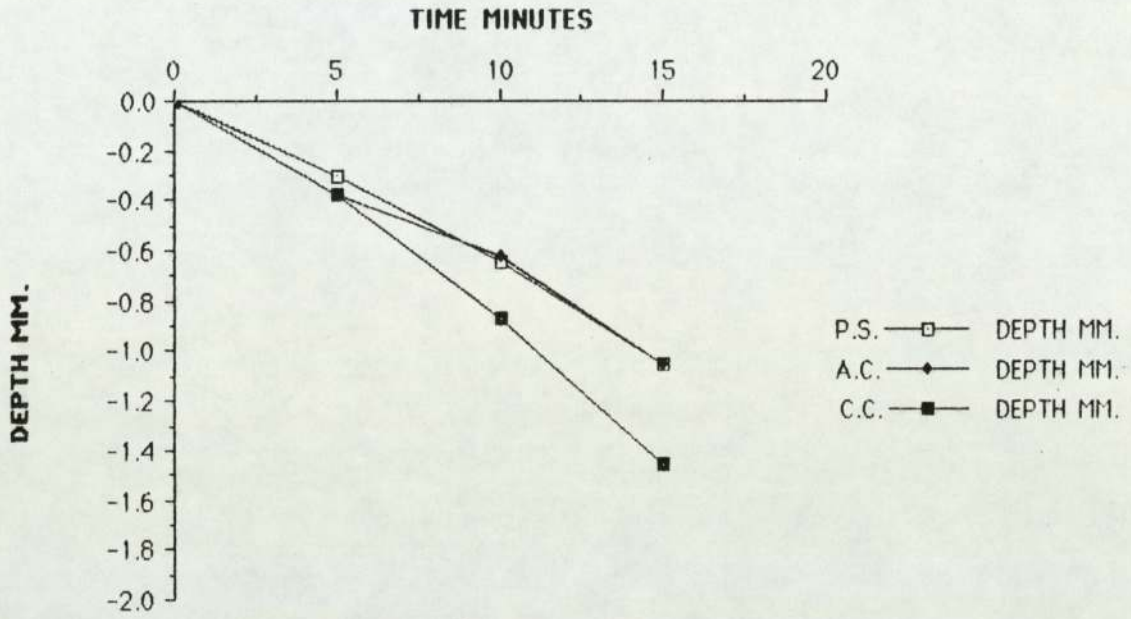


FIG. F3 RATE OF ABRASION RESISTANCE OF MIX 4 AT 28 DAYS FOR DIFFERENT CURING REGIMES.

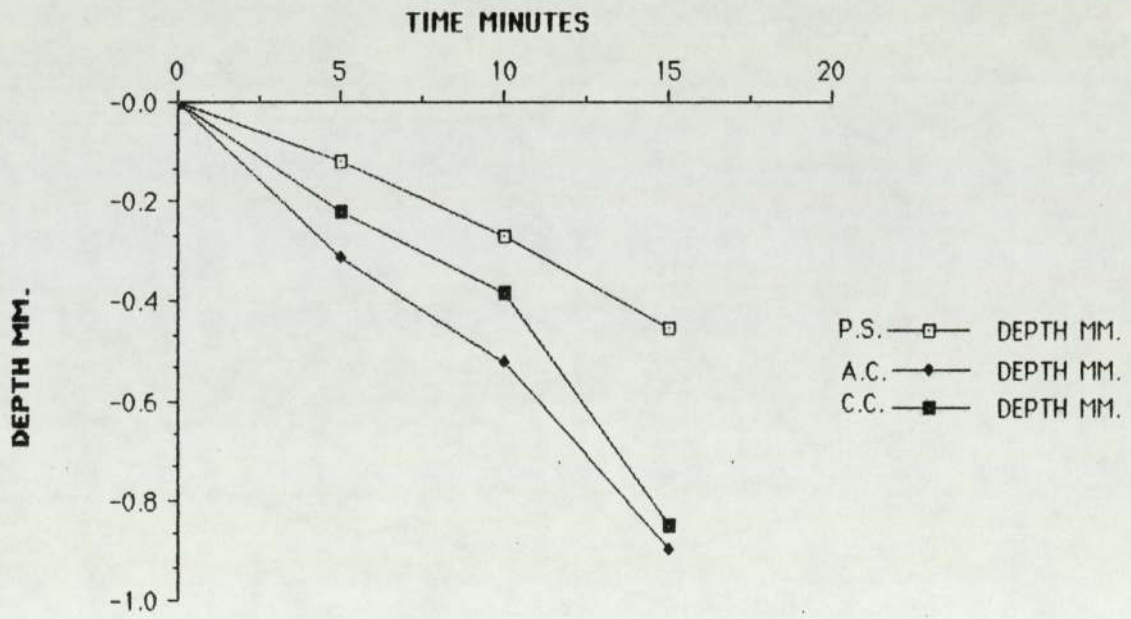


FIG. F4 RATE OF ABRASION RESISTANCE OF MIX 4 AT 90 DAYS FOR DIFFERENT CURING REGIMES.

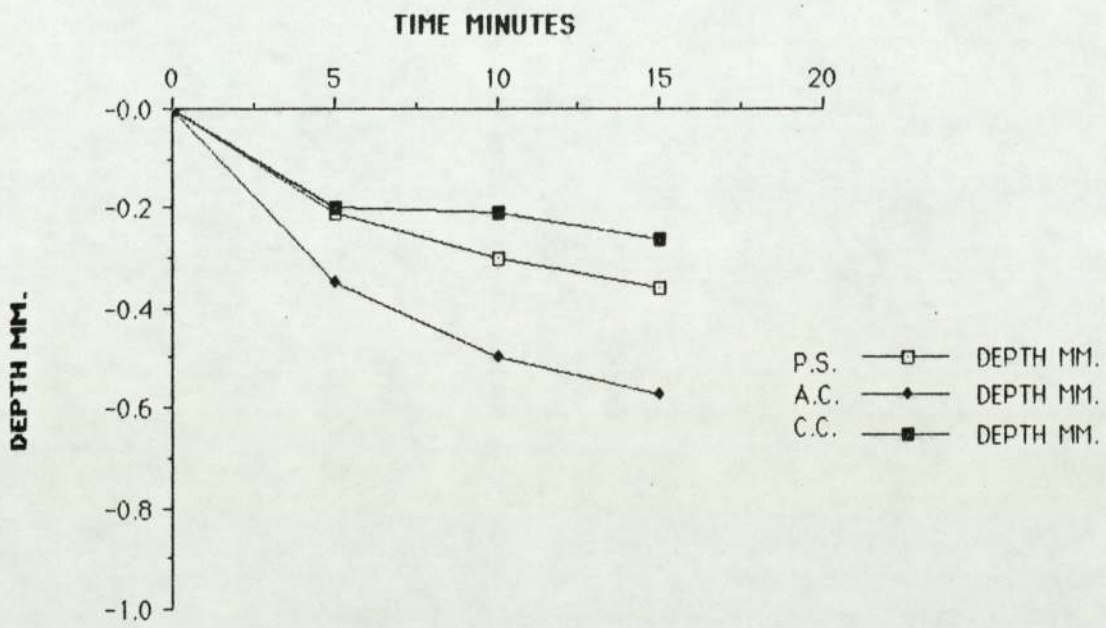


FIG. F5 RATE OF ABRASION RESISTANCE OF MIX 4 AT 180 DAYS FOR DIFFERENT CURING REGIMES.

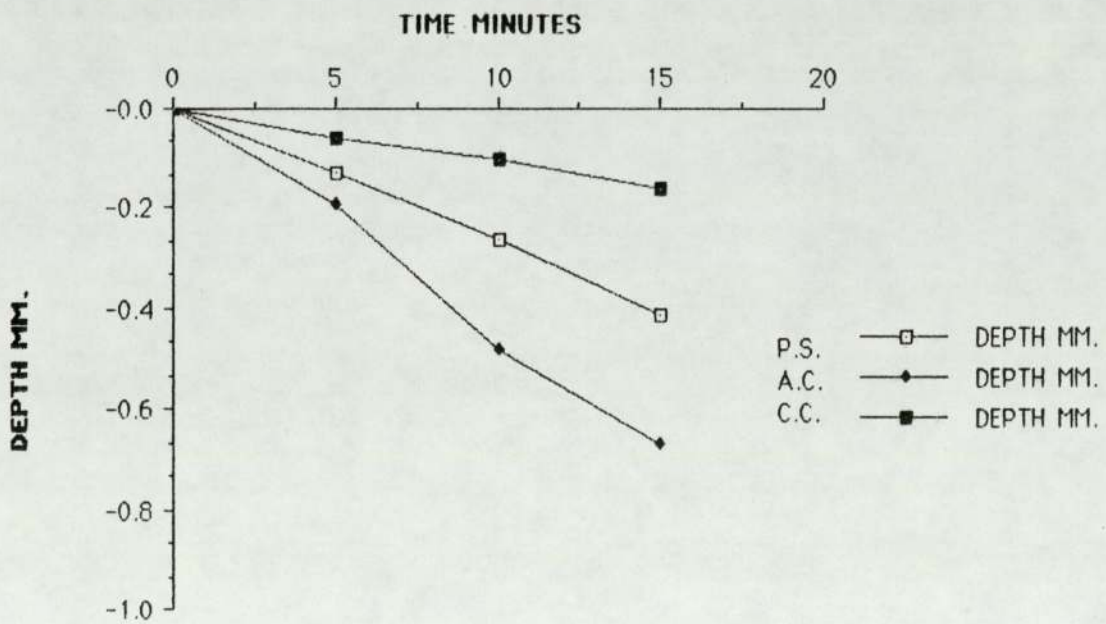


FIG. F6 RATE OF ABRASION RESISTANCE OF MIX 5 AT 28 DAYS FOR DIFFERENT CURING REGIMES.

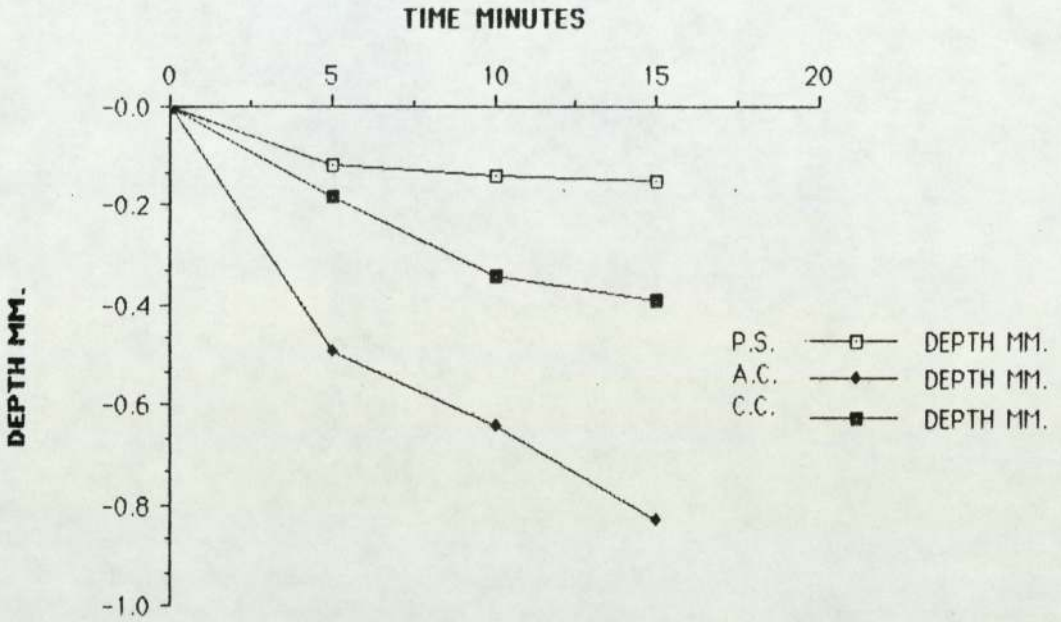


FIG. F7 RATE OF ABRASION RESISTANCE OF MIX 5 AT 90 DAYS FOR DIFFERENT CURING REGIMES.

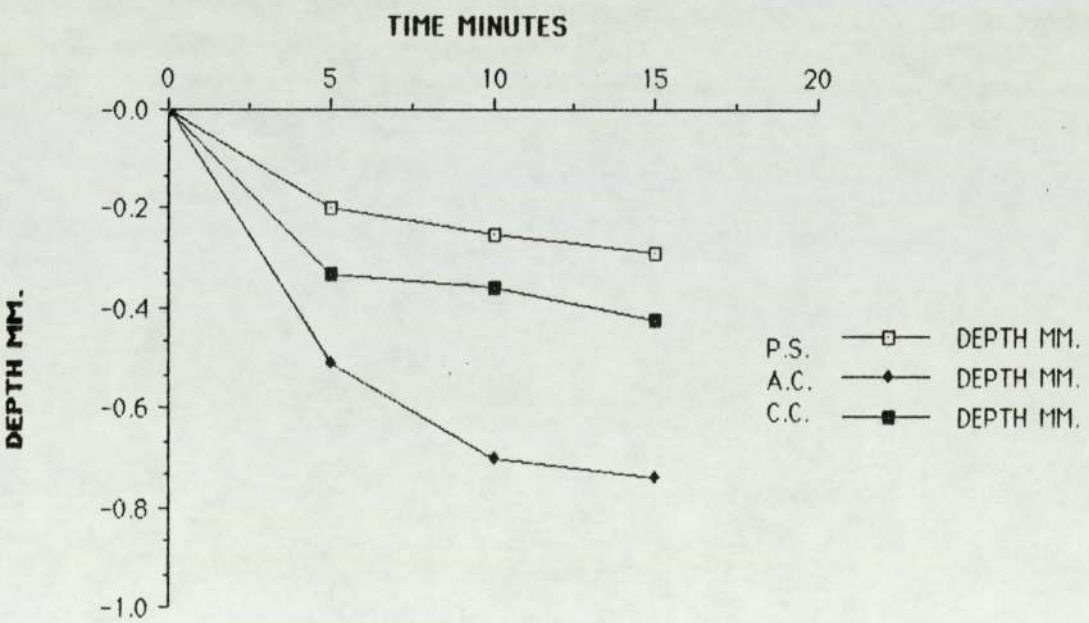


FIG. F8 RATE OF ABRASION RESISTANCE OF MIX 6 AT 28 DAYS FOR DIFFERENT CURING REGIMES.

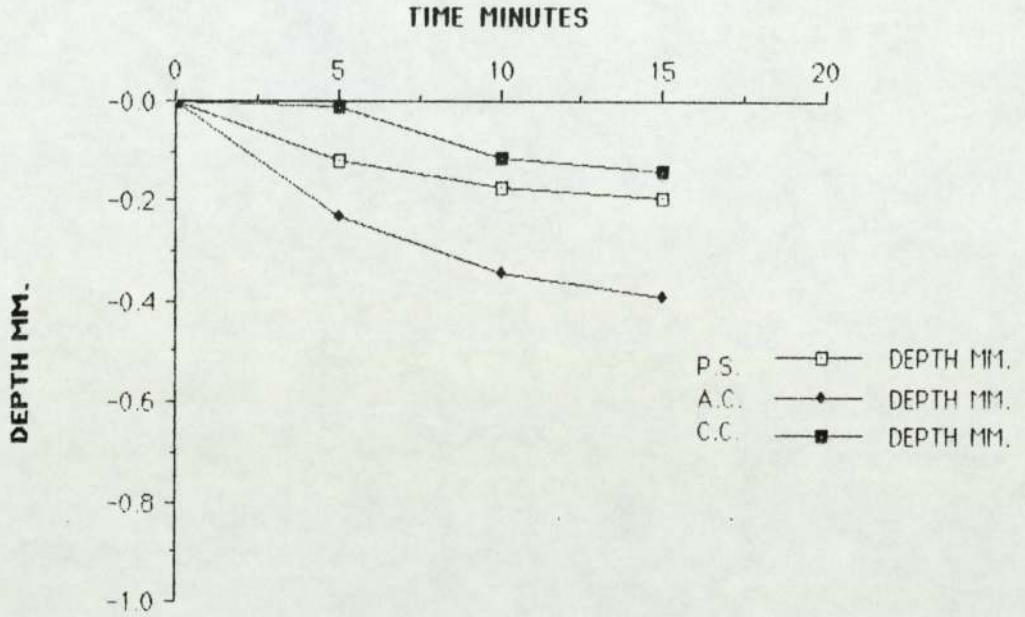


FIG. F9 RATE OF ABRASION RESISTANCE OF MIX 6 AT 90 DAYS FOR DIFFERENT CURING REGIMES.

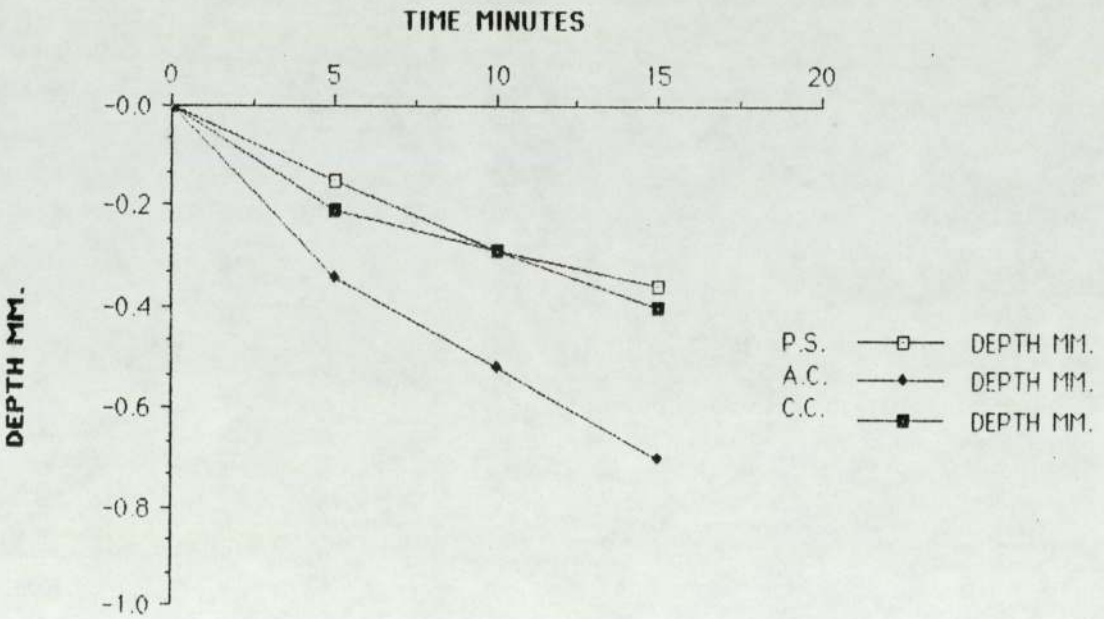


FIG. F10 RATE OF ABRASION RESISTANCE OF MIX 7 AT 28 DAYS FOR DIFFERENT CURING REGIMES.

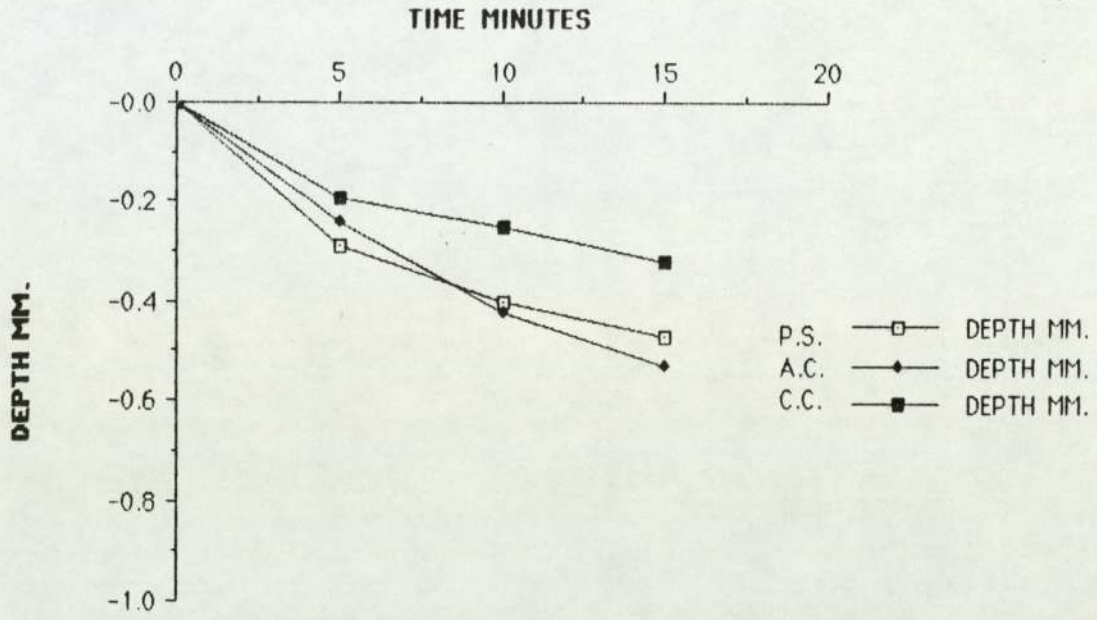


FIG. F11 RATE OF ABRASION RESISTANCE OF MIX 7 AT 90 DAYS FOR DIFFERENT CURING REGIMES.

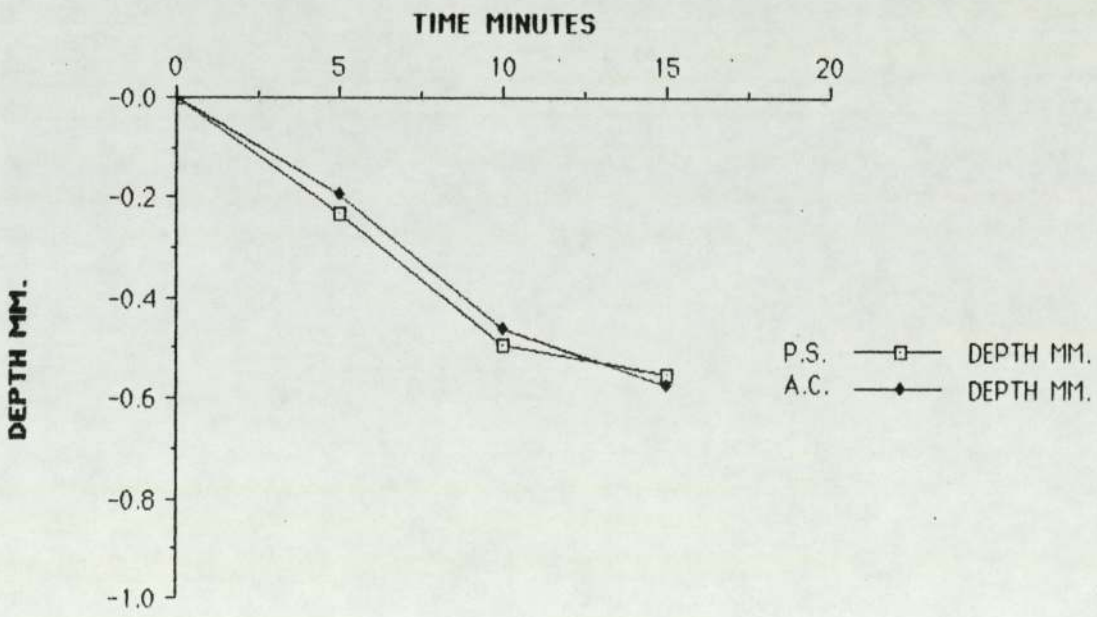


FIG. F12 RATE OF ABRASION RESISTANCE OF MIX 8 AT 28 DAYS FOR P.S. AND A.C. CURING REGIMES.

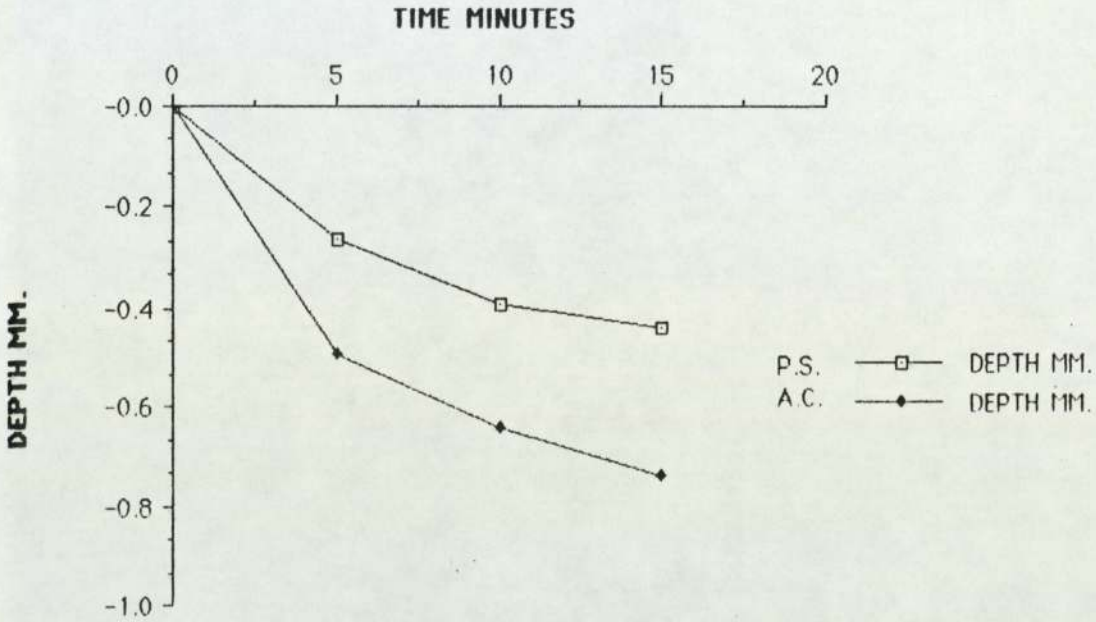


FIG. F13 RATE OF ABRASION RESISTANCE OF MIX 8 AT 90 DAYS FOR A.C. AND P.S. CURING REGIMES.

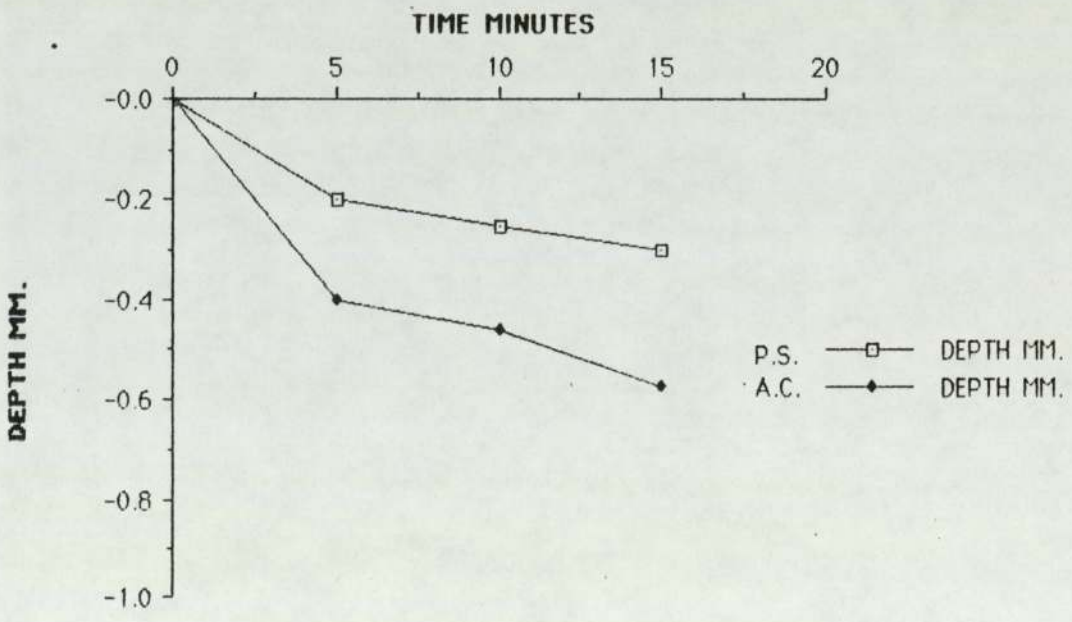


FIG. F14 RATE OF ABRASION RESISTANCE OF MIX 8 AT 180 DAYS FOR A.C. AND P.S. CURING REGIMES.

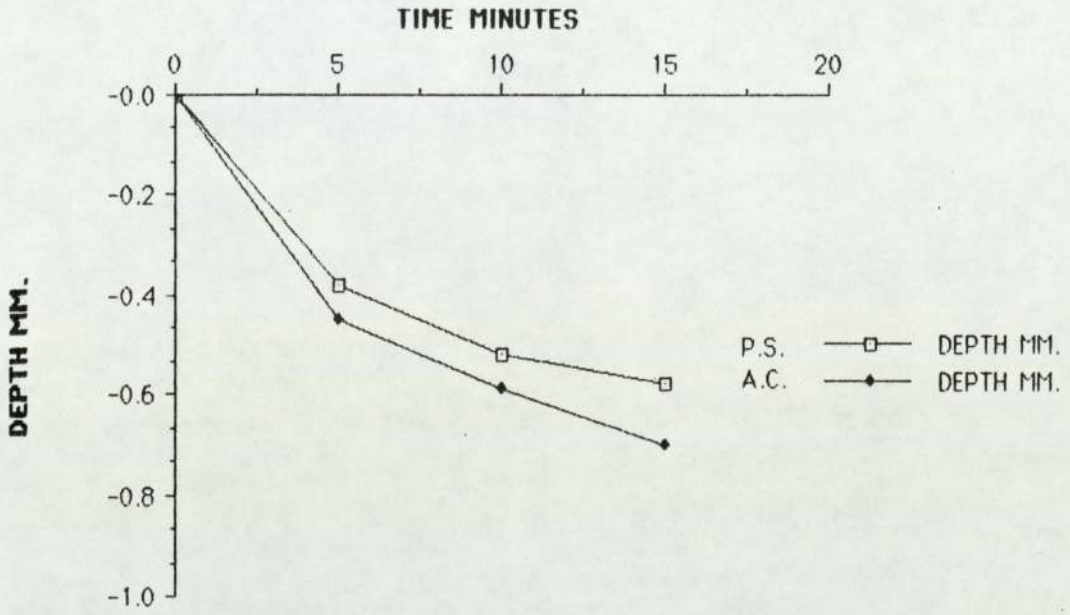


FIG. F15 RATE OF ABRASION RESISTANCE OF MIX 9 AT 28 DAYS FOR A.C. AND P.S. CURING REGIMES.

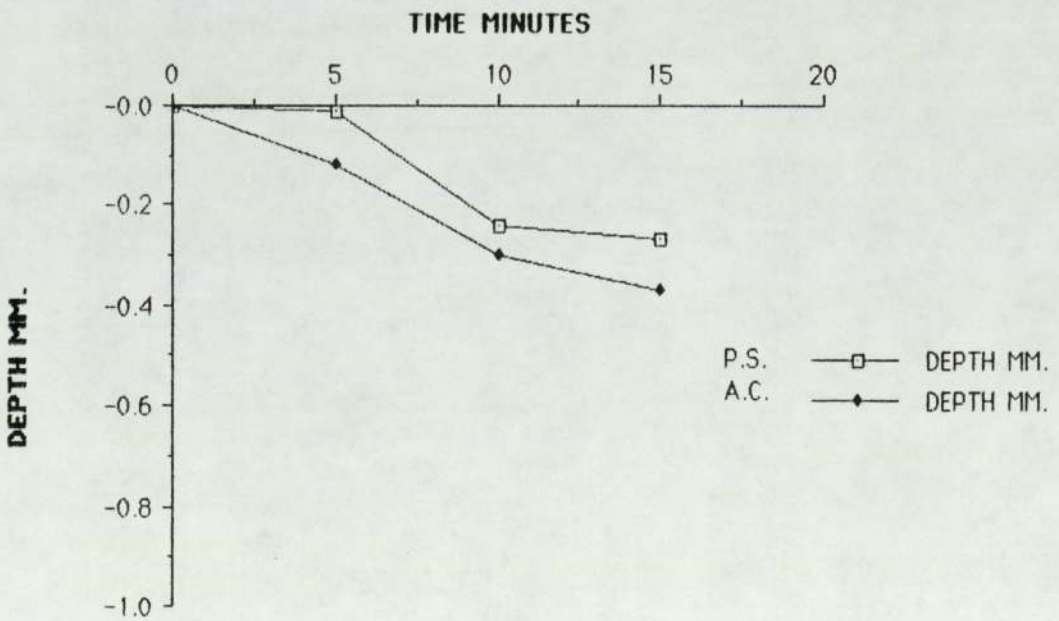


FIG. F16 RATE OF ABRASION RESISTANCE OF MIX 9 AT 90 DAYS FOR A.C. AND P.S. CURING REGIMES.

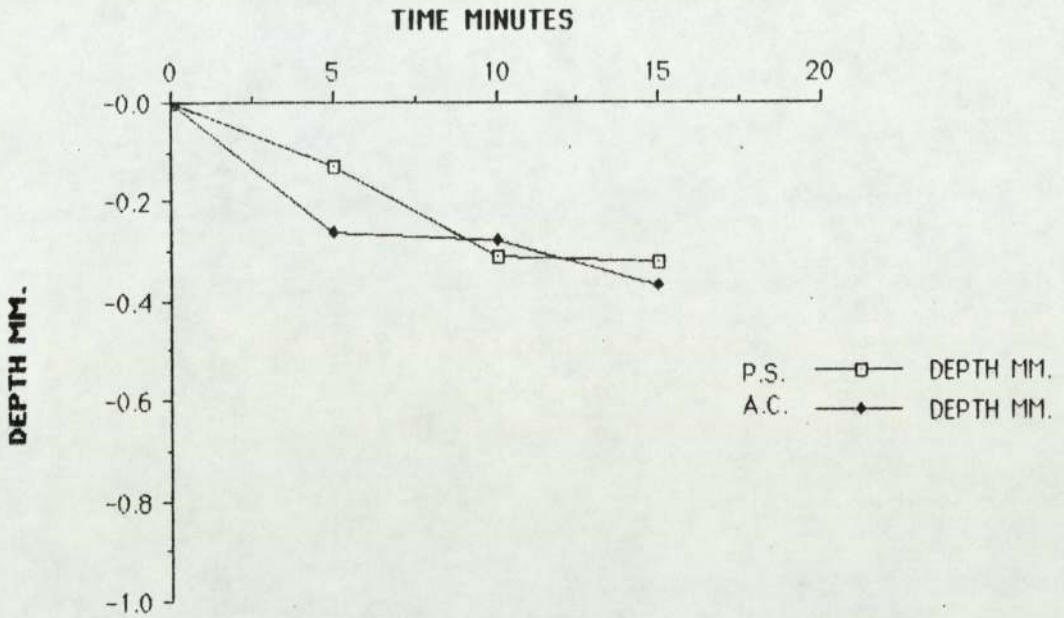


FIG. F17 RATE OF ABRASION RESISTANCE OF MIX 9 AT 180 DAYS FOR A.C. AND P.S. CURING REGIMES.

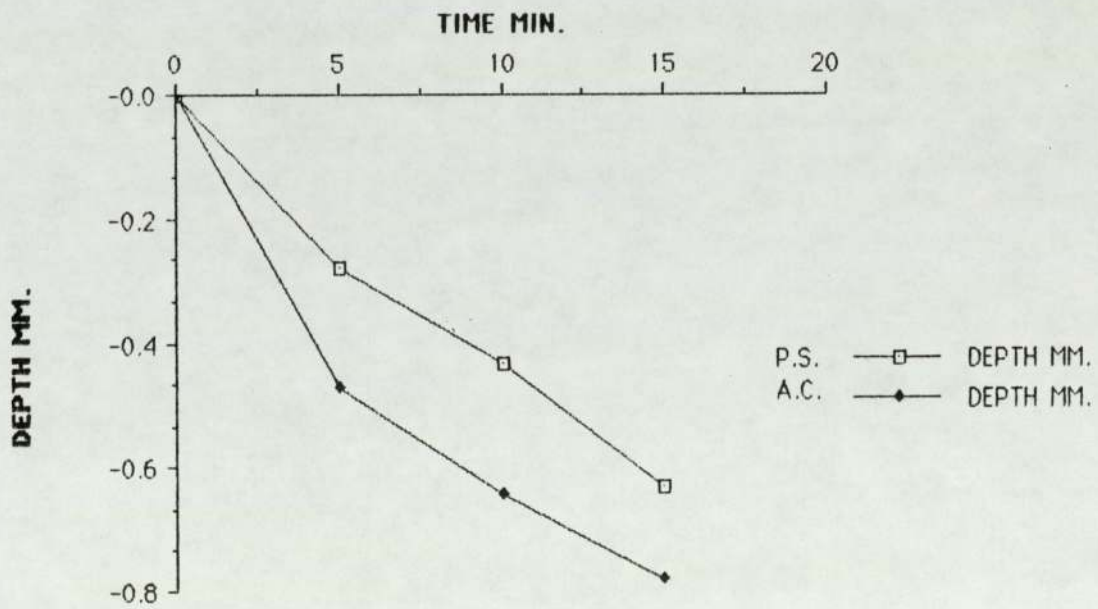


FIG. F18 RATE OF ABRASION RESISTANCE OF MIX 10 AT 28 DAYS FOR DIFFERENT CURING REGIMES.

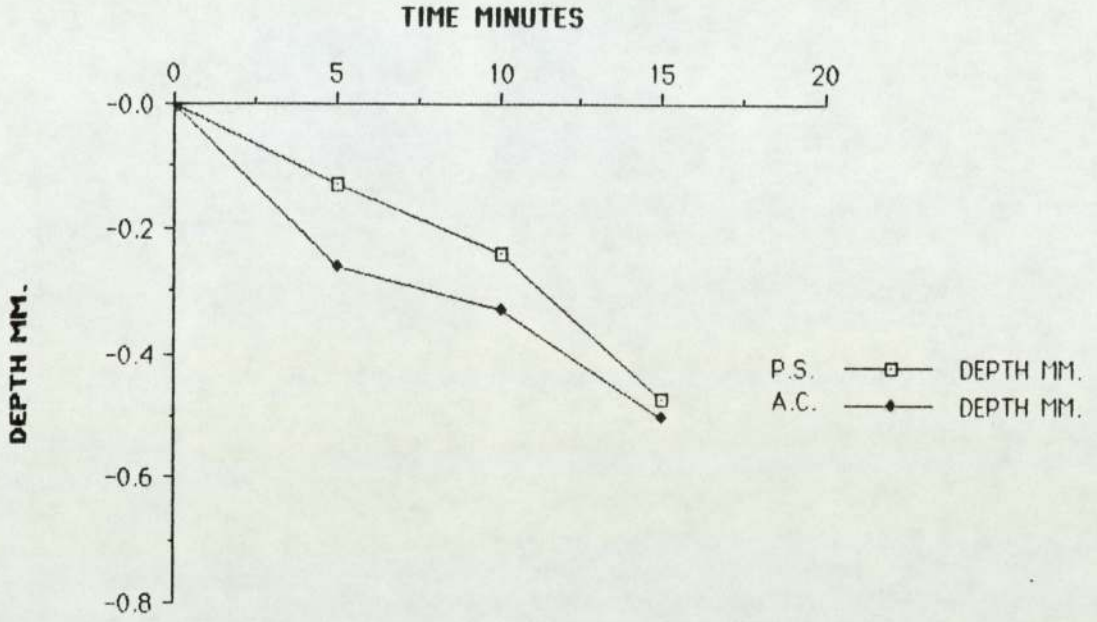


FIG. F19 RATE OF ABRASION RESISTANCE OF MIX 10 AT 90 DAYS FOR DIFFERENT CURING REGIMES.

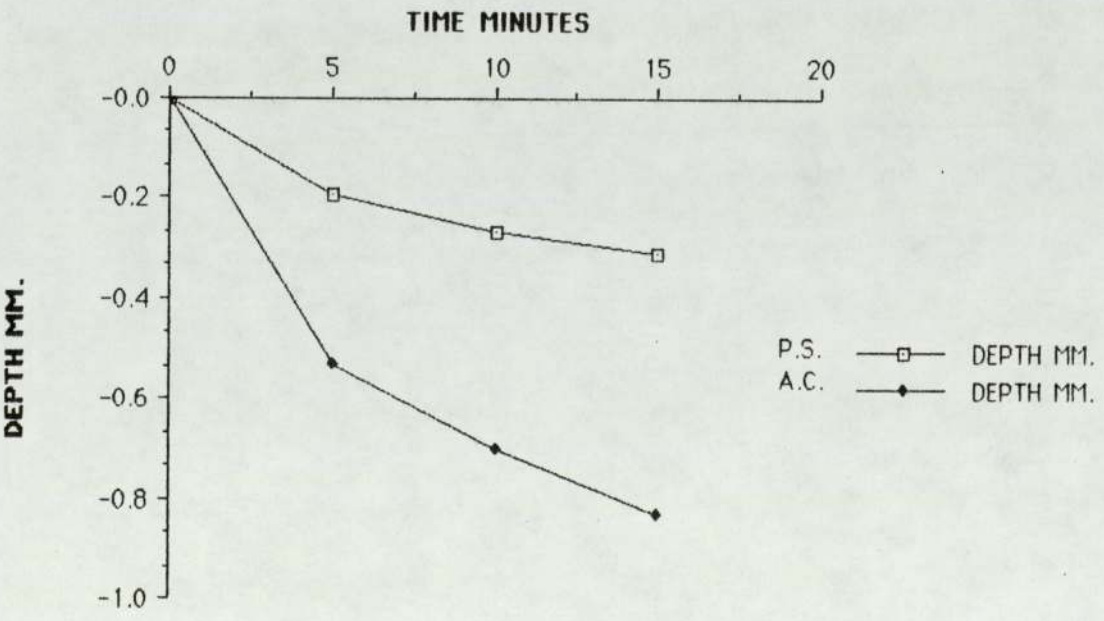


FIG. F20 RATE OF ABRASION RESISTANCE OF MIX 10 AT 180 DAYS FOR DIFFERENT CURING REGIMES.

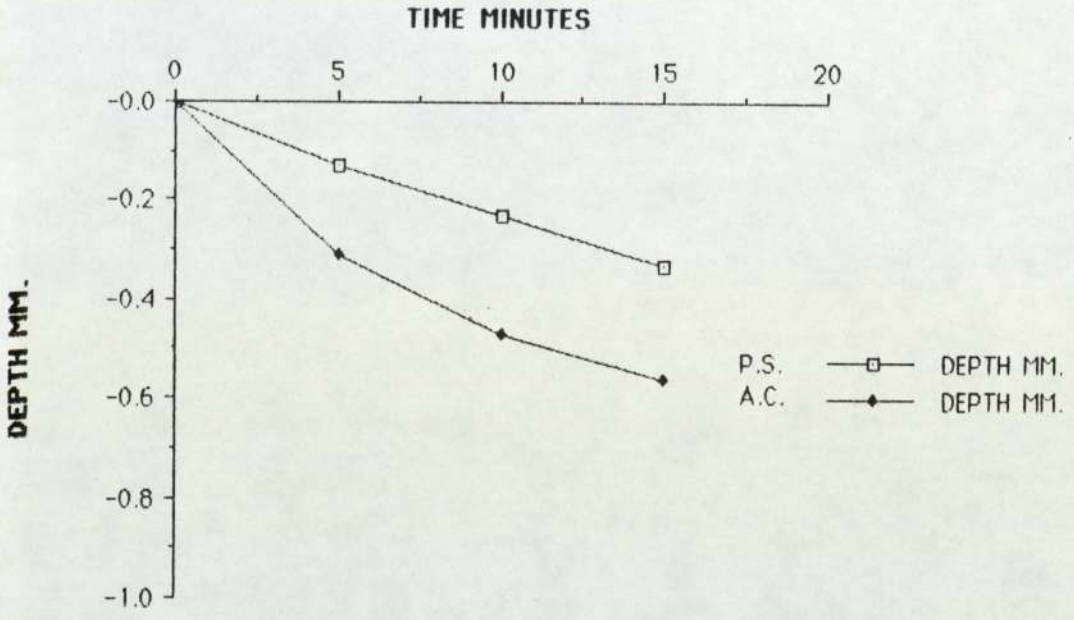


FIG. F21 RATE OF ABRASION RESISTANCE OF MIX 11 AT 28 DAYS FOR DIFFERENT CURING REGIMES.

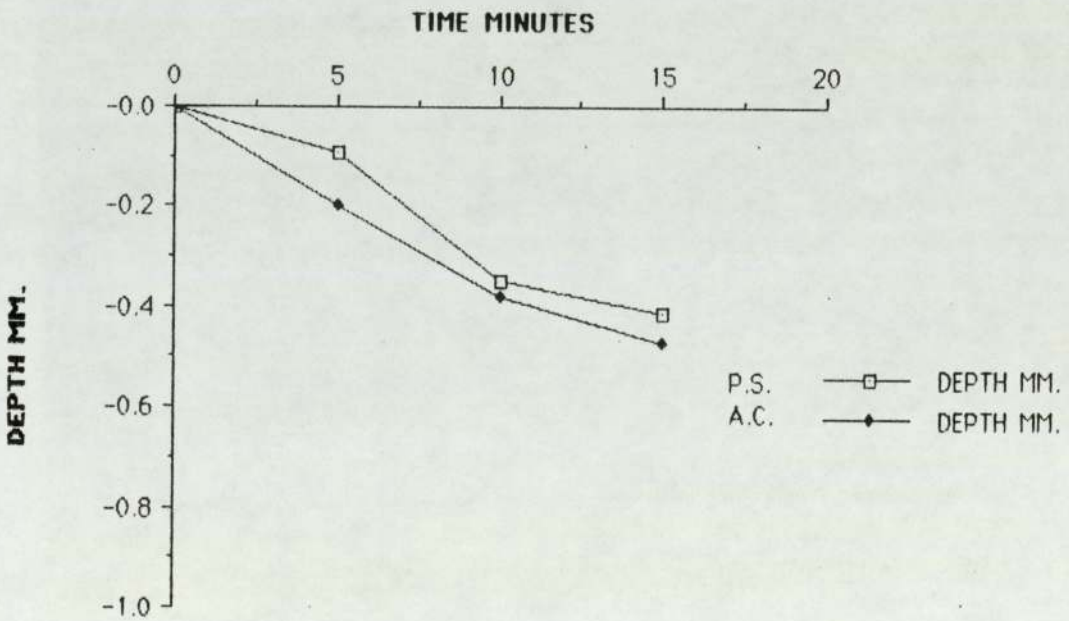


FIG. F22 RATE OF ABRASION RESISTANCE OF MIX 11 AT 90 DAYS FOR DIFFERENT CURING REGIMES.

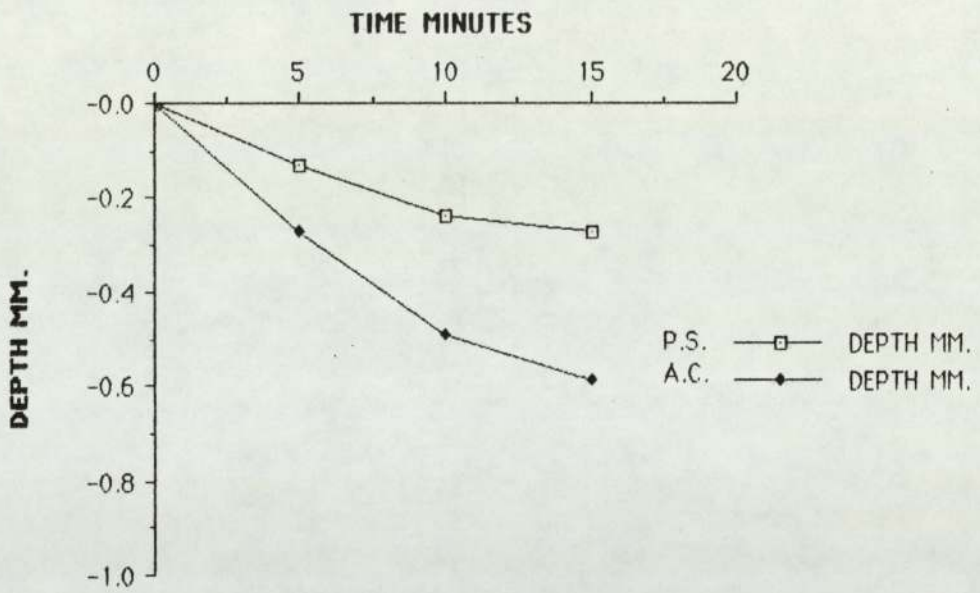


FIG. F23 RATE OF ABRASION RESISTANCE OF MIX 11 AT 180 DAYS FOR DIFFERENT CURING REGIMES.

A P P E N D I X G

The Washburn Formula of the Intrusion of a Non-Wetting Liquid into a Pore

Washburn suggested that the surface tension opposes the entrance of non-wetting liquid into a small pore. This opposing force F_o is given by:

$$F_o = \pi d \gamma \cos \theta$$

Where d is the diameter of the pore, γ is the surface tension of the liquid and θ is the contact angle the liquid makes with the material.

This opposition can be ocvercome by the application of external force F_a given by:

$$F_a = \pi \frac{d^2}{4} P$$

Where P is the applied external pressure. At equilibrium

$$\pi \frac{d^2}{4} P = -\pi d \gamma \cos \theta$$

$$P = \frac{-4 \gamma \cos \theta}{d}$$

A P P E N D I X H

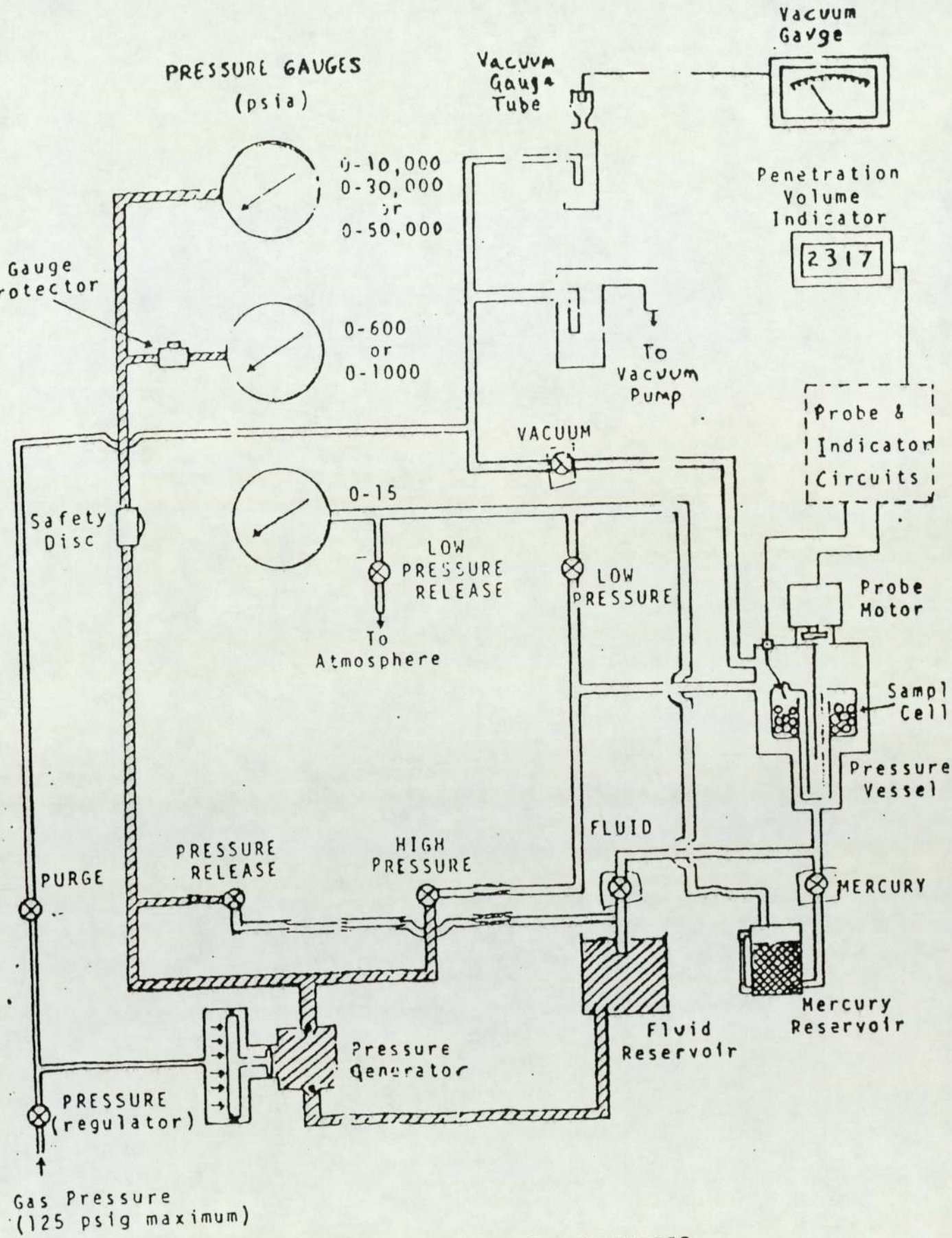


Fig H.1 SCHEMATIC DIAGRAM OF POROSIMETER

A P P E N D I X I

PROCEDURE IN OUTLINE FORM

A. PREPARATION OF SAMPLE AND SAMPLE CELL

1. Wash sample cell with detergent and water and rinse with acetone.

2. Dry sample cell in a vacuum oven or blow clean with dry gas.

3. Weigh the empty sample cell and record as W_c on data sheet.

4. Place sample in sample cell and dry preferably in a vacuum oven. This step is optional depending on the nature of the sample.

5. Weigh the sample cell with sample.

6. Subtract W_c to obtain sample weight and record as W_s on data sheet.

7. Apply a thin film of vacuum grease to the ground surface of both sample flanges. Align top and bottom pieces of the sample cell and press together to form a tight seal. Recommended vacuum greases are Apiezon "H" (MIC P/N: 04-16007) for large piece sample cells used only in Model 910 Series Porosimeters and Apiezon "M" (MIC P/N: 04-16006) for powder sample cells.

8. Another weight should be taken to account for the grease seal if density is to be determined or a blank run is being made.

B. INSTALLATION OF SAMPLE CELL IN PRESSURE VESSEL

NOTE: (1) The Cap Plug/Probe Drive Assembly, MIC P/N: 90-62801 will be referred to as "Head" in the following outline.

(2) Steps designated "a" apply to powder sample cells and those designated "b" apply to large piece sample cells.

1a. Insert the powder sample cell into the holder-retainer, being sure spring is in place. An adapter is required to centre the 20 cc volume x 2 cc penetration sample cell in the holder-retainer.

1b. Place the large piece sample cell on the holder-retainer. Position spacer with flanges up over sample cell and, sighting down through the holes to insure alignment, lower spacer around the sample cell, resting the side pins on the flanges of holder-retainer. Using the pliers supplied with the instrument, place the plier prongs in the bottom slots of spacer and spread holder-retainer flanges to just clear the side pins of the spacer. Keeping the

flanges spread, gently push down on the sample cell using the spacer until the side pins snap into the holes in the flanges..

2a. Before installing the holder-retainer with sample cell, make sure movable probe is full retracted and then clip holder-retainer with sample cell onto the head. The fixed contact should be in the contact cup of the sample cell, but <u>should not touch</u> the feed-through wire.

2b. When installing the assembled holder-retainer/spacer/sample cell onto the head of Model 910 Series Porosimeters, make sure movable probe is fully retracted. Attach spacer to head by inserting plier prongs in top slots of spacer and gently spreading the flanges. Holding the spacer at an angle,clip a flange over one of the pins in the head. Keeping the flanges slightly spread, align the spacer with the head and clip the other flange over the opposite pin. The fixed contact should project down into the tube extending up from feed-through wire of sample cell.

NOTE: When using the powder sample cell with the Model 910 Series Porosimeters, make sure the volume displacement insert, MIC P/90-26806, is placed in the bottom of the pressure vessel.

3. Lift the head with sample cell and holder-retainer (and spacer for Model 910 Series using large piece sample cells) attached into the pressure vessel and close by turning the nut clockwise. When the nut reaches the bottom of its travel, back out 1/4 turn counter-clockwise.

C. <u>EVACUATION OF THE SAMPLE:</u>

1. Close all valves except LOW PRESSURE valve.

2. Switch MASTER and VACUUM switches on.

3. <u>Slowly</u> open VACUUM valve.

4. Close LOW PRESSURE valve when 0.15 psia gauge reads about 0.3 psia.

5. Evacuate to 20 microns Hg or lower.

NOTE: Evacuate a minimum of 1 hour for blank runs.

D. <u>FILLING THE SAMPLE CELL WITH MERCURY</u>

1. Open LOW PRESSURE <u>RELEASE</u> valve to maintain about 9 psia on the 0-15 psia gauge.

2. While watching vacuum gauge, open <u>MERCURY</u> valve about 1/3 turn.

3. If vacuum gauge indicates a pressure increase immediately close MERCURY valve. Close LOW PRESSURE RELEASE valve.

4. When pressure decreases, reopen MERCURY and LOW PRESSURE RELEASE valves.
Continue Steps 1, 2 and 3 as required.

5. Immediately close MERCURY valve when indicator light goes out indicating fill.

6. Close LOW PRESSURE RELEASE valve.

7. Slowly open LOW PRESSURE valve. Leave open.

8. When the vacuum reaches 0 on the 0.15 psia gauge. close VACUUM valve.

NOTE: If necessary to zero the 0-15 psia gauge, leave the VACUUM valve open until a pressure of 100µm Hg or lower is attained, zero the 0-15 psia gauge and then close VACUUM valve.

9. Switch VACUUM switch to OFF.

10. Open MERCURY valve for 5 to 8 minutes. (Indicator light may or may not come in any case proceed)

11. Close MERCURY valve.

E. ESTABLISHING PROBE CONTACT

1. Open LOW PRESSURE RELEASE valve carefully until 0-15 psia gauge indicates 0.5 psia.

2. Zero counter.

3. Set FOLLOW switch to FOLLOW-1 and allow counter to count until it stops.

4a. If counter indicates 200 or more proceed to Step 6.

4b. When using large piece sample cell in Model 910 Series Porosimeters. If counter indicates 10 or more proceed to Step 6.

5a. If counter indicates less than 200 place SET-RESET switch to SET until counter indicates about 1200. Then proceed to Step 6.

5b. When using large piece sample cell in Model 910 Series Porosimeters, if counter indicates less than 10 place SET-RESET switch to SET until counter indicates about 1200. Then proceed to Step 6.

6. Set FOLLOW switch to FOLLOW-2 and SET-RESET switch to RESET until movable probe is retracted (motor ceases to operate).

7. Set FOLLOW and SET-RESET switches to OFF.

8. ZERO counter.

9. Place FOLLOW switch to FOLLOW-1.

10. When indicated light goes out, record counter indication as C_t on data sheet (or C_b for a blank test). This step is used only when determining density or making a blank test.

11. Zero counter.

F. HYPOBARIC PRESSURE ANALYSIS

1. Carefully open LOW PRESSURE RELEASE valve until 0-15 psia gauge indicates 1.0 psia.

2. Allow time for equilibrium and record exact pressure and counter indication on data sheet.

3. Proceed stepwise to atmospheric pressure. Leave LOW PRESSURE RELEASE valve open.

4. Open MERCURY valve and drain Mercury for 2-3 minutes.

5. Close MERCURY valve.

6. Set FOLLOW switch to OFF.

G. FILLING THE SYSTEM WITH FLUID

1. Close LOW PRESSURE valve.

2. Set VACUUM switch to ON.

3. Slowly open VACUUM valve. Leave open 1 to 2 minutes.

4. Close VACUUM valve.

5. Open FLUID valve for 5 seconds and close.

6. Close VACUUM valve.

7. Slowly open FLUID valve. Leave open for 3 minutes.

9. Close FLUID valve.

10. Set VACUUM valve.

11. Set VACUUM switch to OFF and FOLLOW switch to FOLLOW-1.

H. HYPERBARIC PRESSURE ANALYSIS

1. Open HIGH PRESSURE valve.

2. Slowly turn PRESSURE control clockwise until about 20 psia indicated on intermediate pressure gauge.

3. Allow time for equilibrium and record pressure and counter indication on data sheet.

4. Continue stepwise to maximum pressure desired.

I. 1. While maintaining maximum pressure desired, place FOLLOW switch to FOLLOW-2.

2. Zero counter after counter stops.

3. Turn PRESSURE control counter clockwise until it turns firmly.

4. Slowly open FLUID valve and decrease pressure incrementally as desired.

5. Allow time for equilibrium and record pressure and counter indication on data sheet.

6. Continue stepwise until atmospheric pressure is reached. FLUID valve is left open.

J. HYPOBARIC HYSTERESIS ANALYSIS

NOTE: Before continuing hysteresis analysis below atmospheric pressure, it is necessary to drain the fluid from the chamber so that the sample may be evacuated below atmospheric pressure. This is accomplished as follows:

1. Open FLUID valve completely.

2. Close HIGH PRESSURE valve.

3. Set FOLLOW switch to OFF.

4. Turn PRESSURE control clockwise until about 6000 (10-12,000for dual chamber units) psia is indicated on high pressure gauge. Leave PRESSURE control rac to maintain pressure.,

5. Open PURGE valve and then open VACUUM valve until bubbling occurs in fluid reservoir.

6. Close the PURGE, FLUID and VACUUM valves.

7. Place the VACUUM switch to ON.

8. Open the LOW PRESSURE valve.

9. Close LOW PRESSURE RELEASE valve.

10. Set the FOLLOW switch to FOLLOW-2.

11. Open VACUUM valve until about 13 psia is indicated on the 0-15 psia gauge.

12. Allow time for equilibrium and record pressure and counter indication on data sheet.

13. Continue stepwise until desired lower pressure is obtained. (About 1.0 psia is practical lower limit).

14. Select SET-RESET switch to RESET until movable probe is retracted (motor ceases to operate).

15. Set FOLLOW and SET-RESET switches to OFF.

16. Open LOW PRESSURE RELEASE valve and then open the VACUUM valve for about 1 minute.

17. Continue with Clean-Up and Shut-Down Procedure beginning with Step 10.

K. CLEAN-UP AND SHUT-DOWN PROCEDURE:

1. Turn PRESSURE control counter clockwise until it turns freely.

2. Slowly open FLUID valve until pressure gauges come to atmospheric pressure.

3. Place FOLLOW switch to FOLLOW-2 and SET-RESET switch to RESET until movable probe is retracted (motor ceases to operate).

4. Set FOLLOW and SET-RESET switches to OFF.

5. Close HIGH PRESSURE valve.

6. Slowly turn PRESSURE control clockwise until about 6000 (10-12,000 for dual control units) psia is indicated on high pressure gauge. Leave PRESSURE control set to maintain pressure.

7. Open PURGE valve and then open VACUUM valve until bubbling occurs in fluid reservoir.

8. Close FLUID and PURGE valves.

9. Place VACUUM switch to ON and open LOW PRESSURE valve for about 1 minute.

10. Close LOW PRESSURE RELEASE valve.

11. Close LOW PRESSURE valve and allow vacuum pump to pump for 1 minute.

12. Open LOW PRESSURE RELEASE valve until 9 psia is indicated on 0-15 psia gauge. Close LOW PRESSURE RELEASE valve.

13. Open MERCURY valve until pressure drops to 6 psia on 0-15 psia gauge.

14. Close MERCURY valve.

15. Switch VACUUM and MASTER switches to OFF.

16. Open LOW PRESSURE and LOW PRESSURE RELEASE valves.

17. Open pressure vessel and remove head. Remove sample cell from head. If density is to be determined or a blank test is being made, the following steps must be completed:

    a) Wipe excess fluid from precision bore tube and exterior of sample cell. (Pipe cleaners are helpful to absorb fluid from precision bore tube)

    b) Remove mercury from contact cup of sample cell. If all fluid has been cleaned from precision

bore tube, cap and bore with one's finger and gently invert sample tube to empty contact cup. When cleaning the large piece sample cell, a pipe cleaner is helpful in removing Mercury from the contact cup.

c) Weigh sample cell with sample and Mercury and record as W_t on data sheet.

18. Open PURSE valve. Pressure may be increased to increase flow of air through chambers. This will expedite chamber clean-up.

19. Clean fluid from interior of pressure vessel and surface of Mercury.

20. With pipe cleaners clean oil from ports inside pressure vessel where vacuum and low pressure lines enter.

21. Change O-ring if necessary. Grease with Apiezon "H" or silicone vacuum grease as needed.

22. Clean probe mechanism on the head.,

NOTE Pressure vessel can be sealed with the head and evacuated as time allows. This helps to "suck" fluid from recesses in the head and aids in cleaning the probe mechanism. (Step 19 above may have to be repeated).

23. Add 30cc of Mercury to pressure vessel (30cc for each chamber used). Be sure fluid is not floating on top of the Mercury.

24. Open MERCURY valve, drain Mercury until level falls to smaller ID of pressure vessel and then close MERCURY valve.

NOTE When using the powder accessory kit with the Model 910 Series Porosimeters, be sure that the Mercury is sufficiently drained and that the volume displacement inset is not floating on the Mercury in the bottom of the chamber.

25. Turn PRESSURE control counter clockwise until it turns freely.

26. Carefully open PRESSURE RELEASE valve, let high pressure gauges come to atmospheric pressure and then close PRESSURE RELEASE valve.

27. All valves should be closed and all switches should be OFF.

APPENDIX J

Example Calculation of Pore Size Distribution

Porosimeter data and calculation for a concrete mix.

$$p = - \frac{4 \gamma \cos \theta}{d}$$

γ for mercury = 485 dynes/cm (485×10^{-6} N/mm)

θ is the contact angle between the oven dried

sample and mercury = 117^{o}

Table 3.1 shows the calculation of the pore size distribution.

J.1

Sample Weight (W_s) = 5.6505 g

Cell Factor = 0.000751 cm^3/count

A Applied Pressure (psi)	B Penetration Counter Indication	C Corrected Counter Indication (B - "Blank" Result)	D Pore Diameter (117° Contact Angle) (124.9/A) Microns	E Volume of Pores of Indicated Diameter and Larger C (Factor/W_s) cm^3/g
1	6	6	124.9000	0.0008
3	12	12	41.6333	0.0016
5	15	15	24.9800	0.0020
8	18	18	15.6125	0.0024
11	21	21	11.3545	0.0028
50	48	48	2.4980	0.0064
100	69	69	1.2490	0.0092
200	88	88	0.6245	0.0117
300	101	101	0.4163	0.0134
400	114	114	0.3122	0.0152
500	120	120	0.2498	0.0159
700	128	128	0.1784	0.0170
900	139	139	0.1388	0.0185
1200	149	149	0.1041	0.0198
1400	157	157	0.0892	0.0209
1600	165	165	0.0781	0.0219
1800	176	176	0.0694	0.0234
2000	187	187	0.0624	0.0248
2400	208	208	0.0520	0.0276
2800	225	225	0.0446	0.0299
3200	241	241	0.0390	0.0320
3600	255	255	0.0347	0.0339
4000	268	268	0.0312	0.0356
4400	278	278	0.0284	0.0369
4800	286	286	0.0260	0.0380
5200	308	308	0.0240	0.0409
5600	312	312	0.0223	0.0415
6000	316	316	0.0208	0.0420
6500	323	323	0.0192	0.0429
7000	338	338	0.0178	0.0449
8000	348	346	0.0156	0.0460
9000	349	361	0.0139	0.0480
10000	374	369	0.0125	0.0490
11000	382	376	0.0114	0.0500
12000	392	384	0.0104	0.0510
13500	400	391	0.0092	0.0520
15000	411	399	0.0083	0.0530
17000	420	206	0.0073	0.0540
19000	431	414	0.0066	0.0550
21000	440	421	0.0059	0.0560
23000	450	429	0.0054	0.0570
26000	460	436	0.0048	0.0580
29000	468	440	0.0043	0.0585
32000	477	444	0.0039	0.0590
35000	485	448	0.0036	0.0595
38000	498	454	0.0033	0.0603
42000	504	455	0.0030	0.0605
46000	517	459	0.0027	0.0610
50000	522	460	0.0025	0.0611

Example calculation of pore size distribution

APPENDIX K

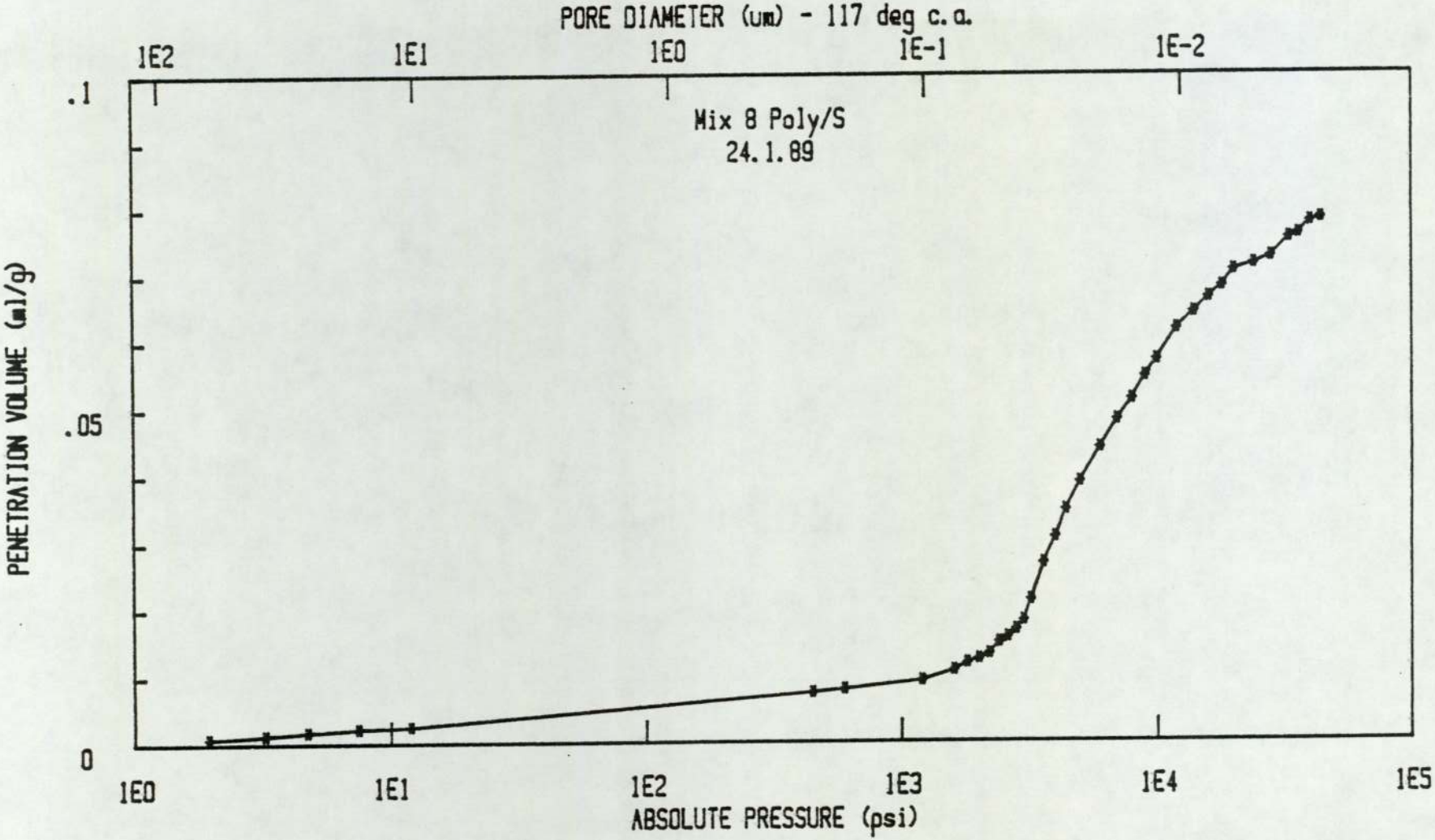

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
.1
Mix 8 Poly/S
24.1.89
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K1

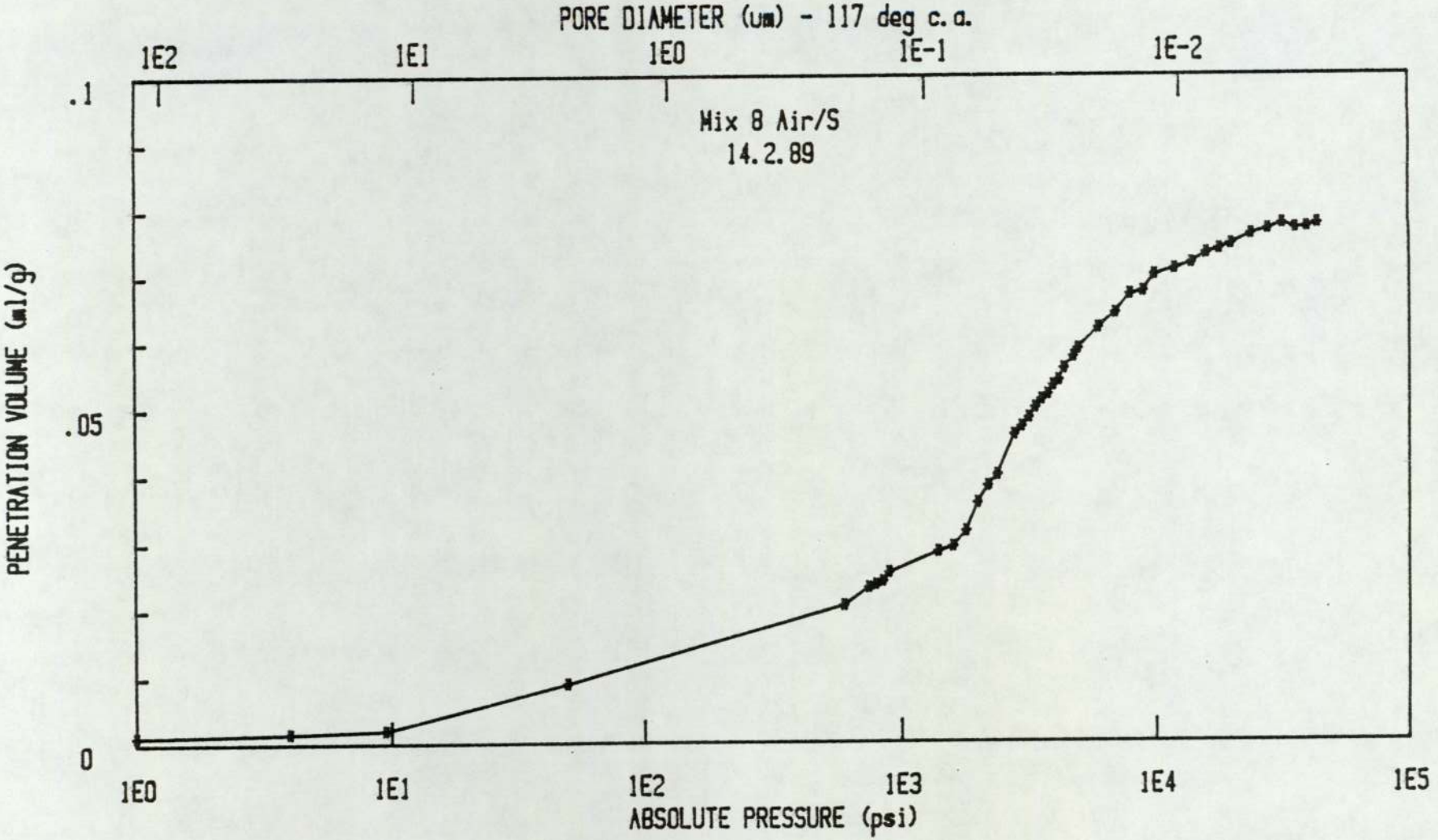
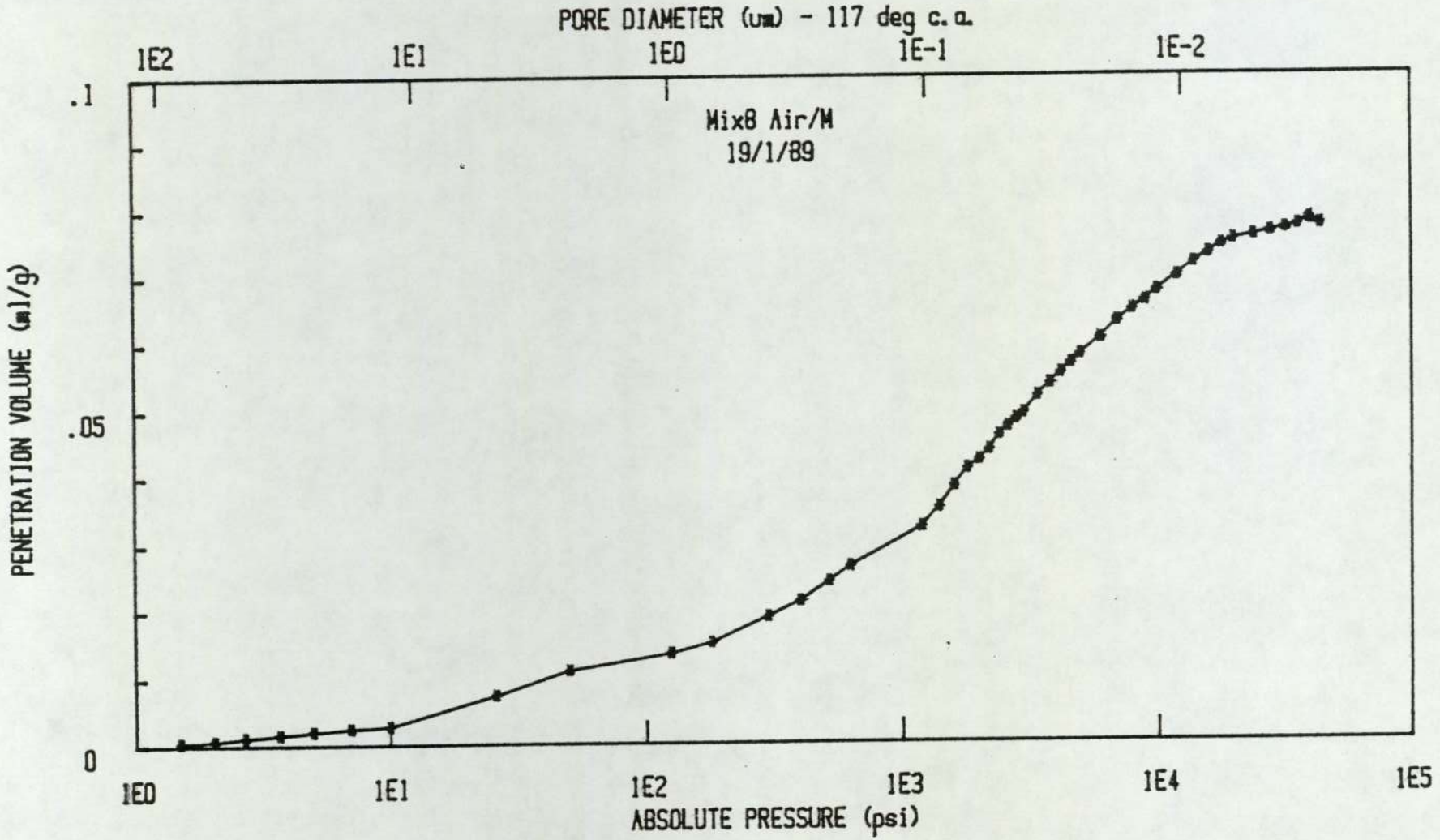

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
.1
Mix 8 Air/S
14.2.89
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K2


PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
.1
.05
0
Mix8 Air/M
19/1/89
PENETRATION VOLUME (ml/g)
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

IGURE K3

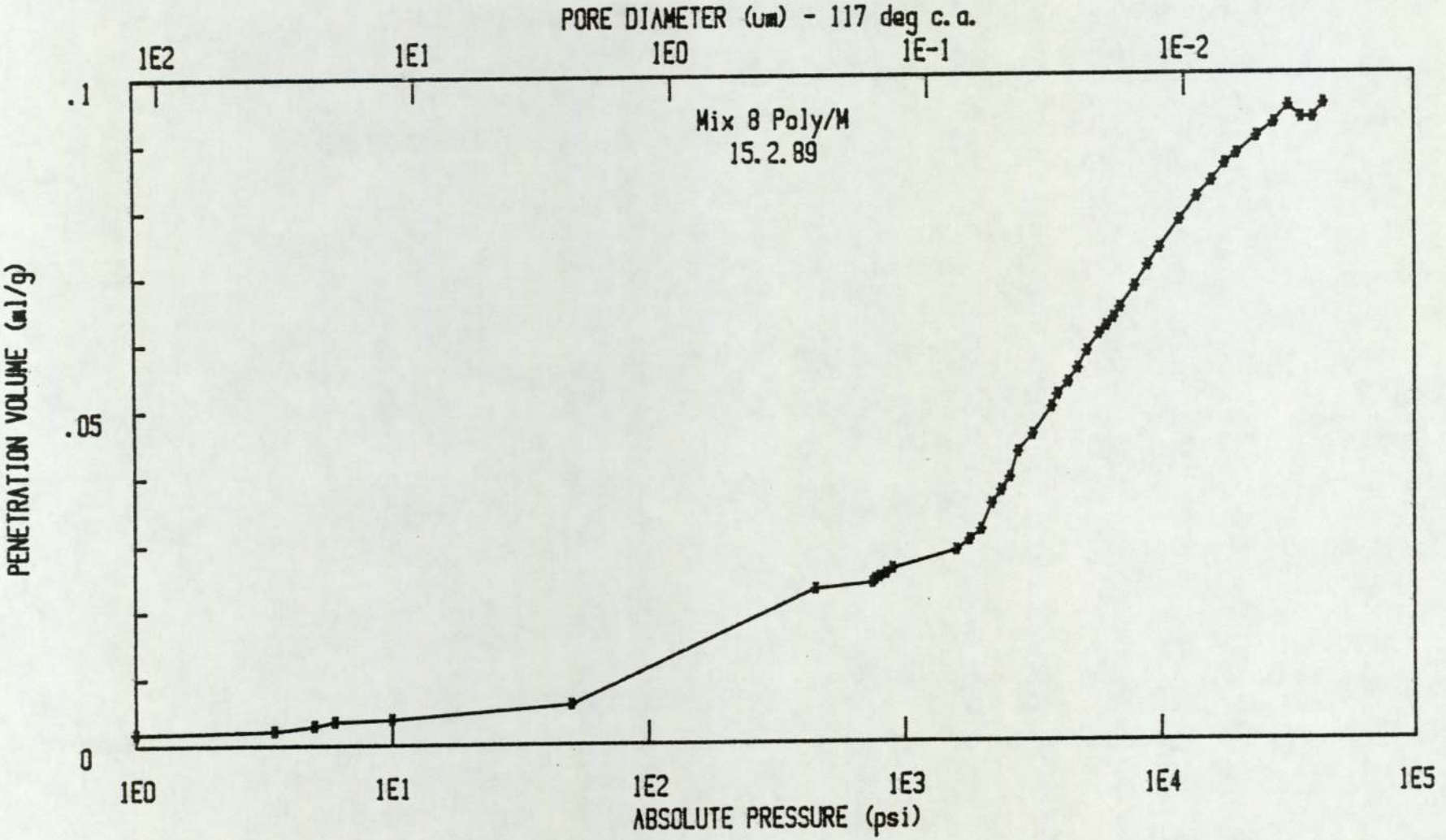

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
.1
.05
0
Mix 8 Poly/M
15.2.89
PENETRATION VOLUME (ml/g)
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K4

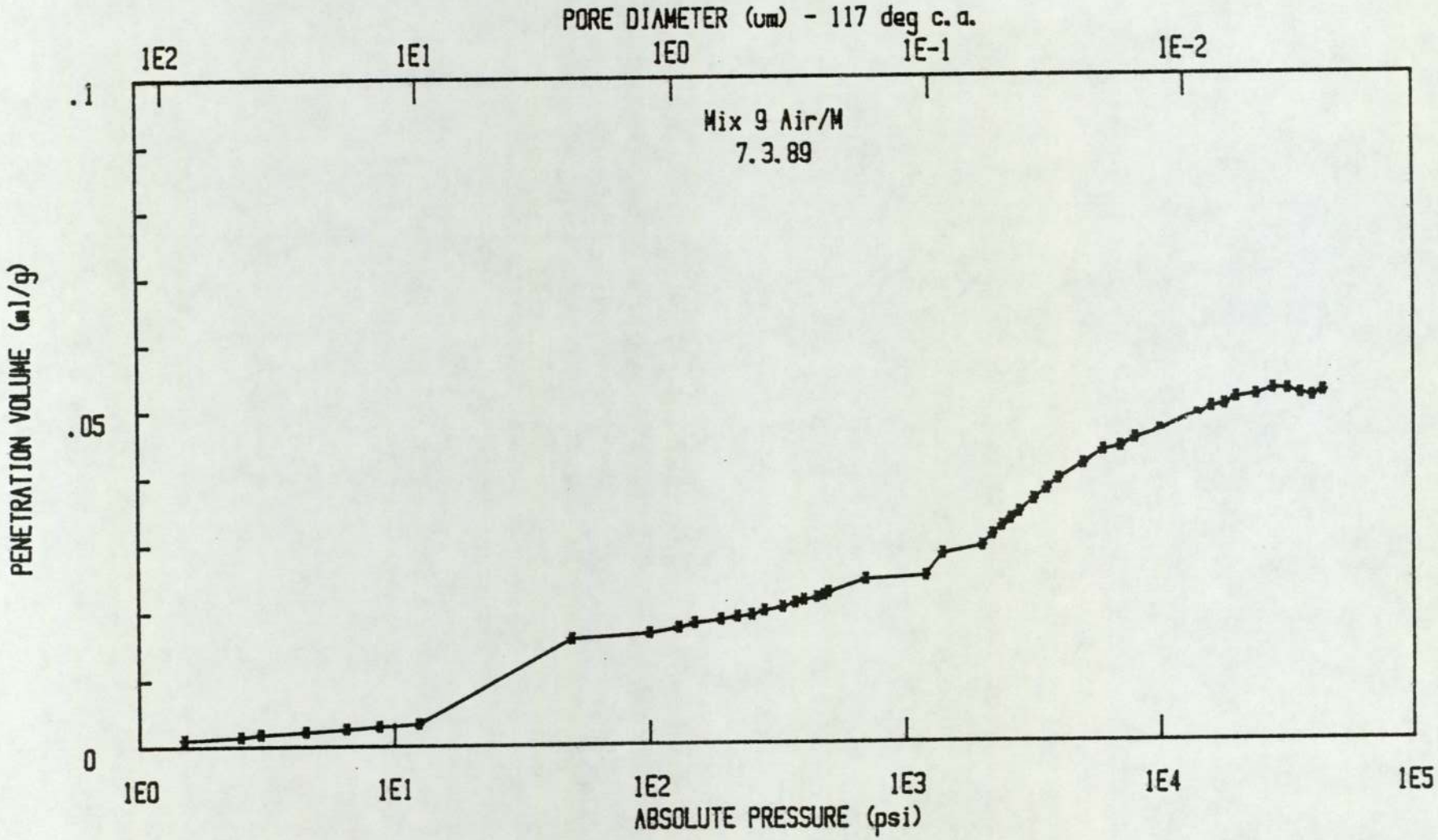

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
.1
.05
0
Mix 9 Air/M
7.3.89
PENETRATION VOLUME (ml/g)
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K5

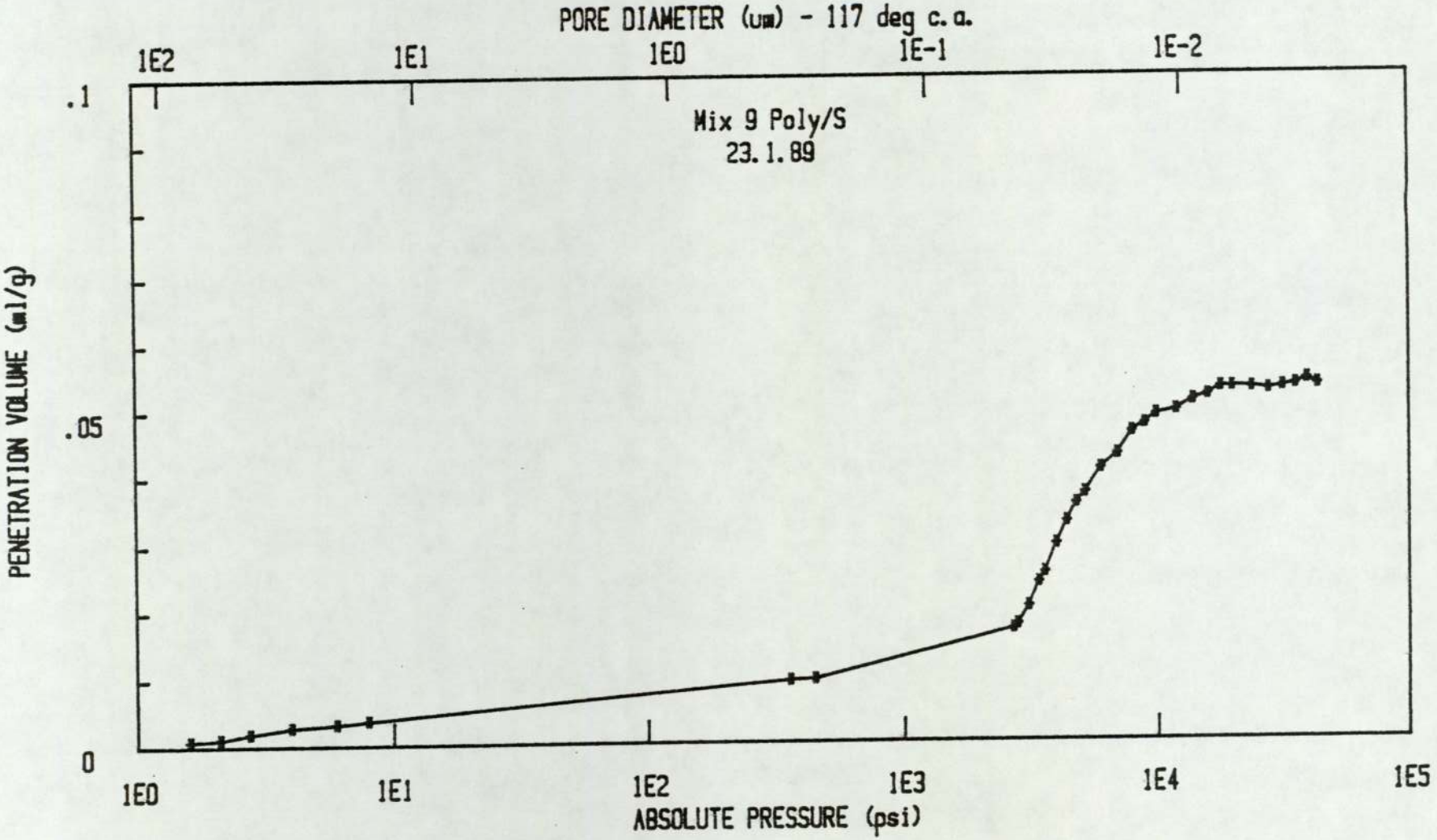

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
.1
.05
0
Mix 9 Poly/S
23.1.89
PENETRATION VOLUME (ml/g)
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K6

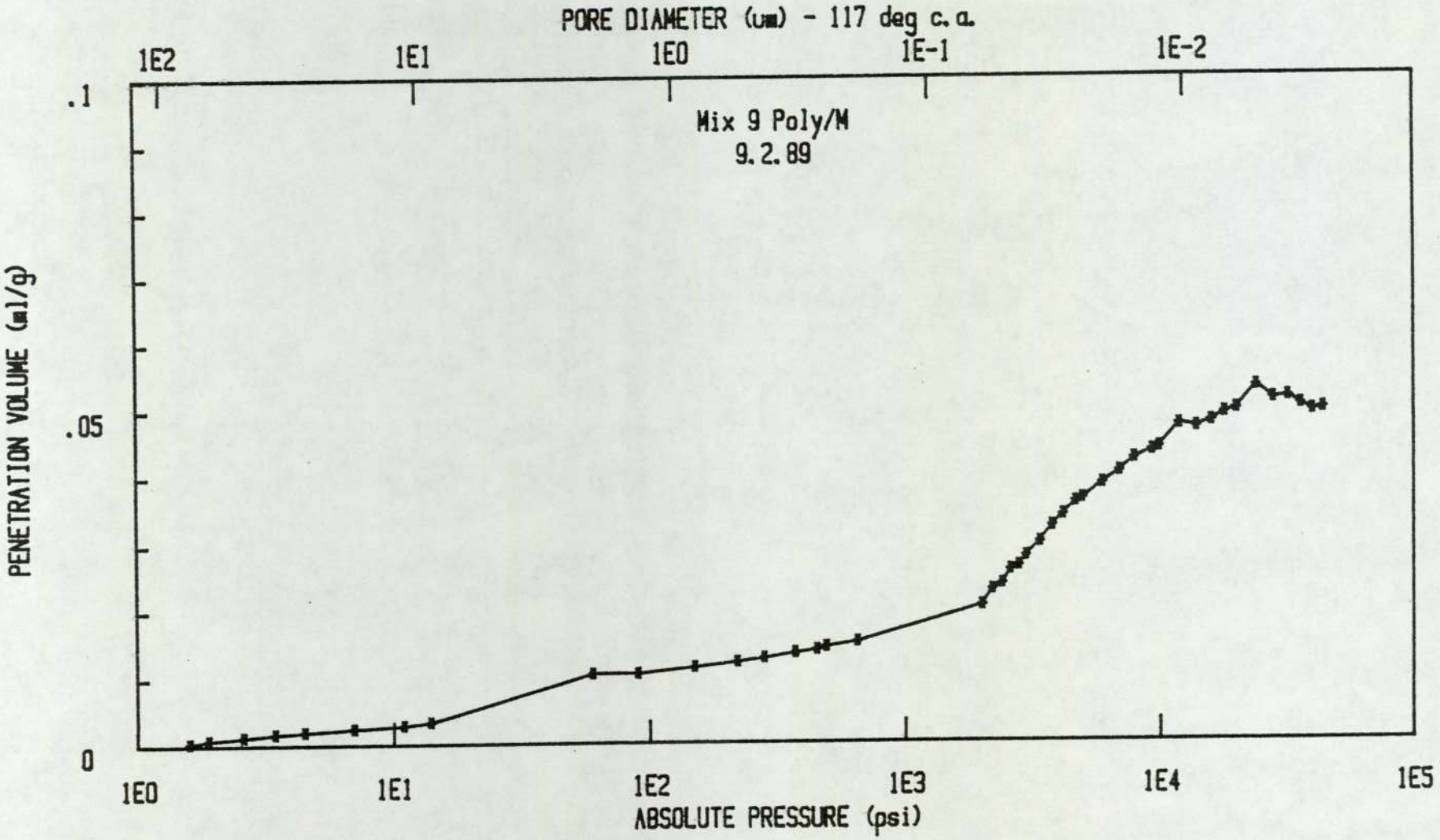

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
.1
Mix 9 Poly/M
9.2.89
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K7

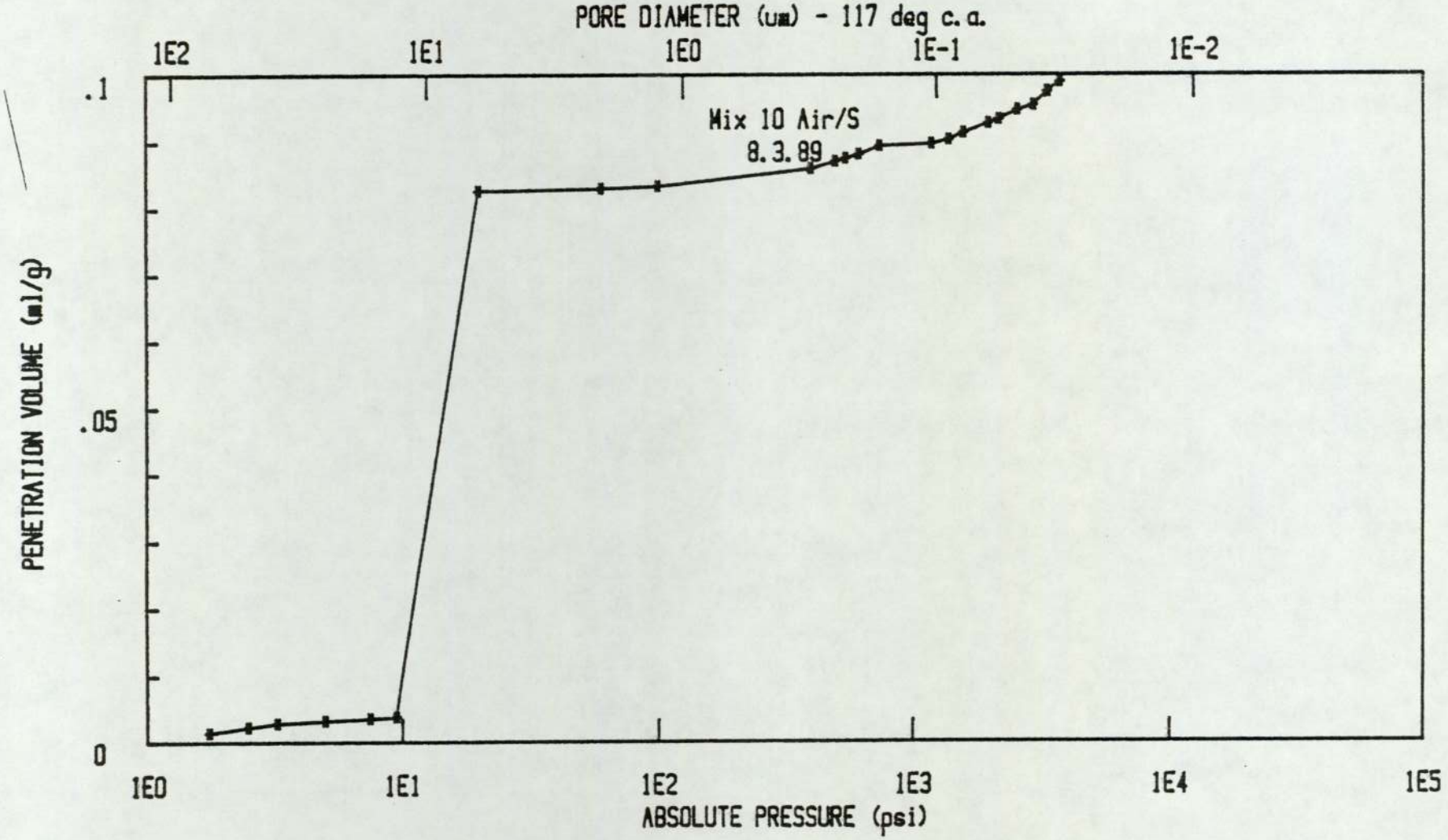

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
.1
.05
0
Mix 10 Air/S
8.3.89
PENETRATION VOLUME (ml/g)
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K8

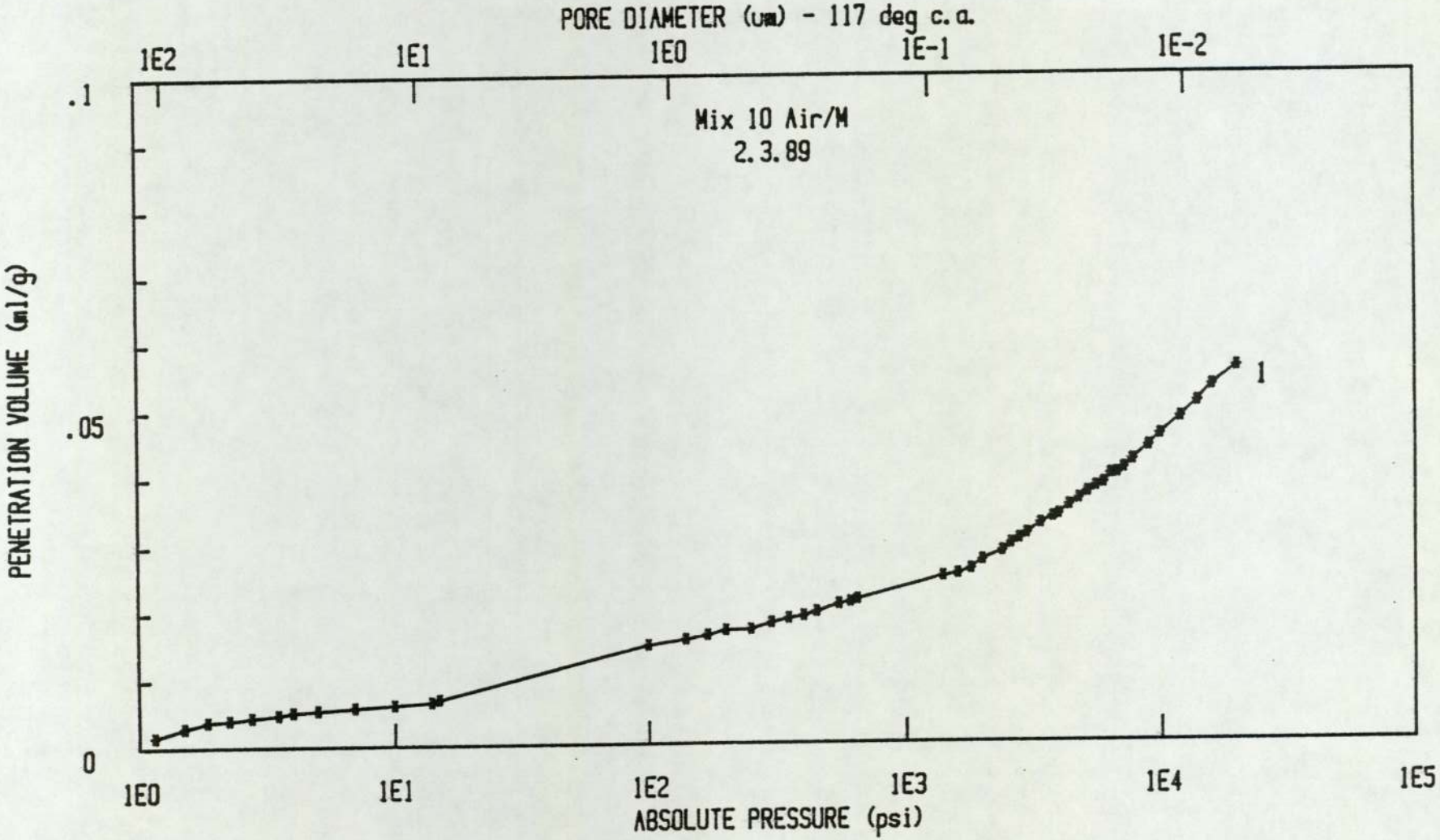

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
.1
Mix 10 Air/M
2.3.89
PENETRATION VOLUME (ml/g)
.05
0
1
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K9

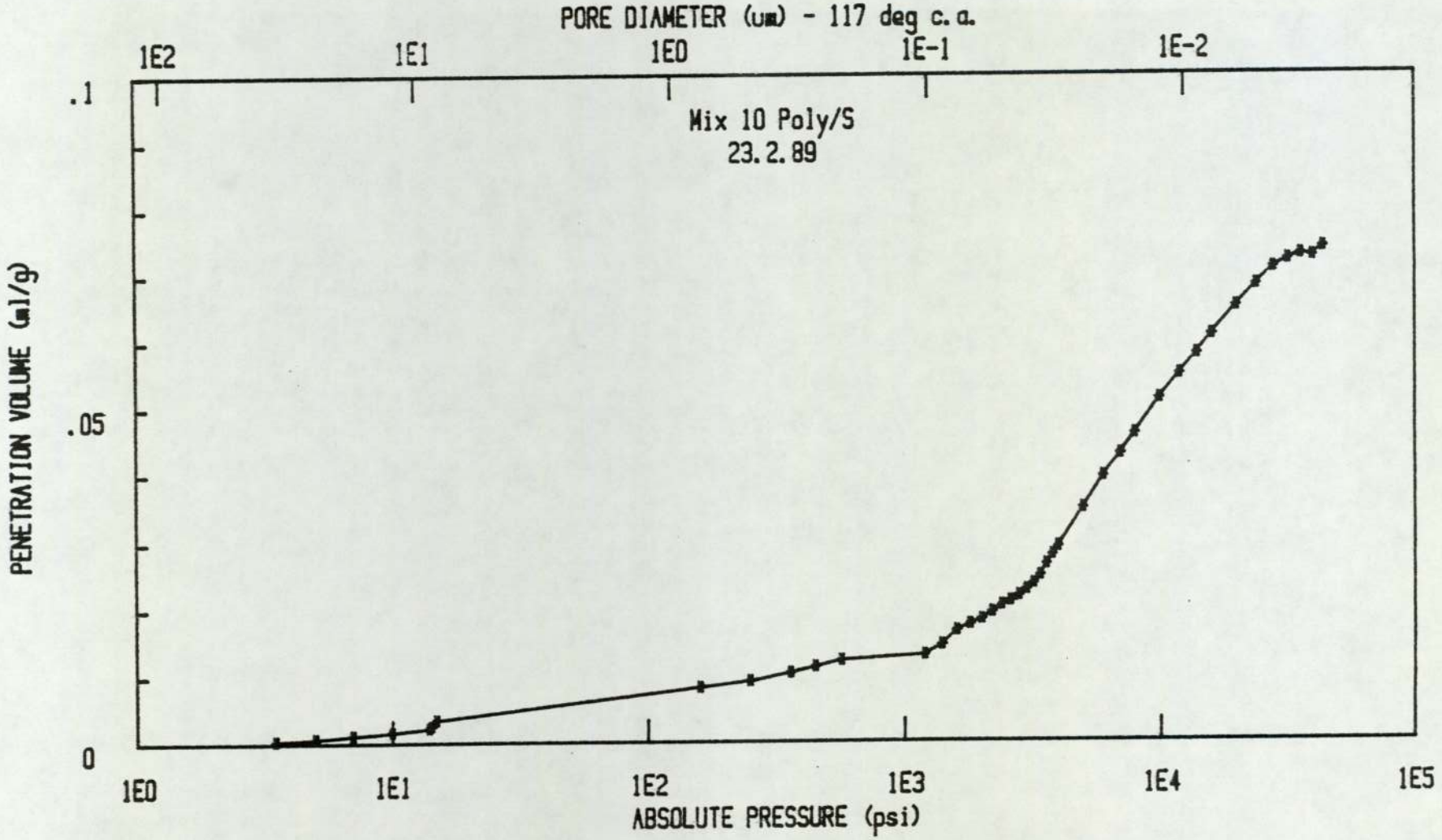

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
.1
Mix 10 Poly/S
23.2.89
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K1O

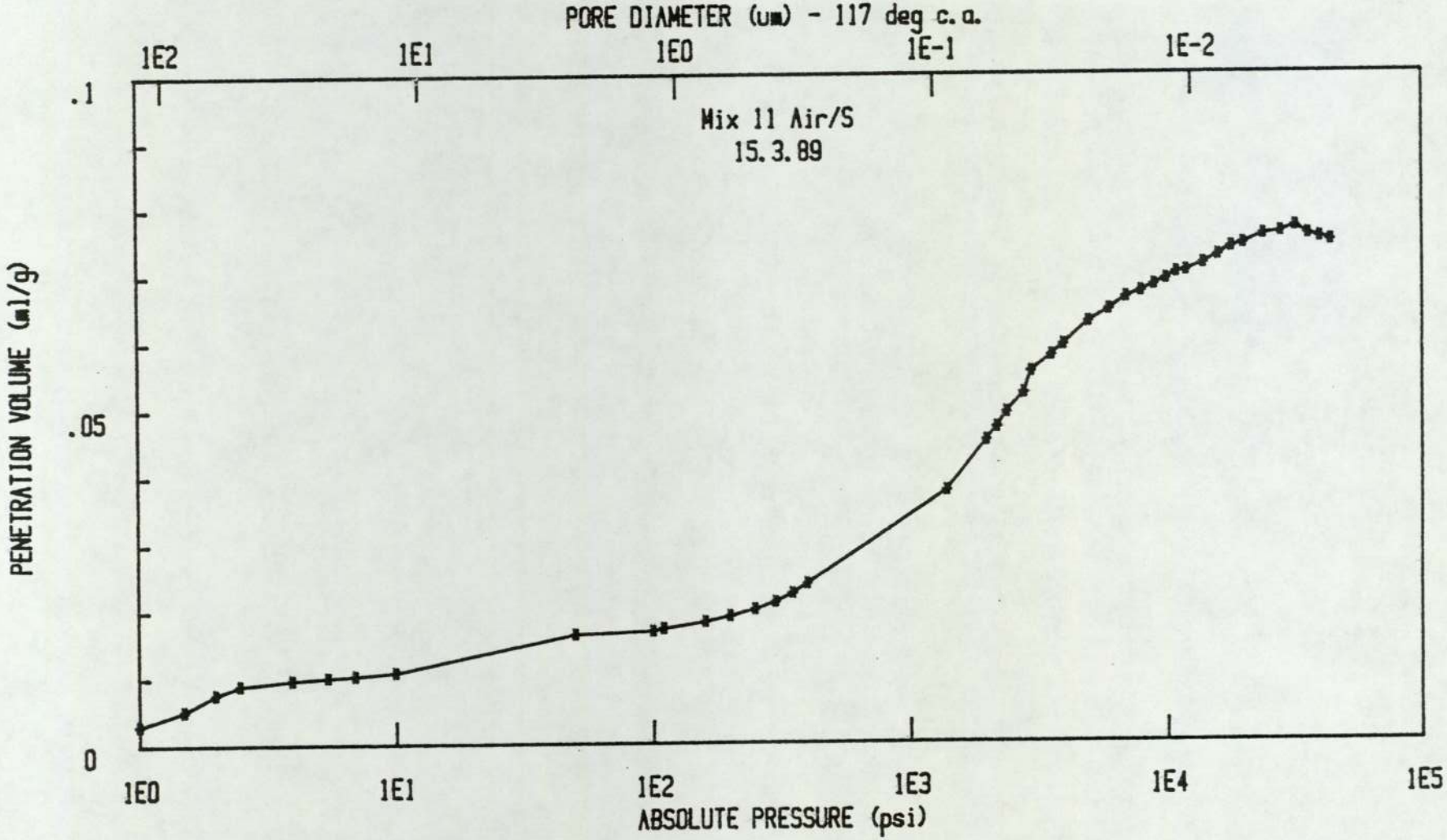

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
.1
.05
0
Mix 11 Air/S
15.3.89
PENETRATION VOLUME (ml/g)
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K11

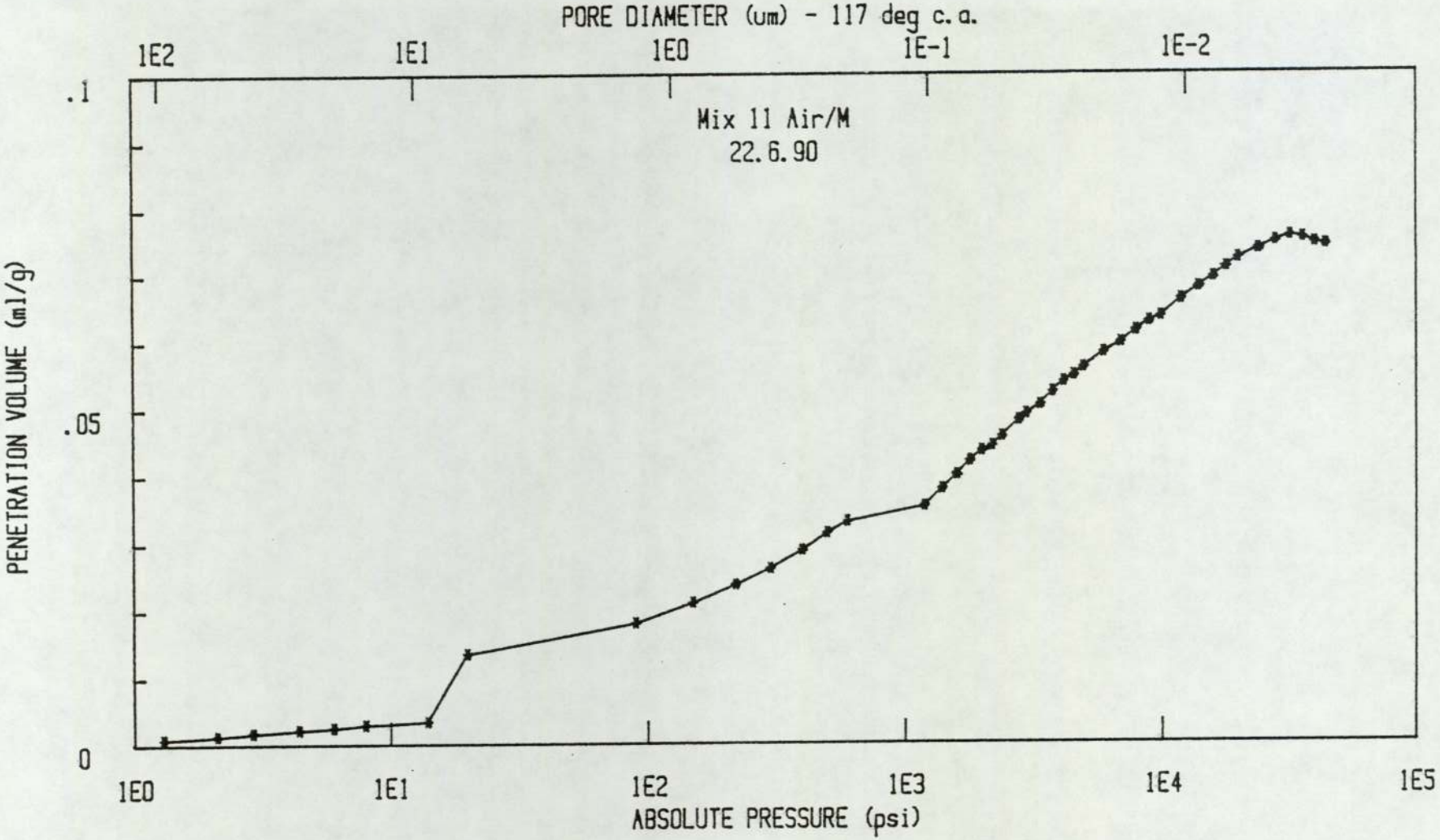

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
.1
.05
0
Mix 11 Air/M
22.6.90
PENETRATION VOLUME (ml/g)
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K12

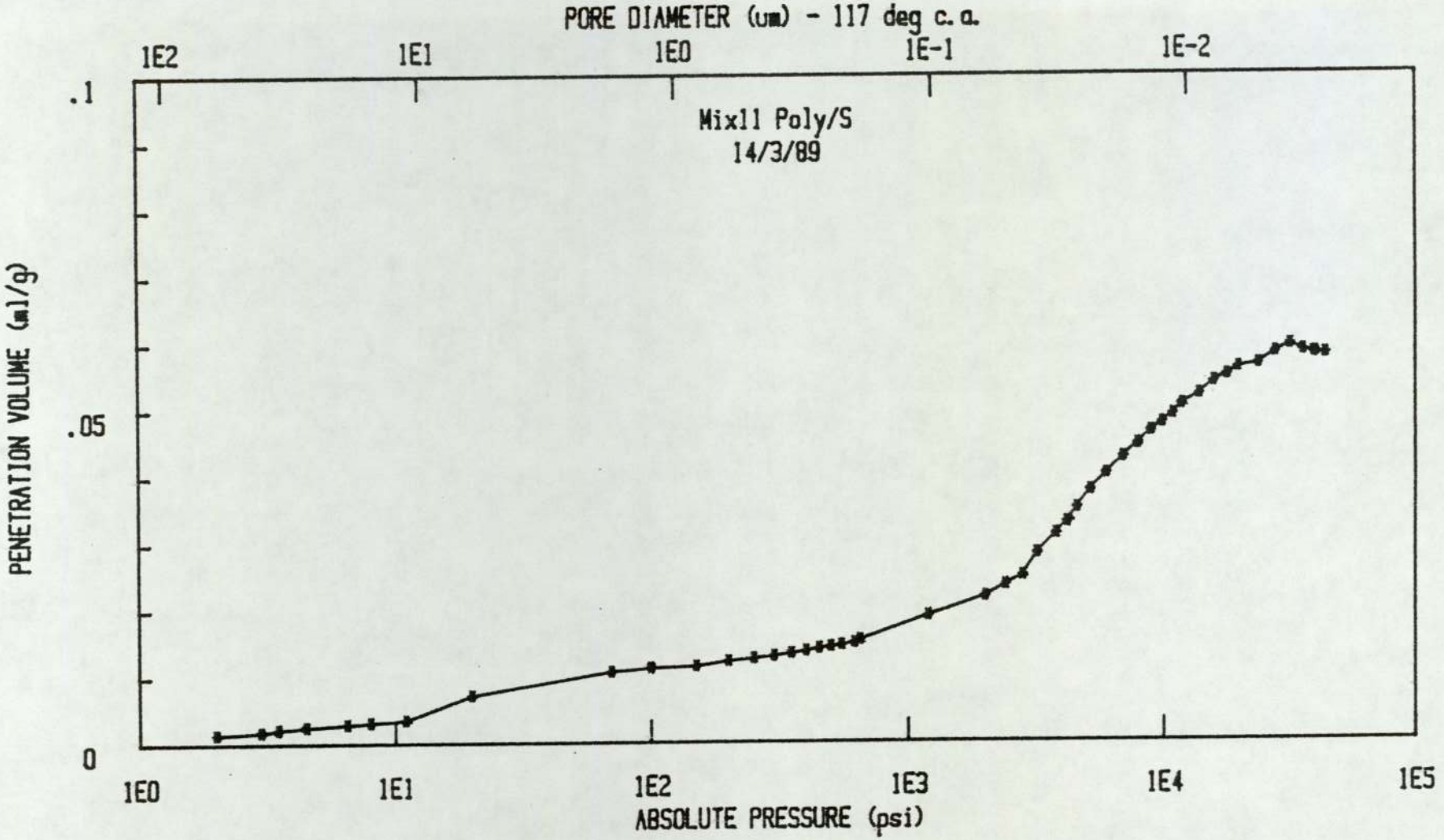

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
.1
.05
0
Mix11 Poly/S
14/3/89
PENETRATION VOLUME (ml/g)
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K13

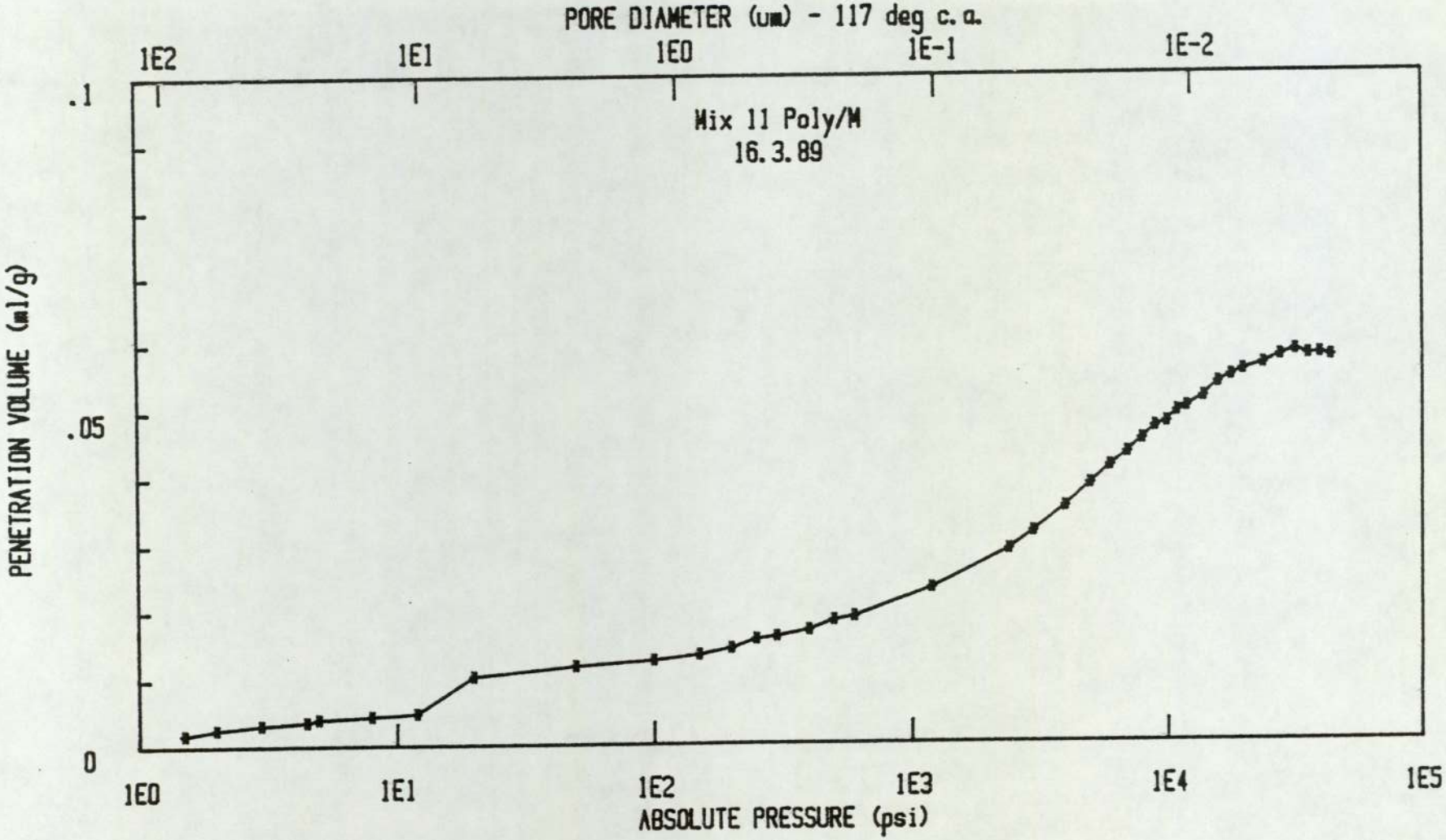

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
.1
.05
0
Mix 11 Poly/M
16.3.89
PENETRATION VOLUME (ml/g)
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K14

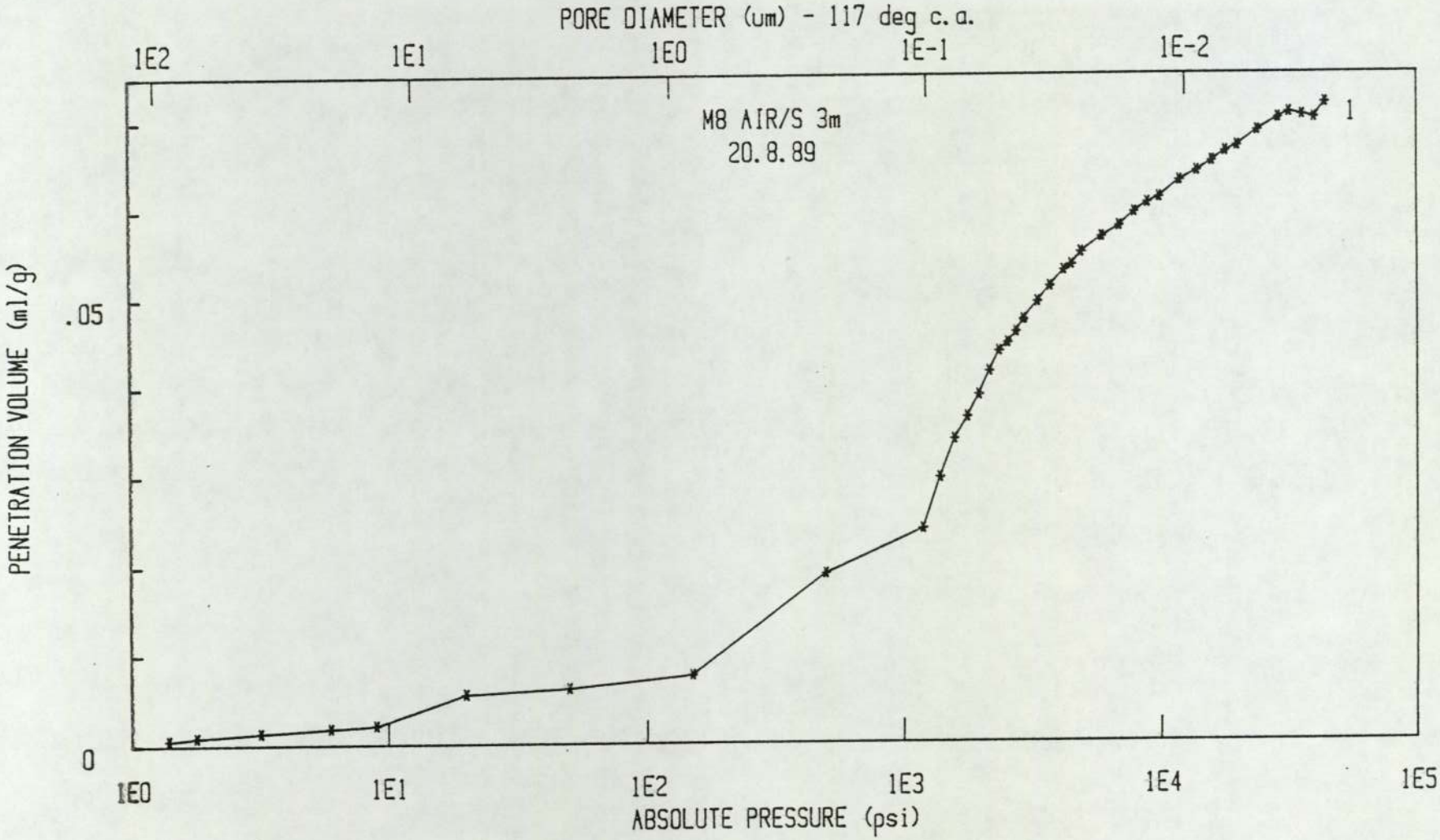

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M8 AIR/S 3m
20.8.89
1
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K15

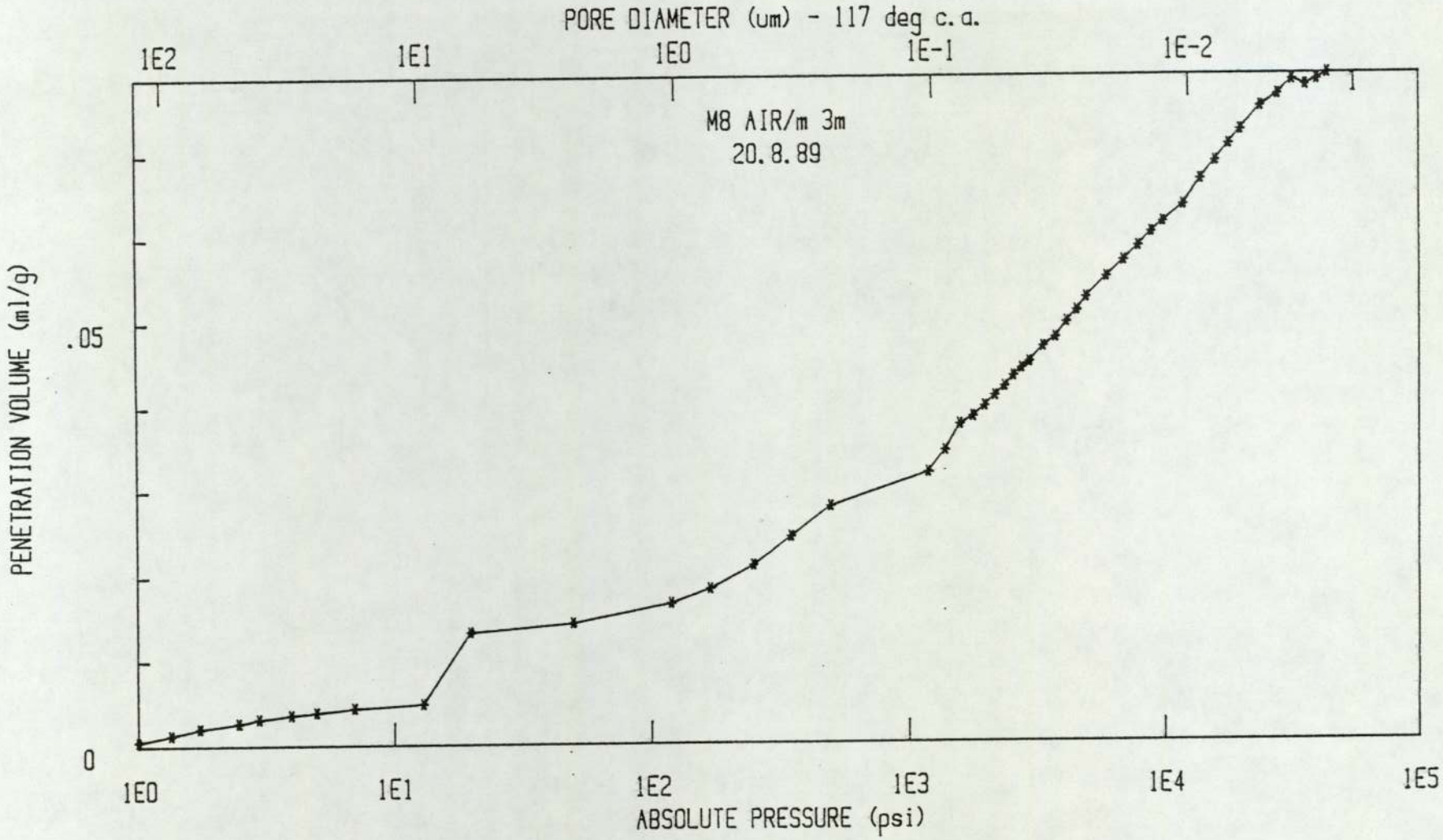

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M8 AIR/m 3m
20.8.89
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K16

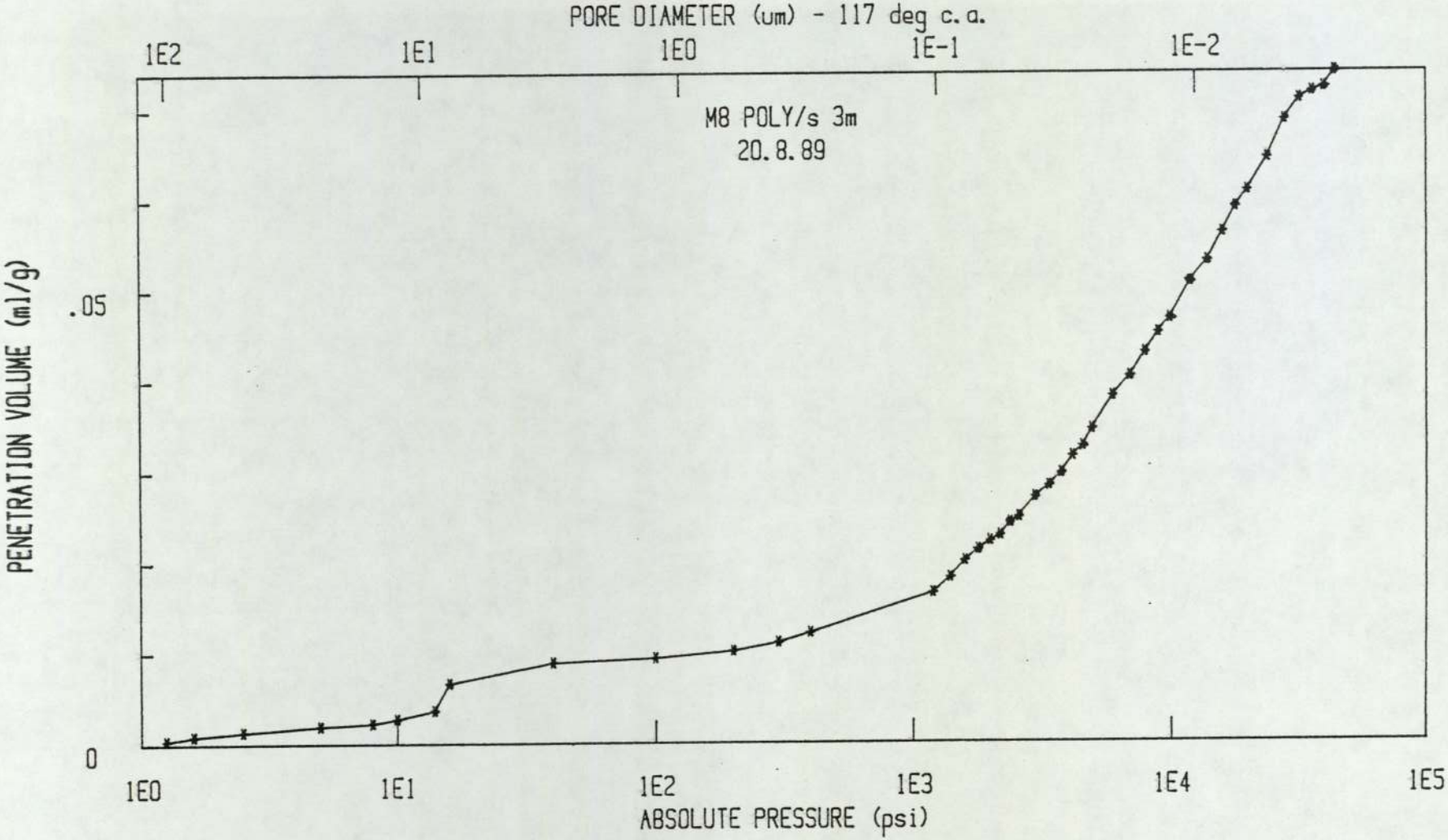

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M8 POLY/s 3m
20.8.89
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K17

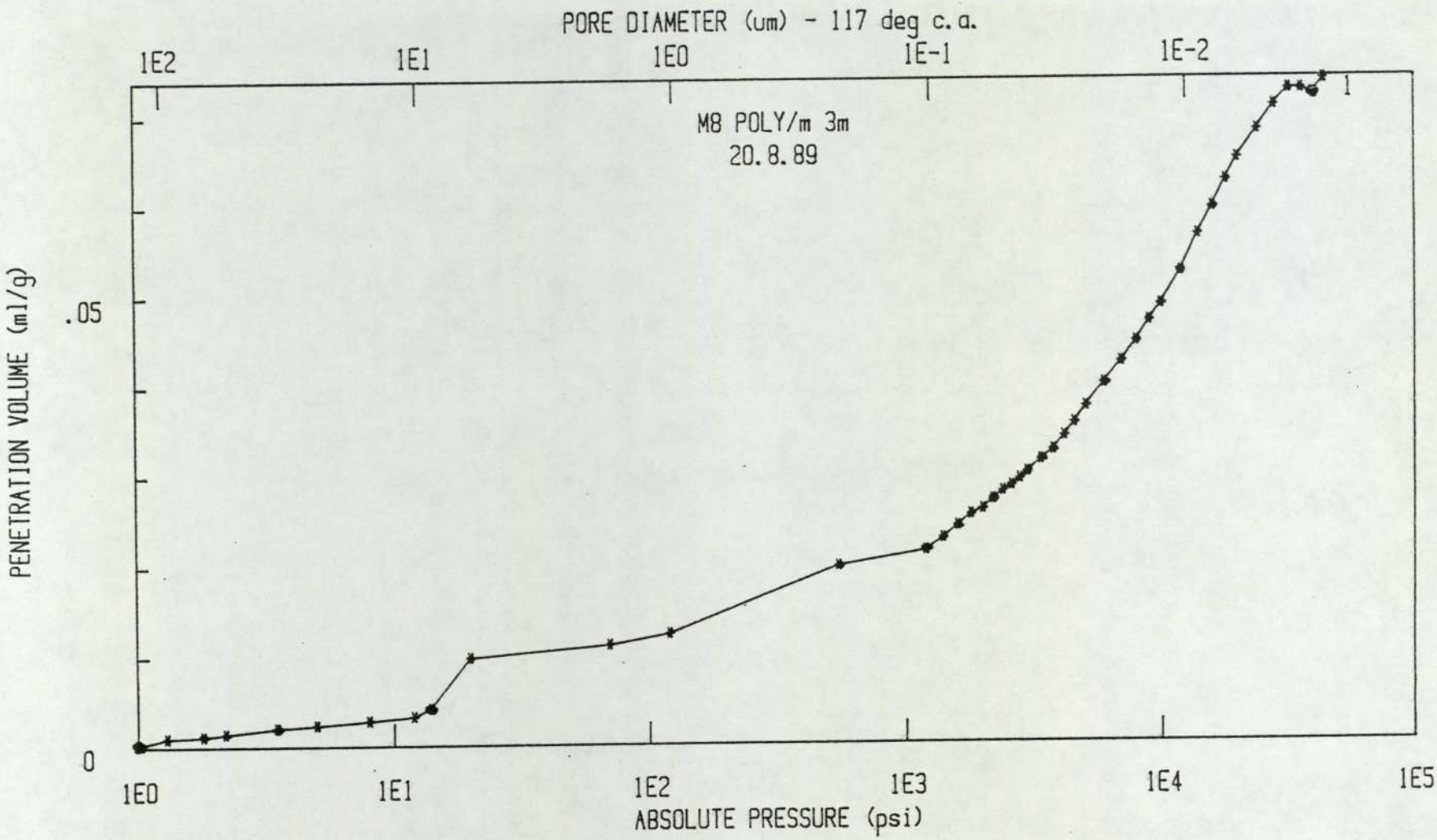

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M8 POLY/m 3m
20.8.89
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K18

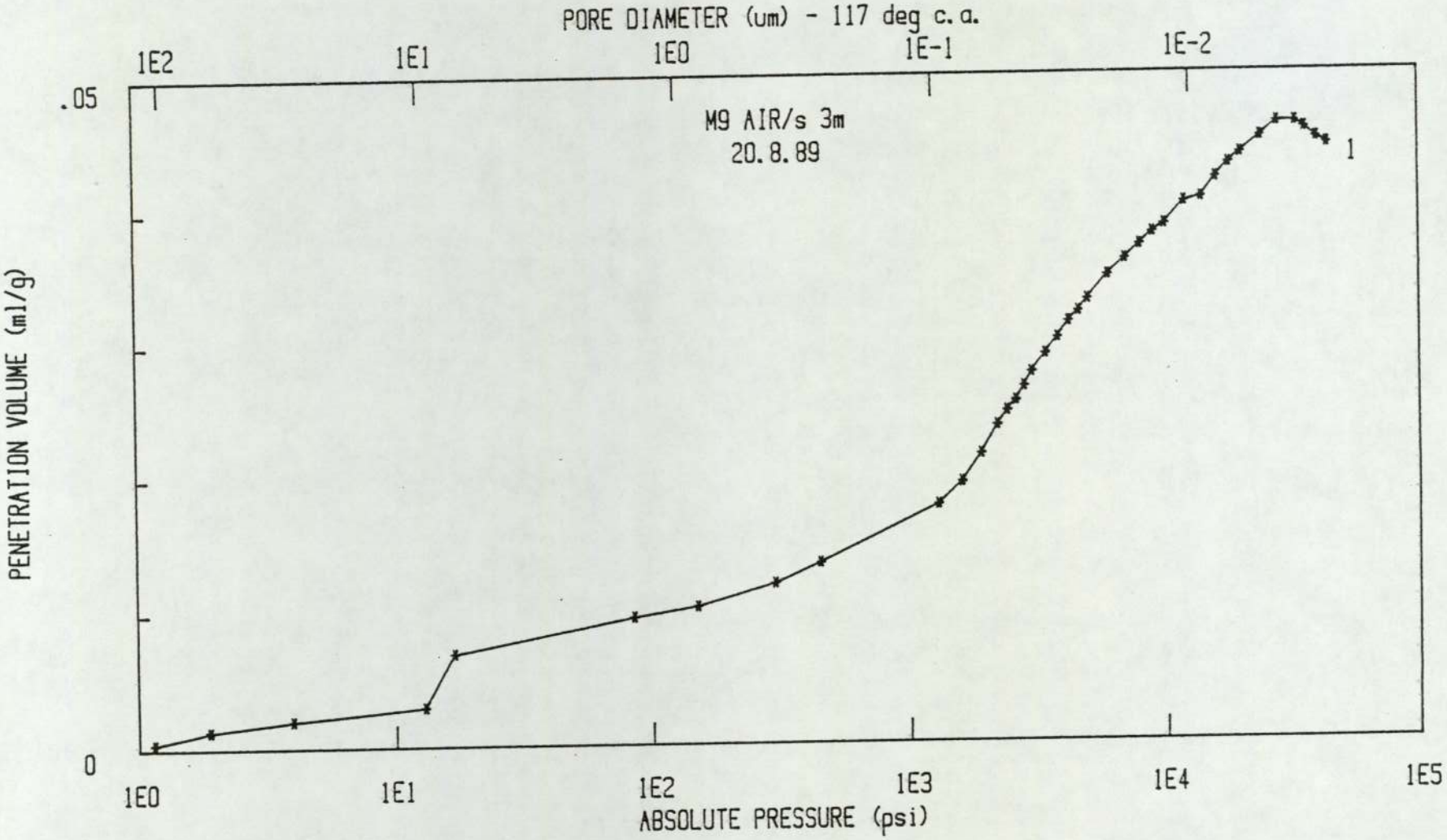

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
.05
0
M9 AIR/s 3m
20.8.89
1
PENETRATION VOLUME (ml/g)
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K19

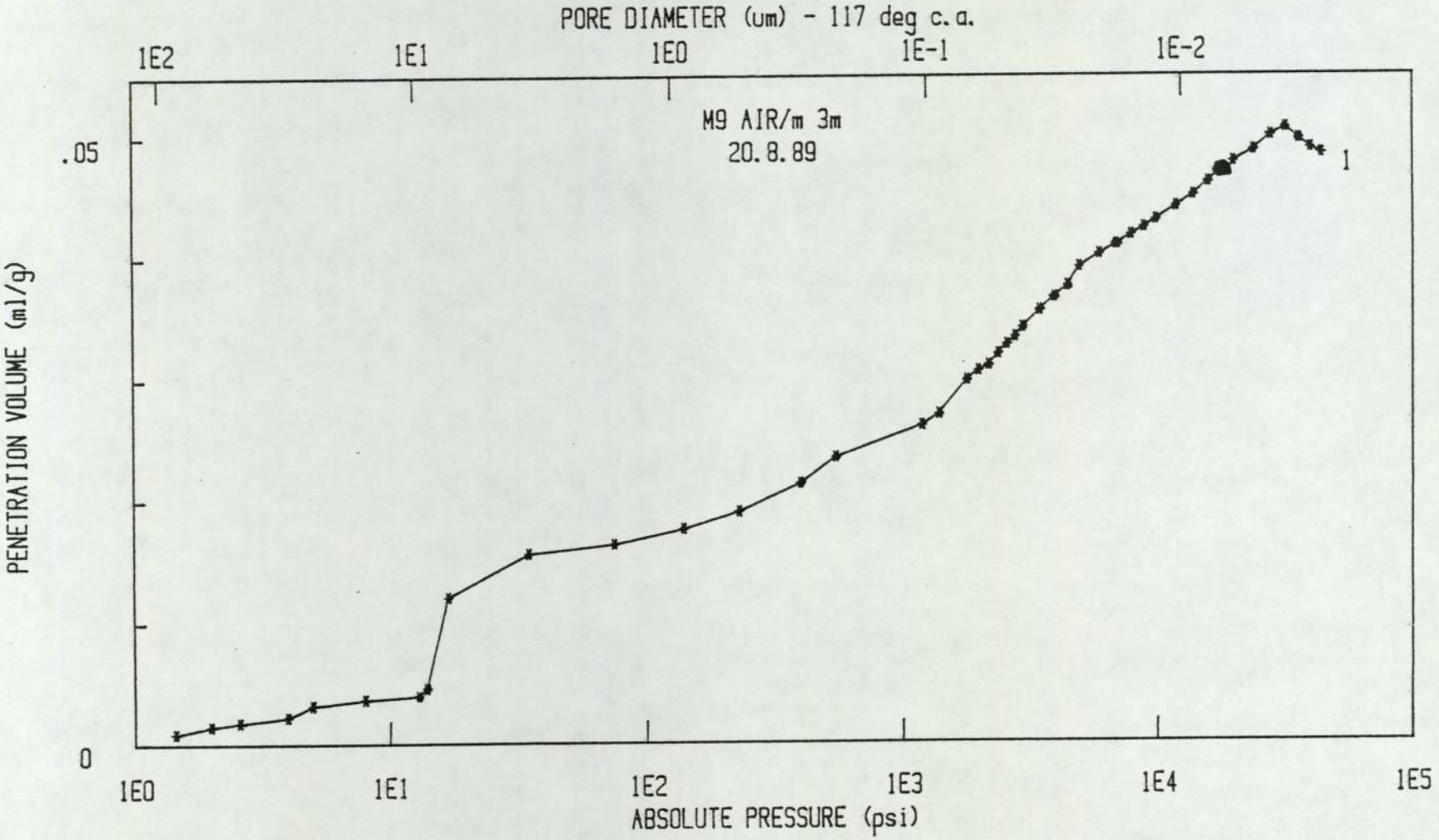

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M9 AIR/m 3m
20.8.89
1
.05
0
PENETRATION VOLUME (ml/g)
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K20

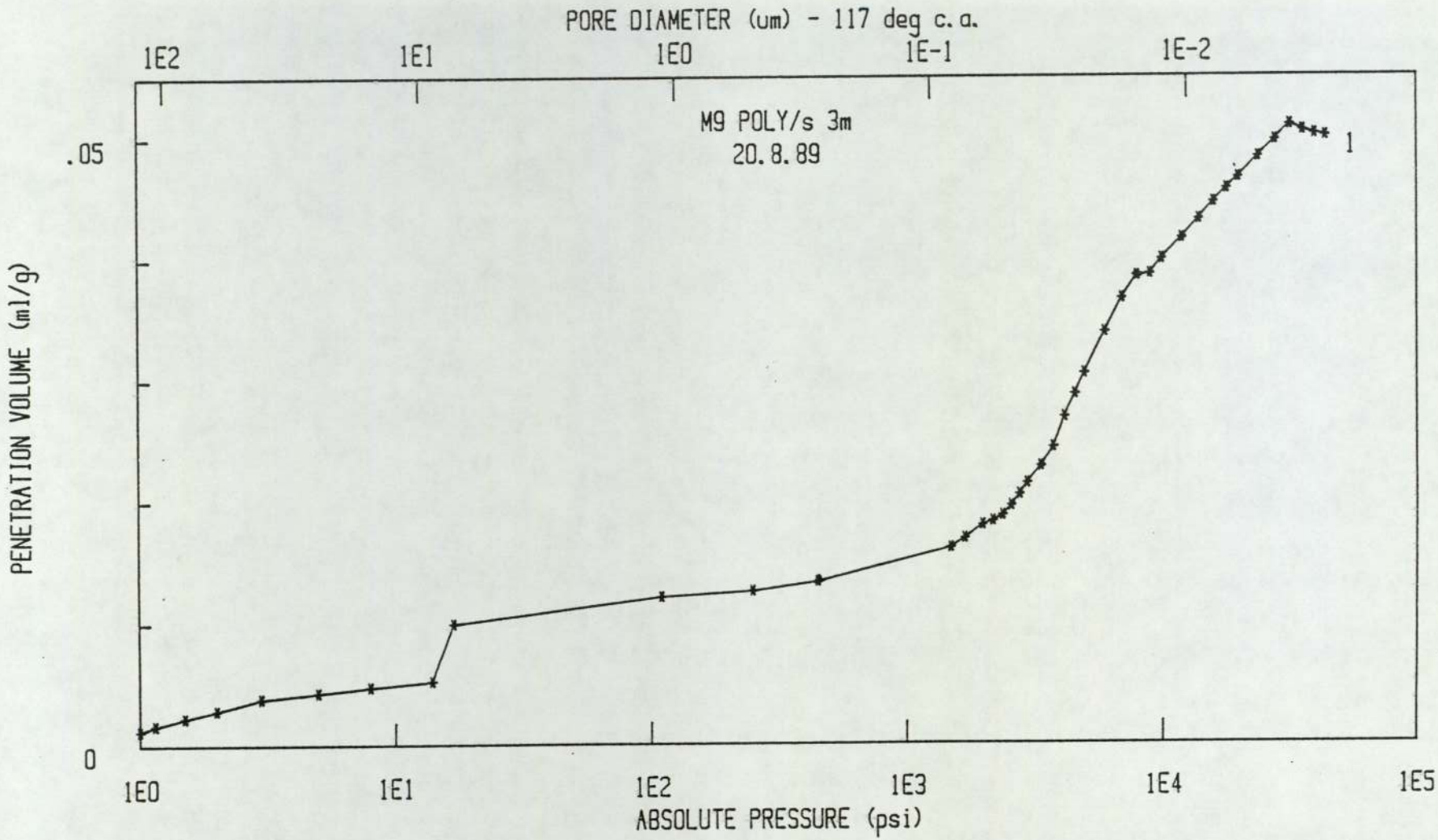

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M9 POLY/s 3m
20.8.89
1
.05
0
PENETRATION VOLUME (ml/g)
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K21

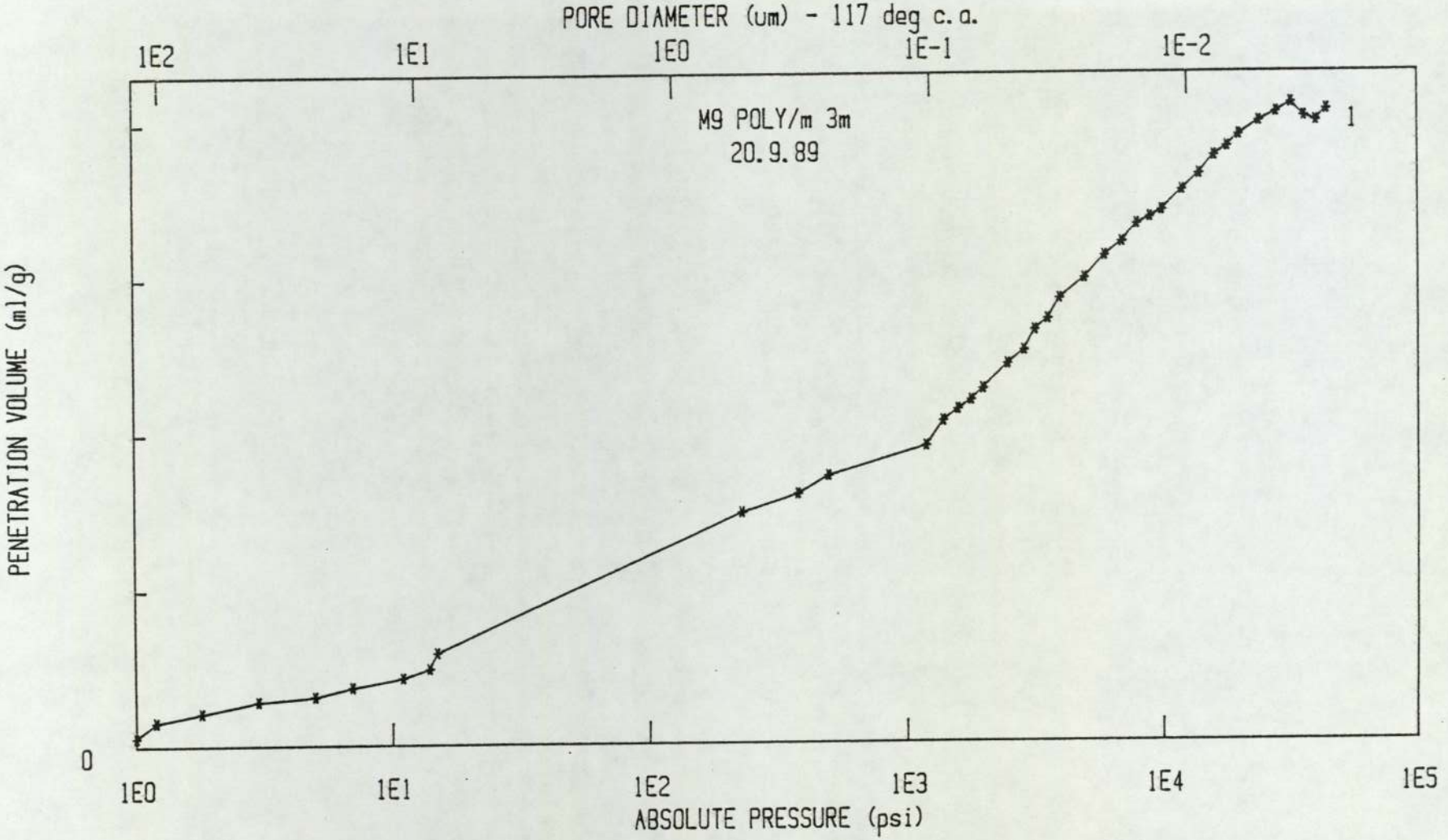

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M9 POLY/m 3m
20.9.89
1
PENETRATION VOLUME (ml/g)
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K22

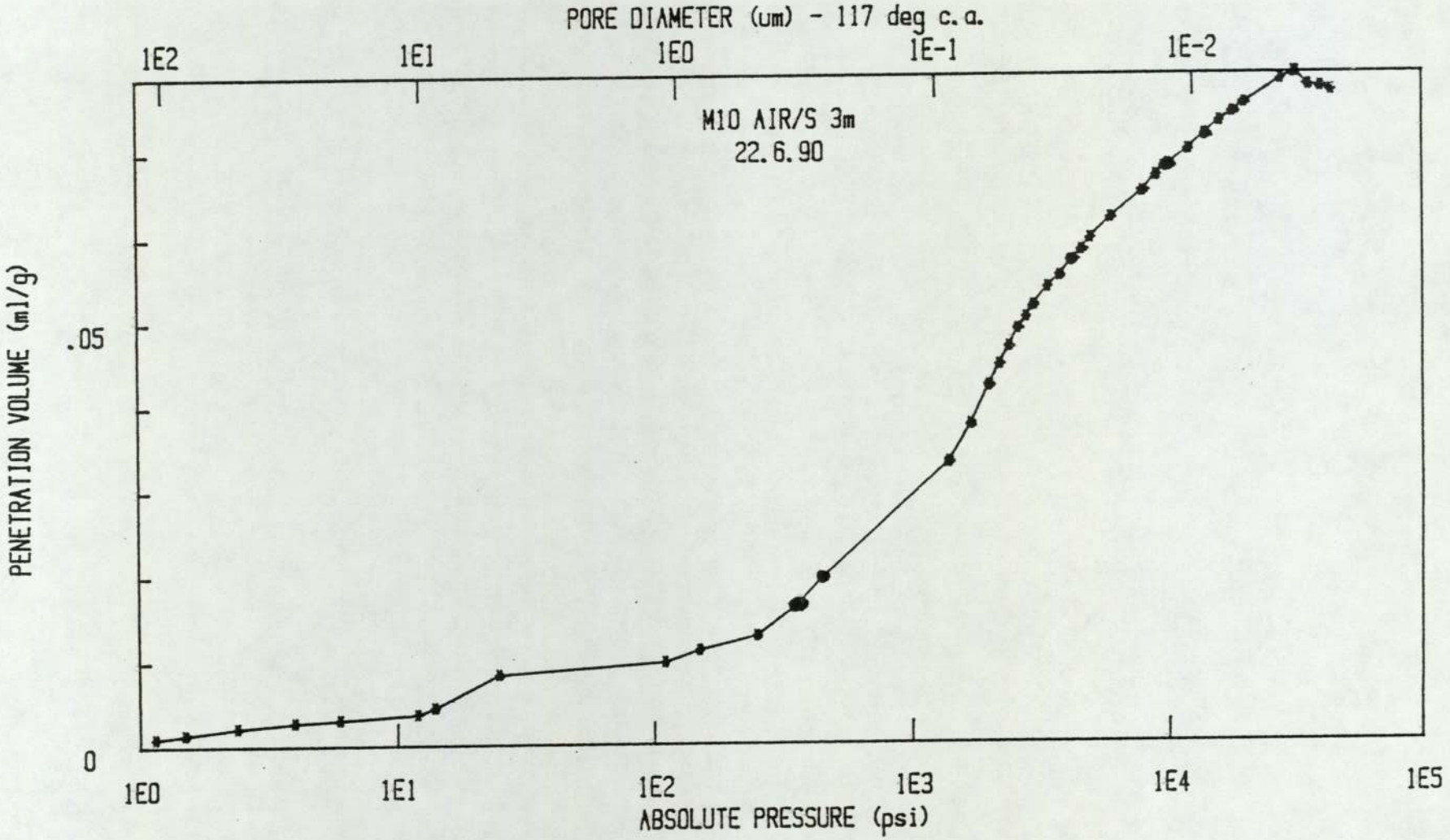

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M10 AIR/S 3m
22.6.90
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K23

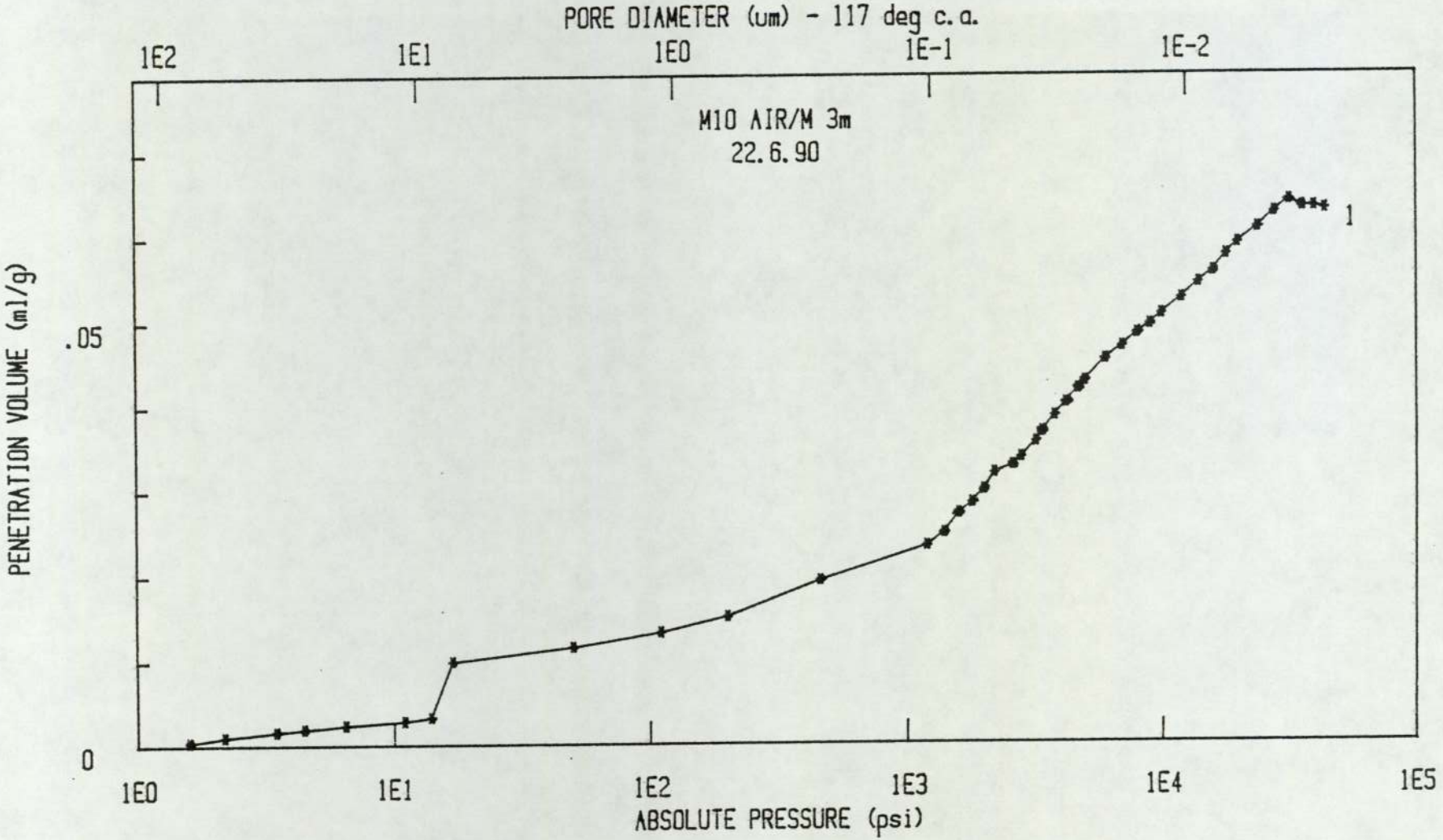

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M10 AIR/M 3m
22.6.90
1
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K24

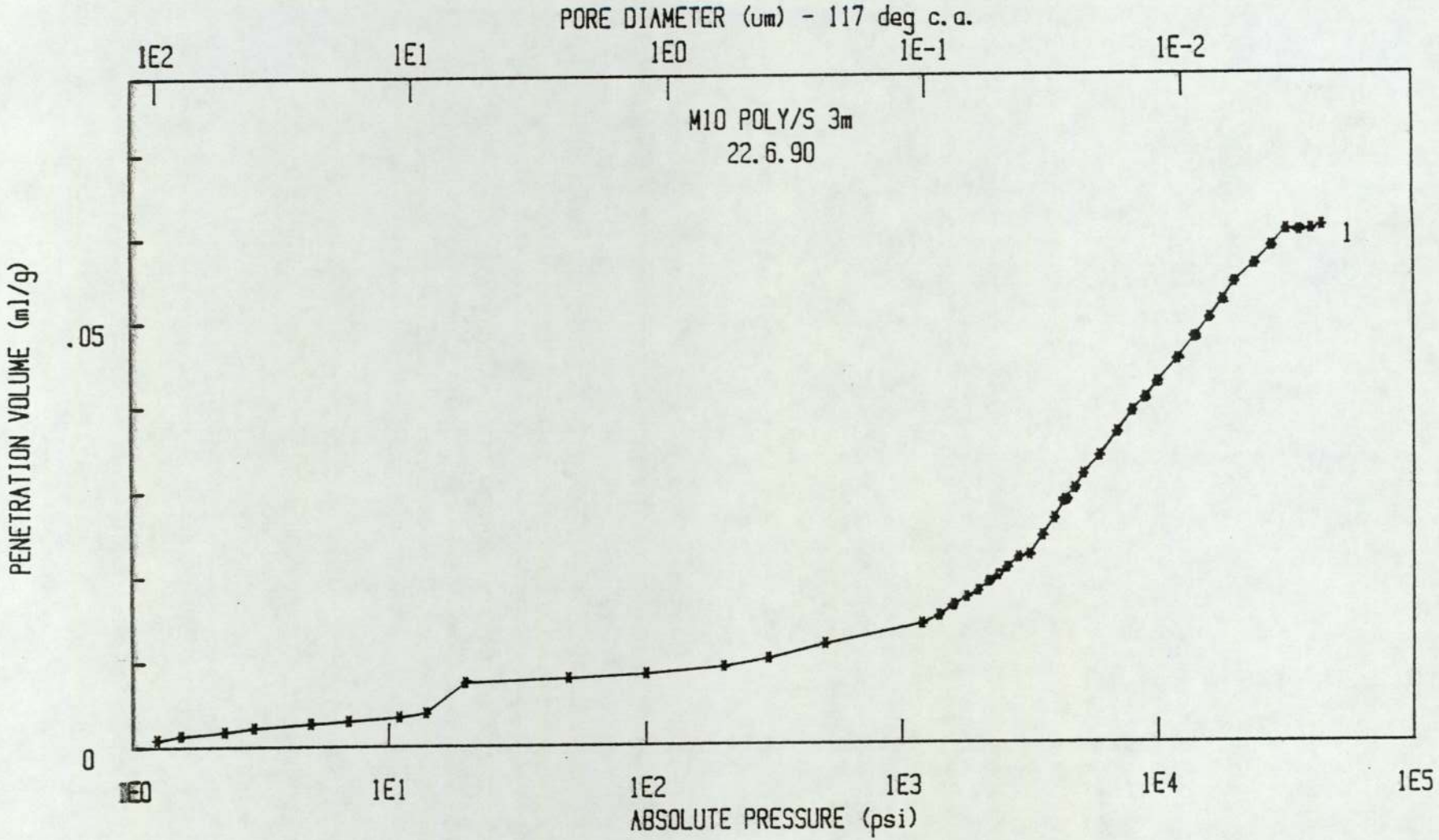

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M10 POLY/S 3m
22.6.90
1
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K25

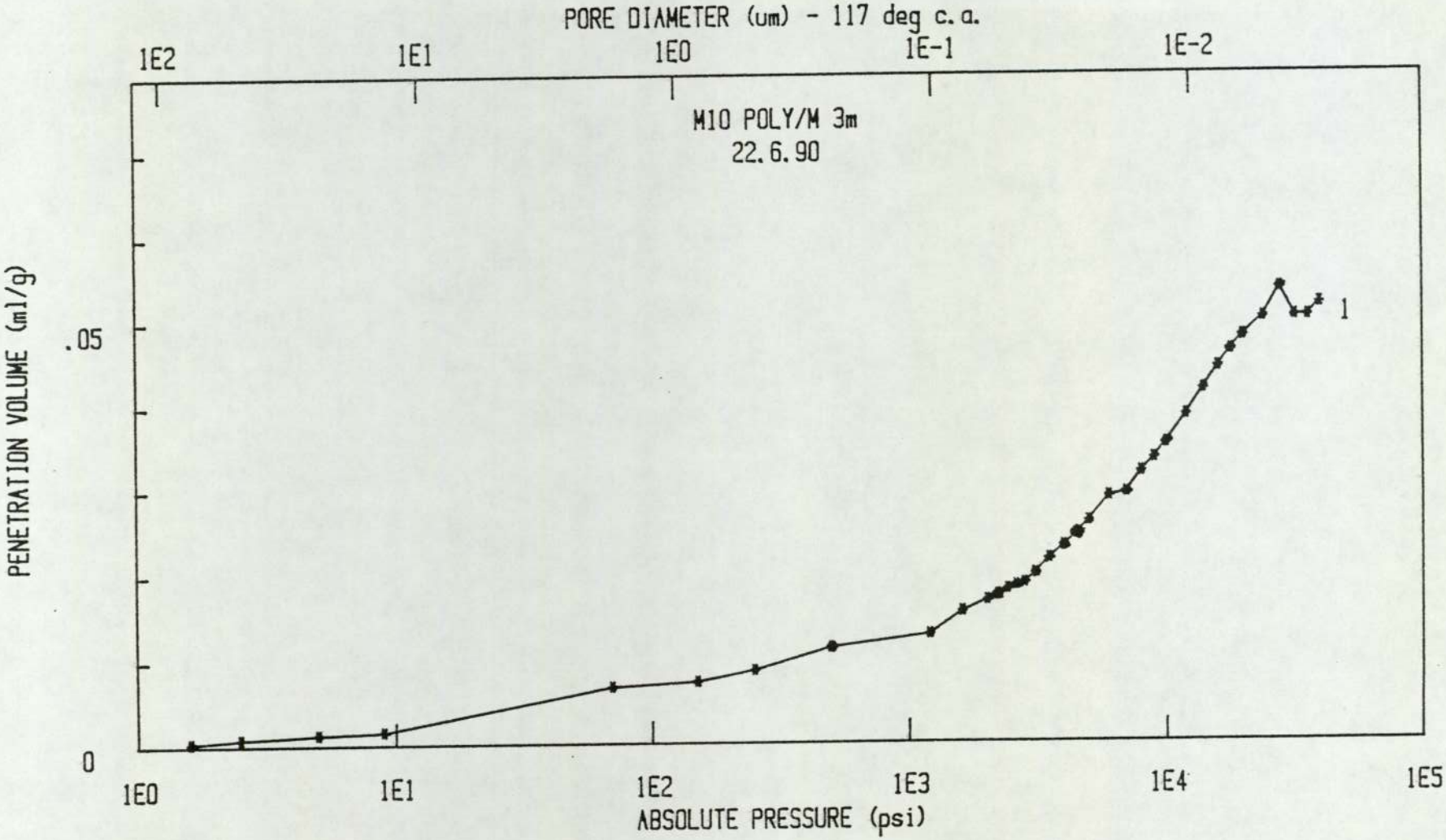

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M10 POLY/M 3m
22.6.90
PENETRATION VOLUME (ml/g)
.05
0
1
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K26

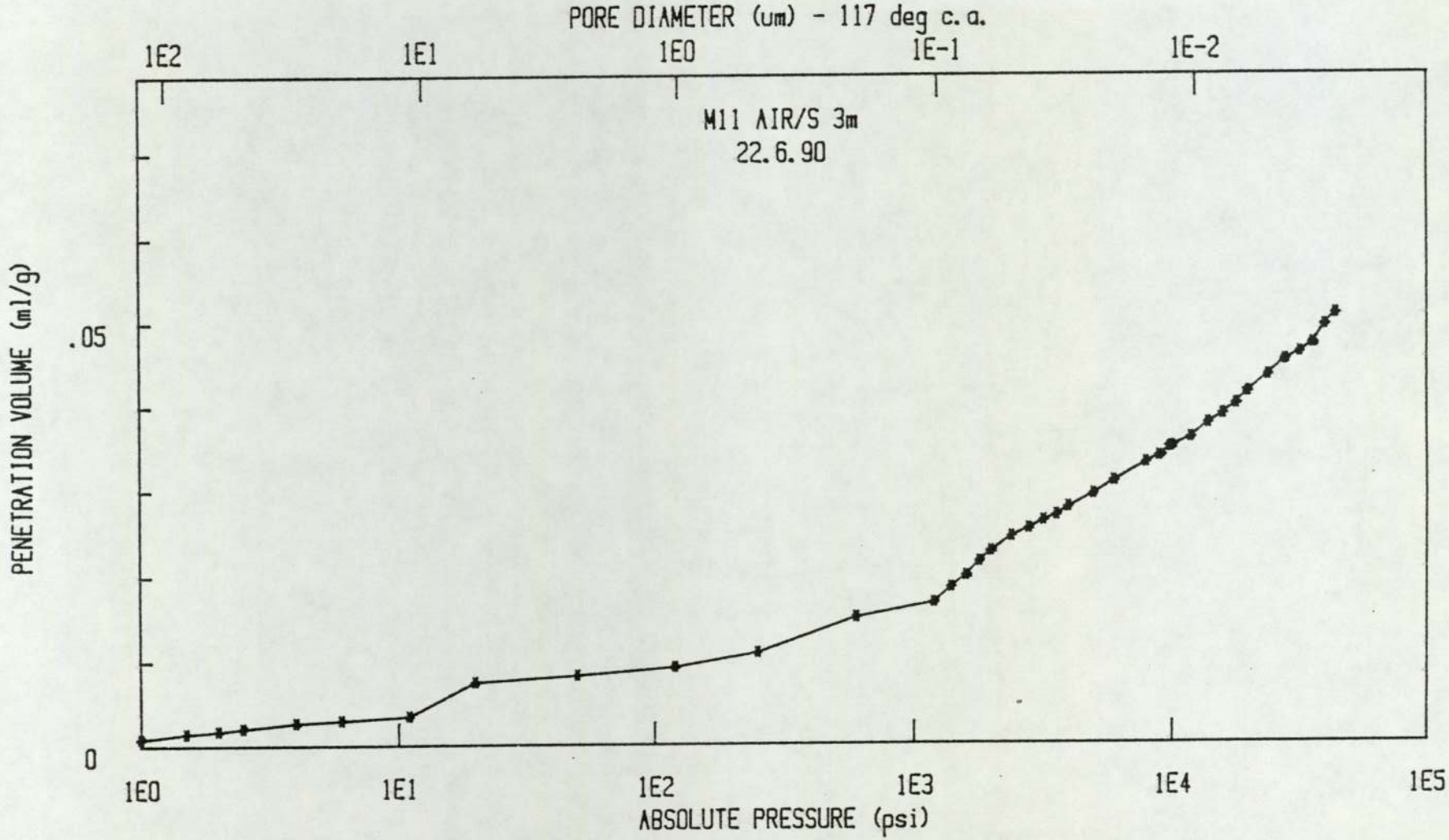

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M11 AIR/S 3m
22.6.90
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K27

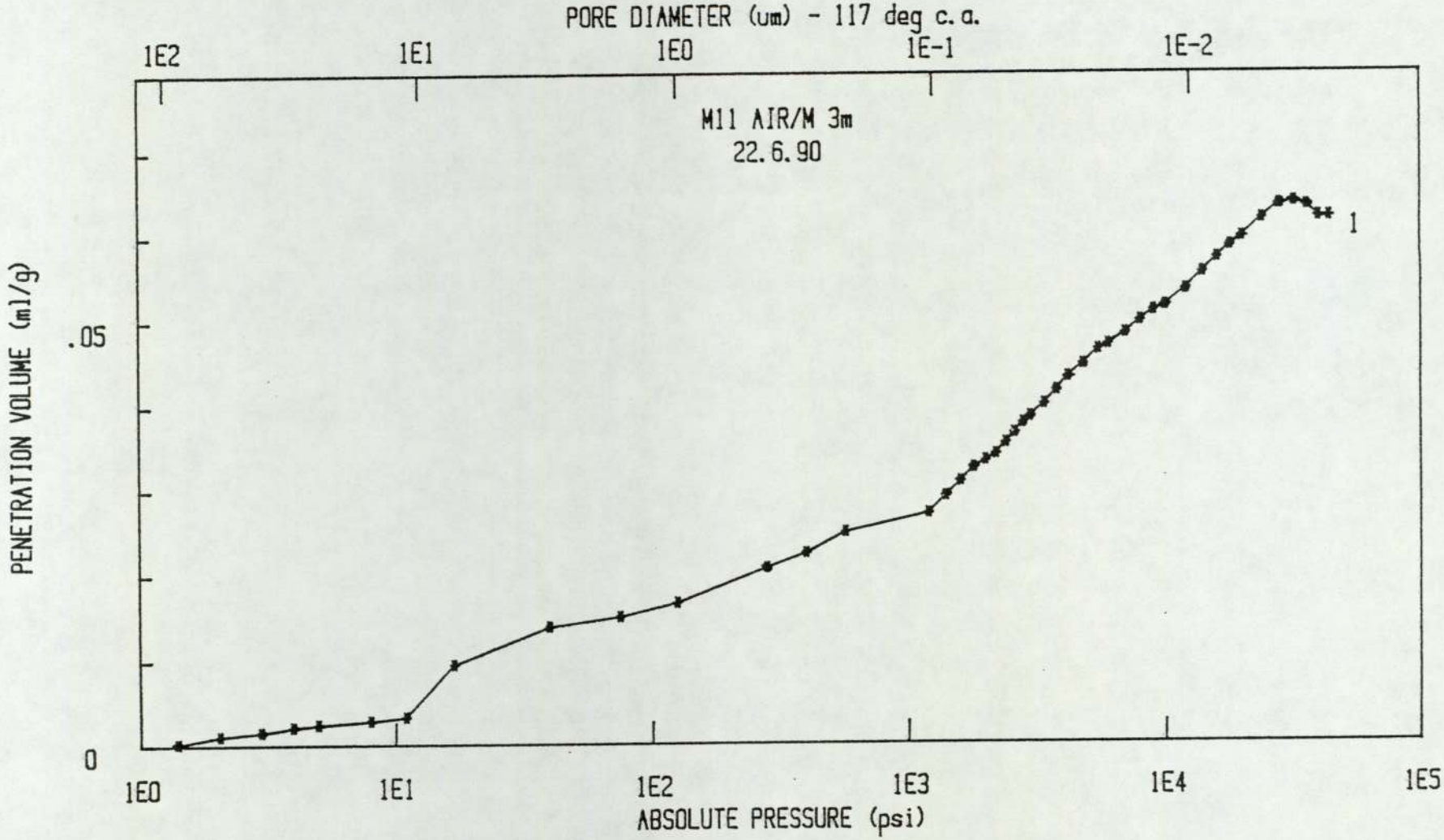

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M11 AIR/M 3m
22.6.90
1
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K28

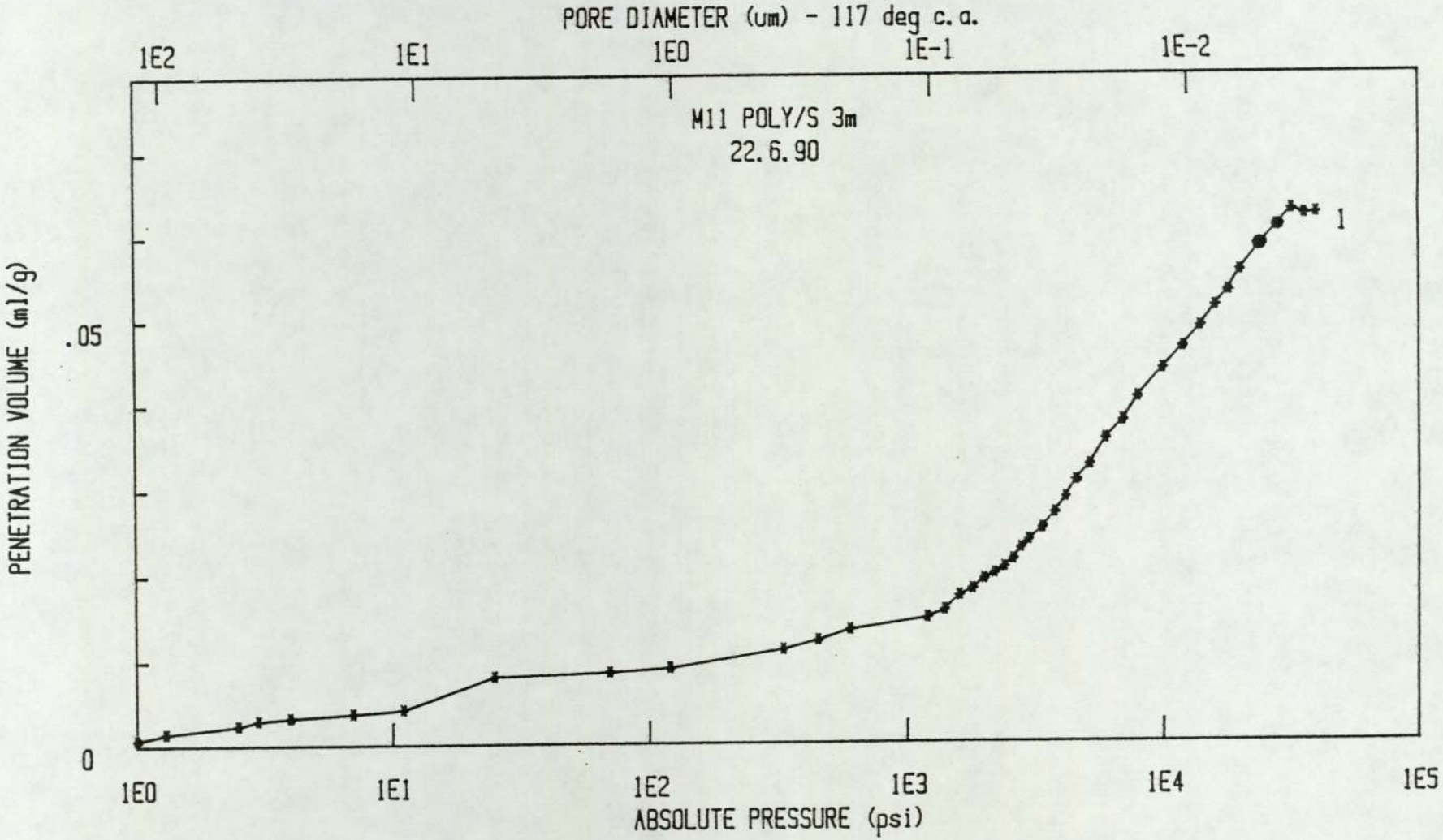

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M11 POLY/S 3m
22.6.90
1
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K29

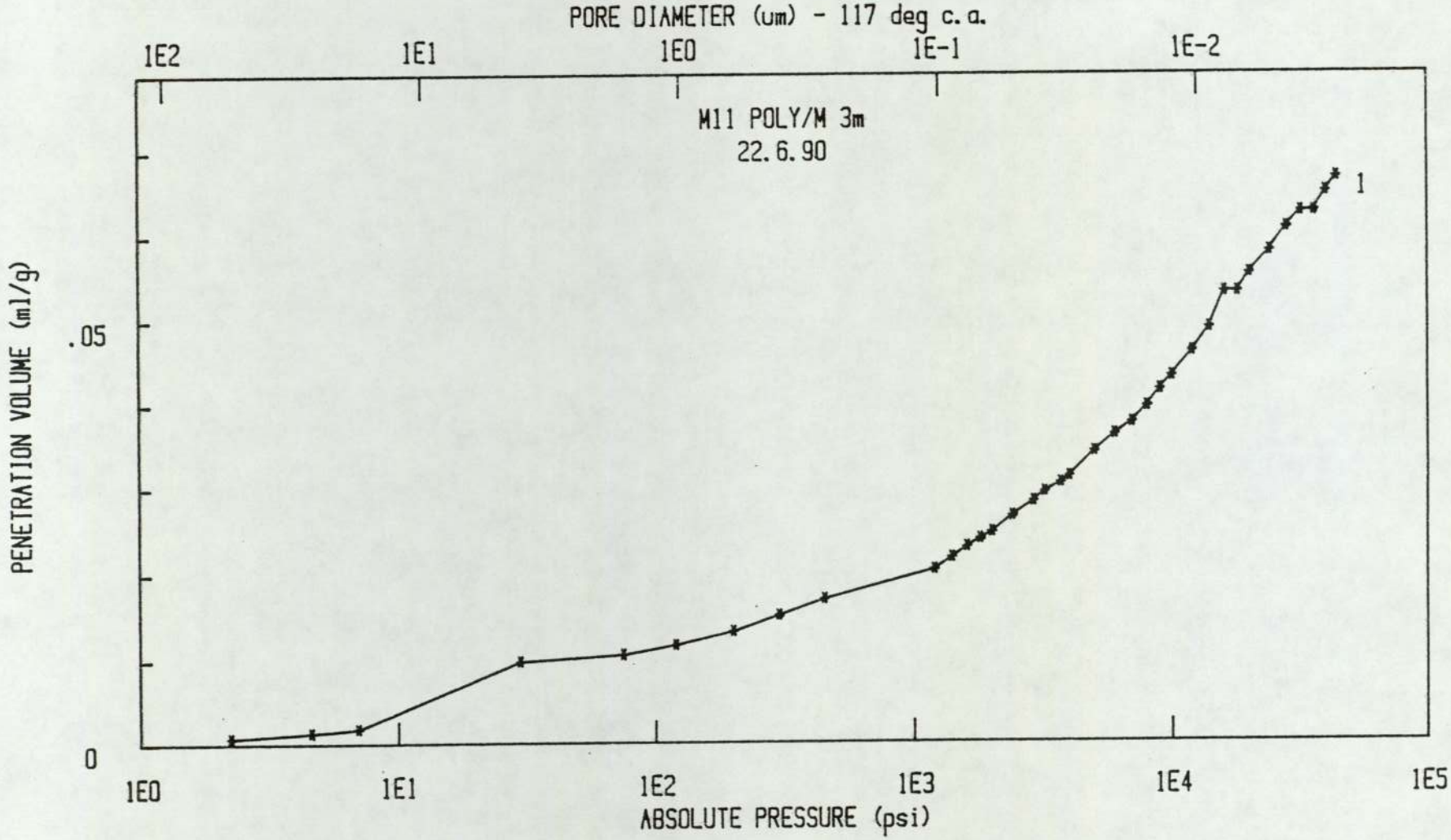

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M11 POLY/M 3m
22.6.90
1
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K3O

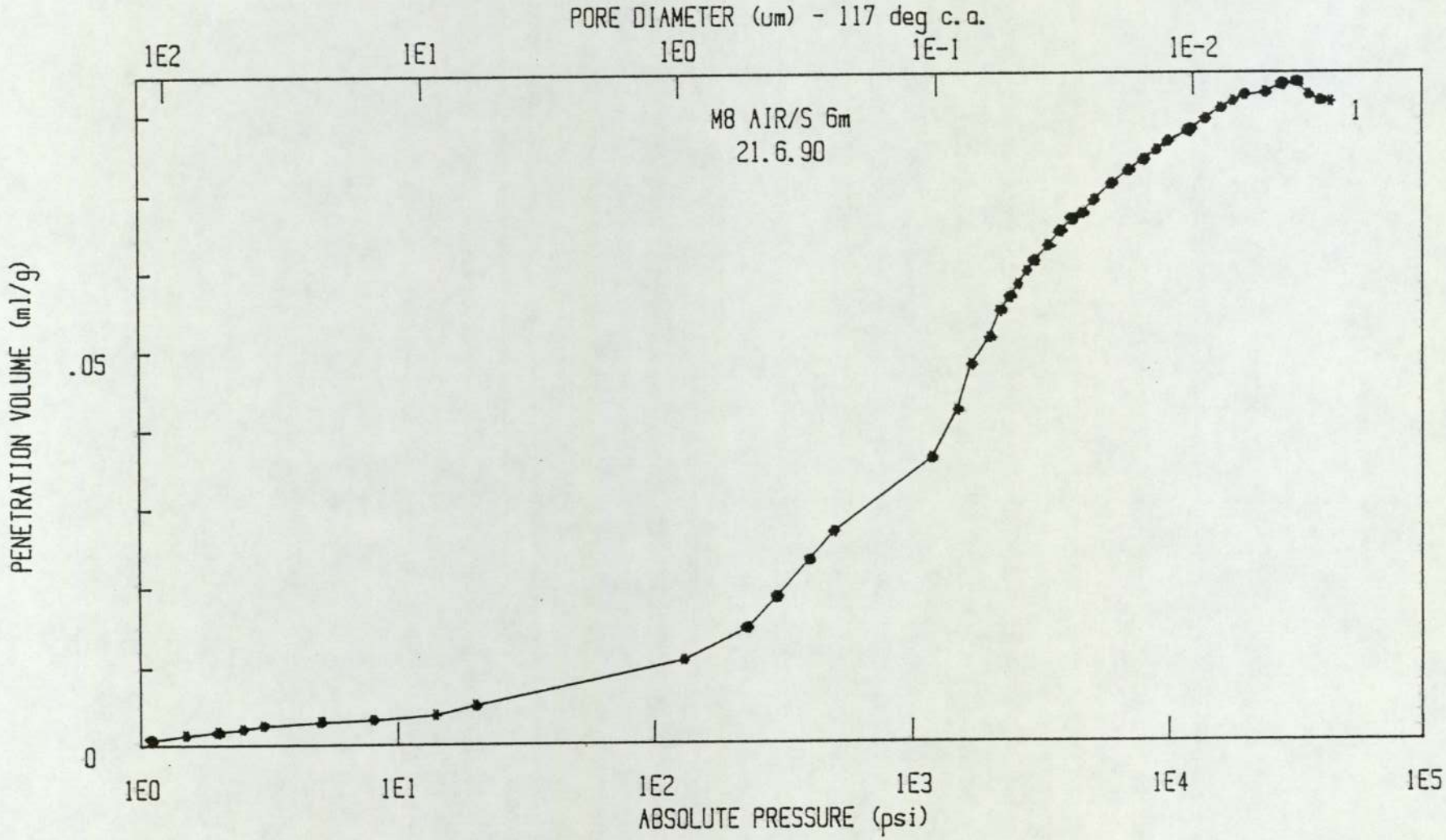

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M8 AIR/S 6m
21.6.90
1
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K31

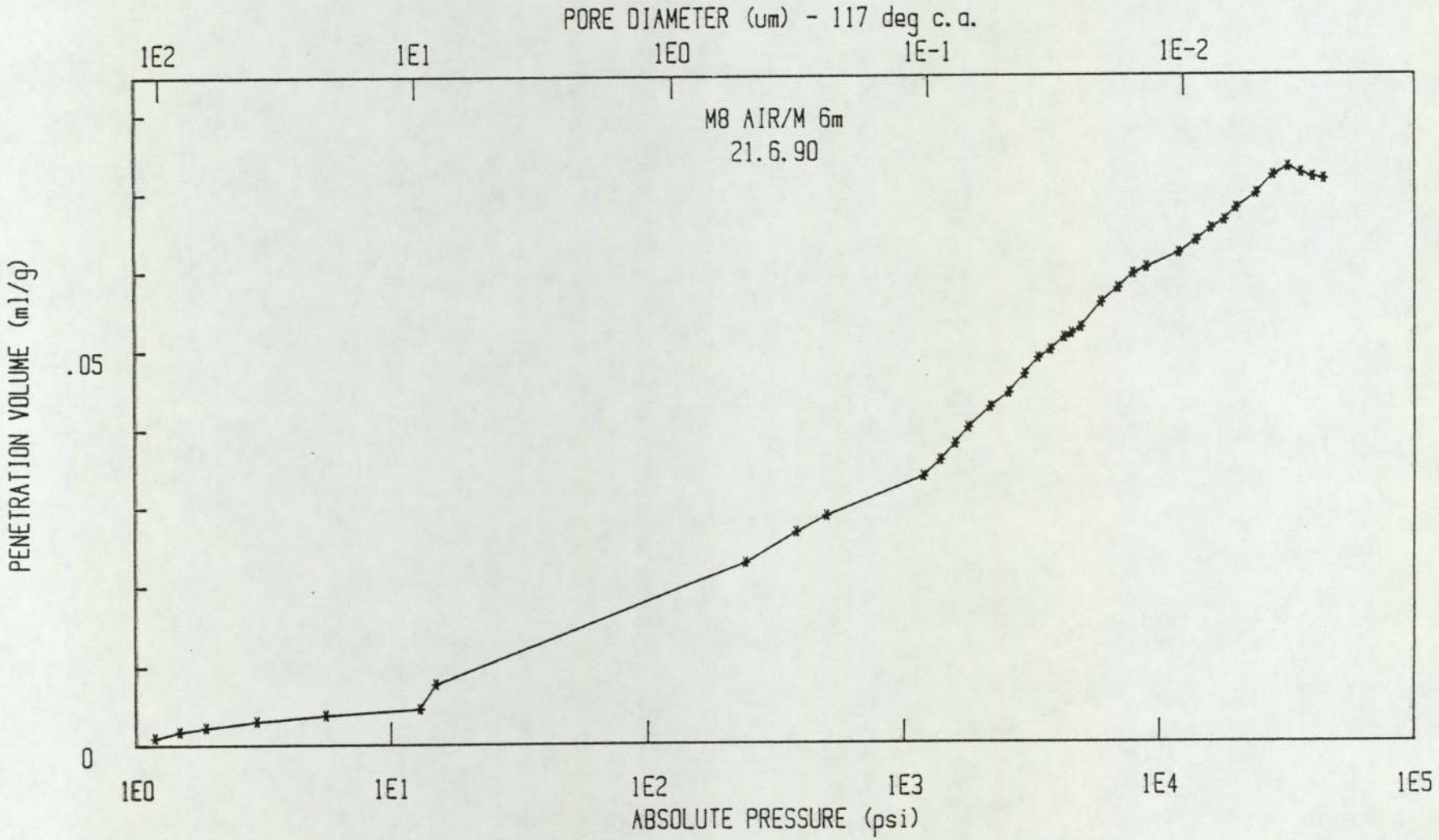

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M8 AIR/M 6m
21.6.90
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K32

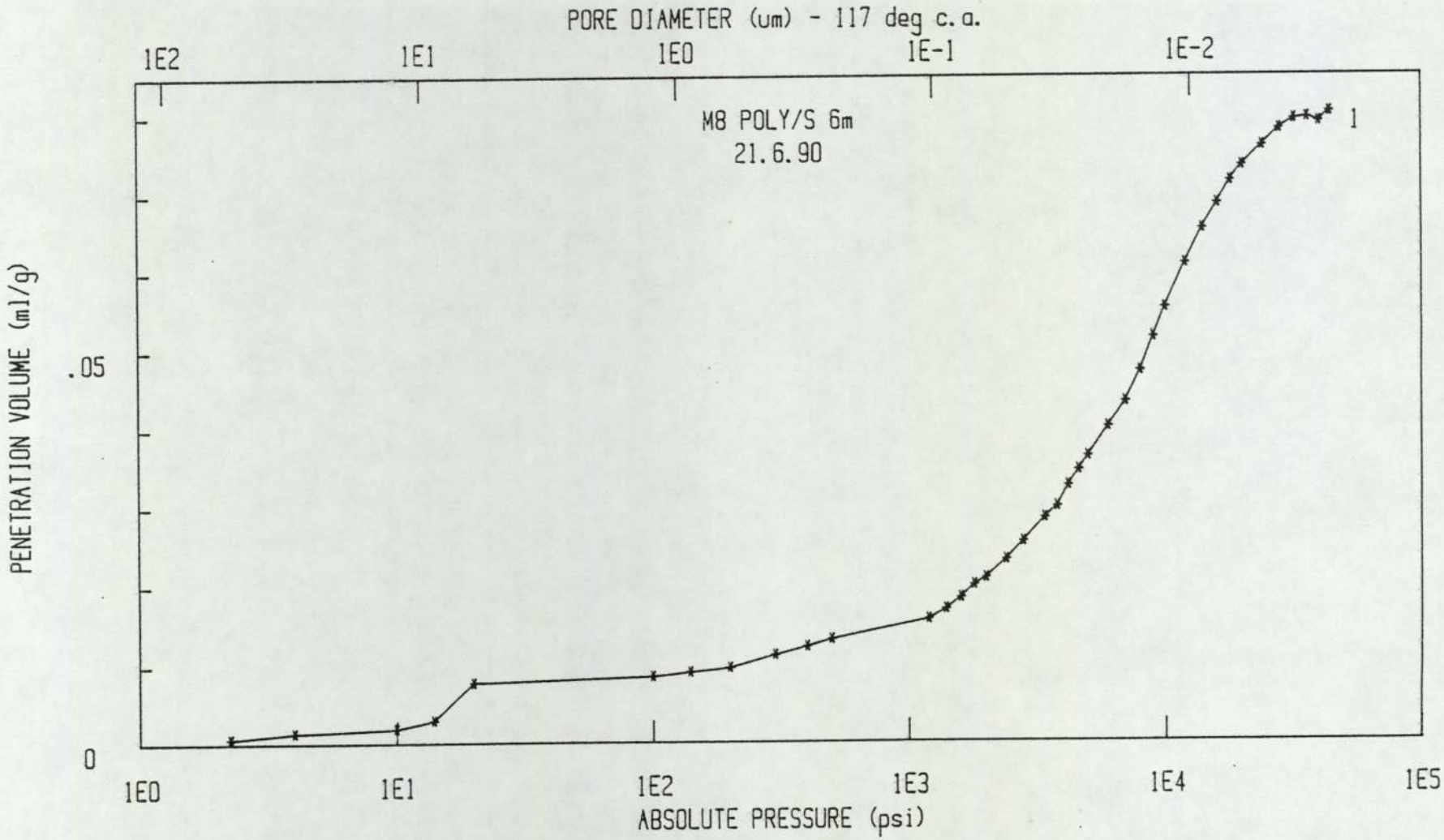

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M8 POLY/S 6m
21.6.90
1
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K33

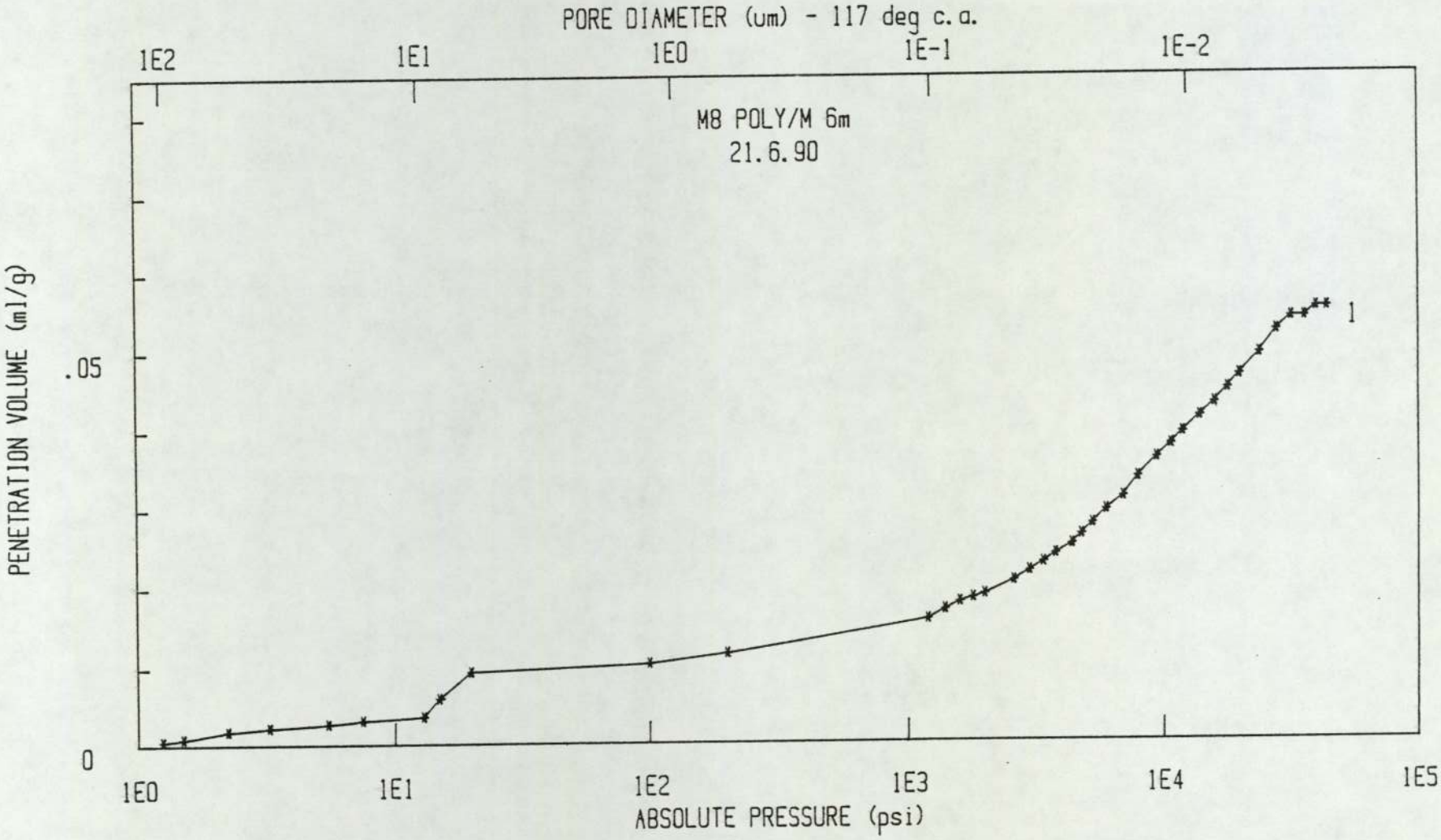

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M8 POLY/M 6m
21.6.90
PENETRATION VOLUME (ml/g)
.05
0
1
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K34

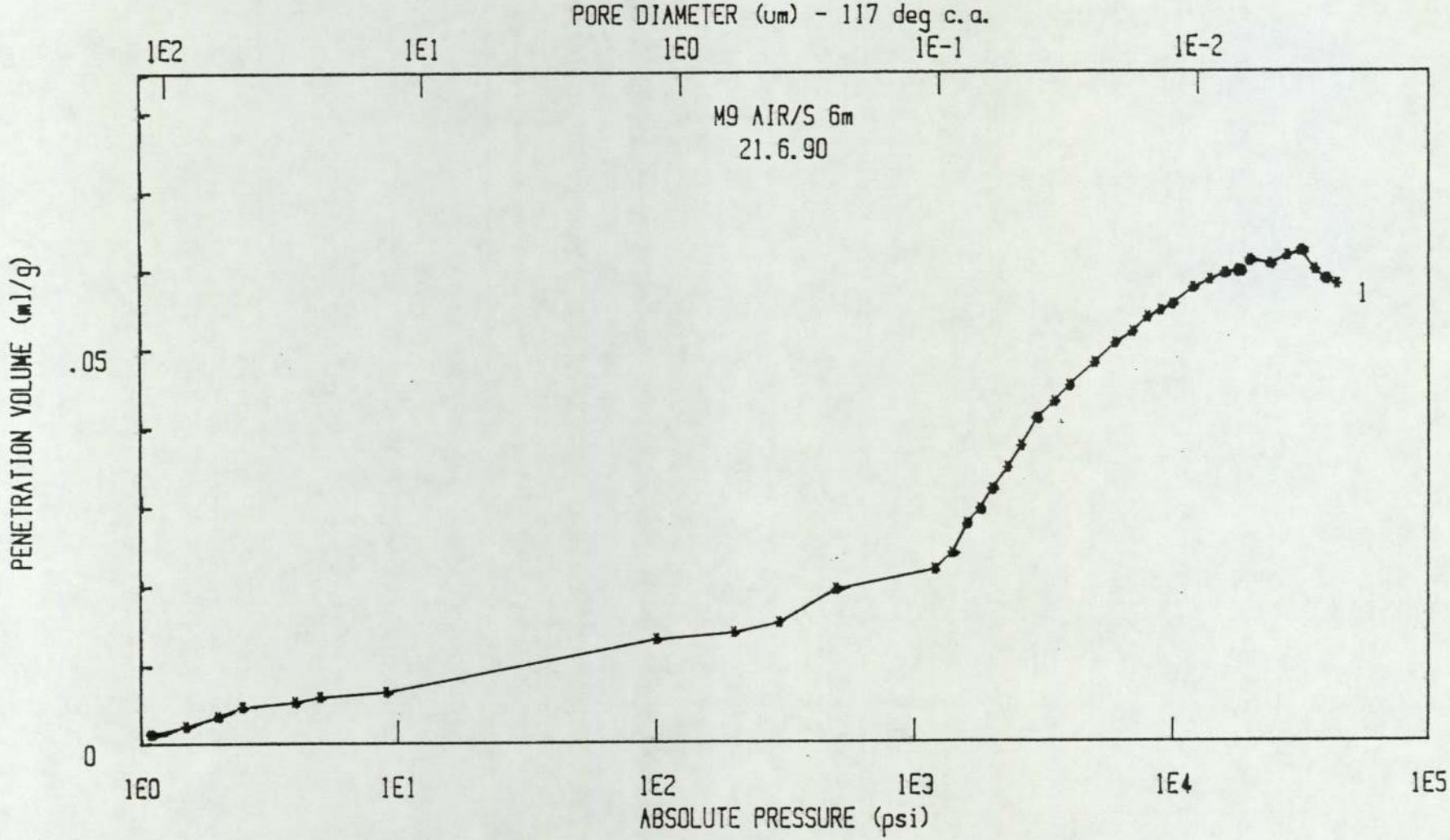

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M9 AIR/S 6m
21.6.90
PENETRATION VOLUME (ml/g)
.05
0
1
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K35

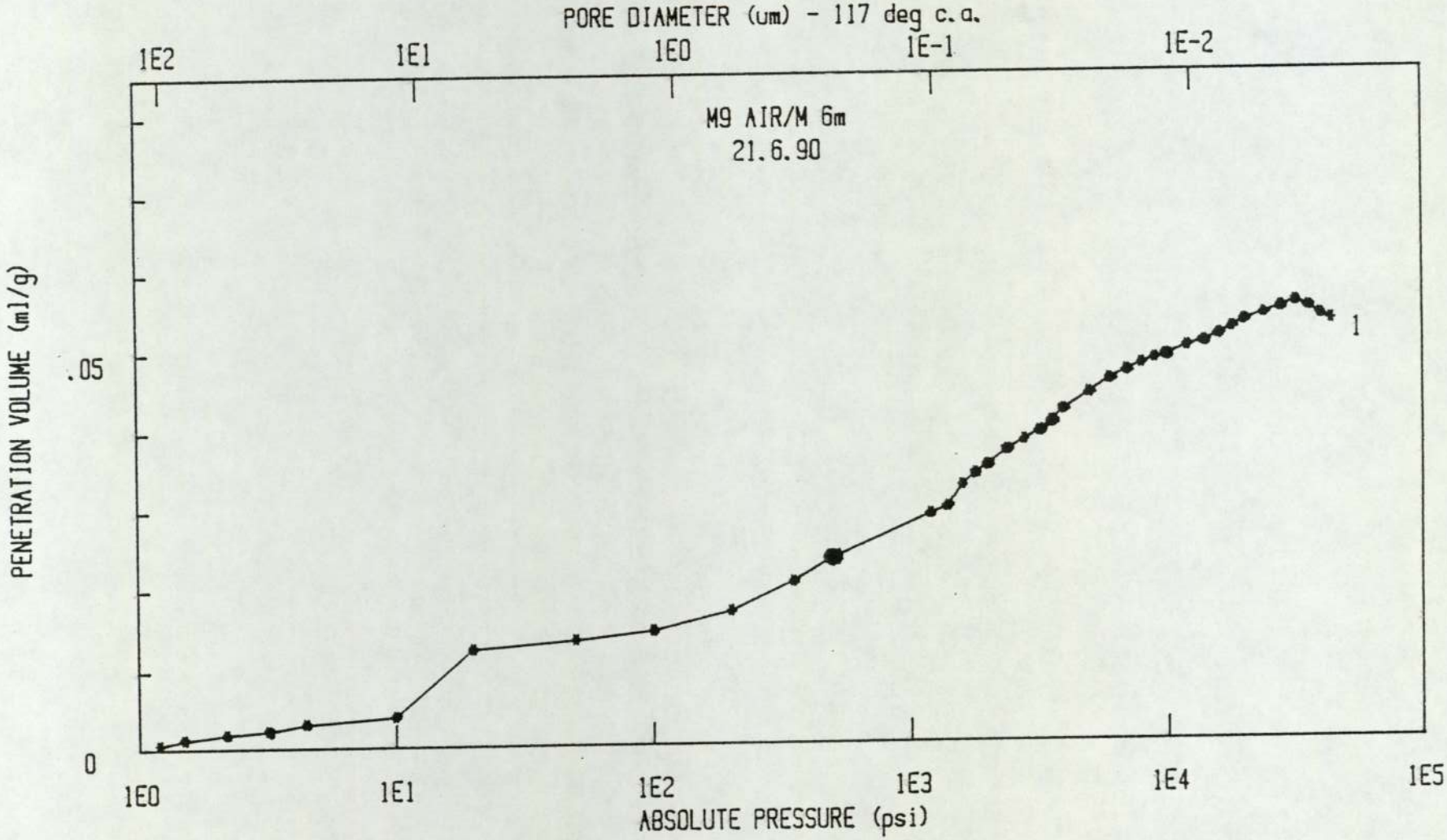

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M9 AIR/M 6m
21.6.90
PENETRATION VOLUME (ml/g)
.05
0
1
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K36

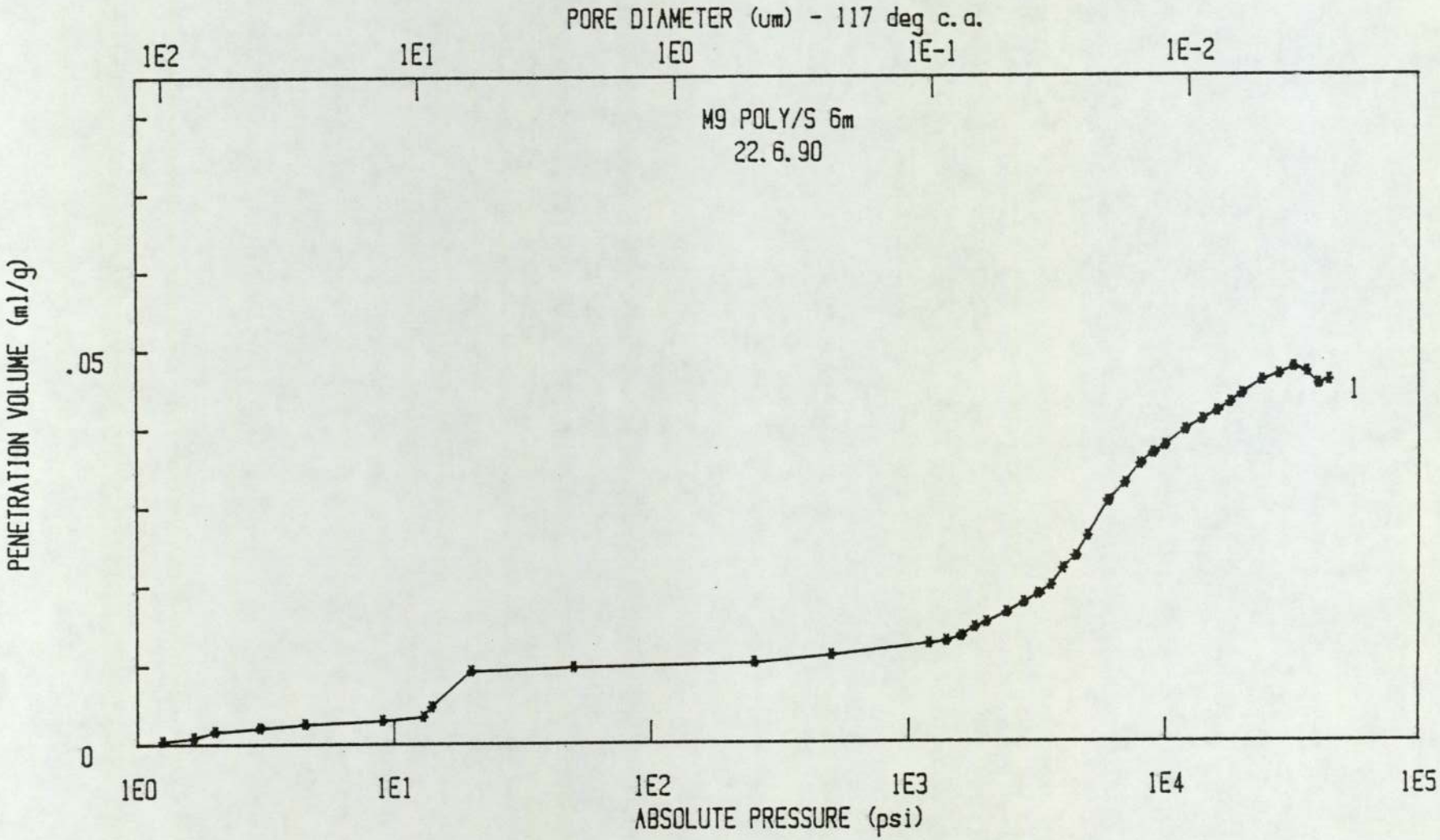

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M9 POLY/S 6m
22.6.90
PENETRATION VOLUME (ml/g)
.05
0
1
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K37

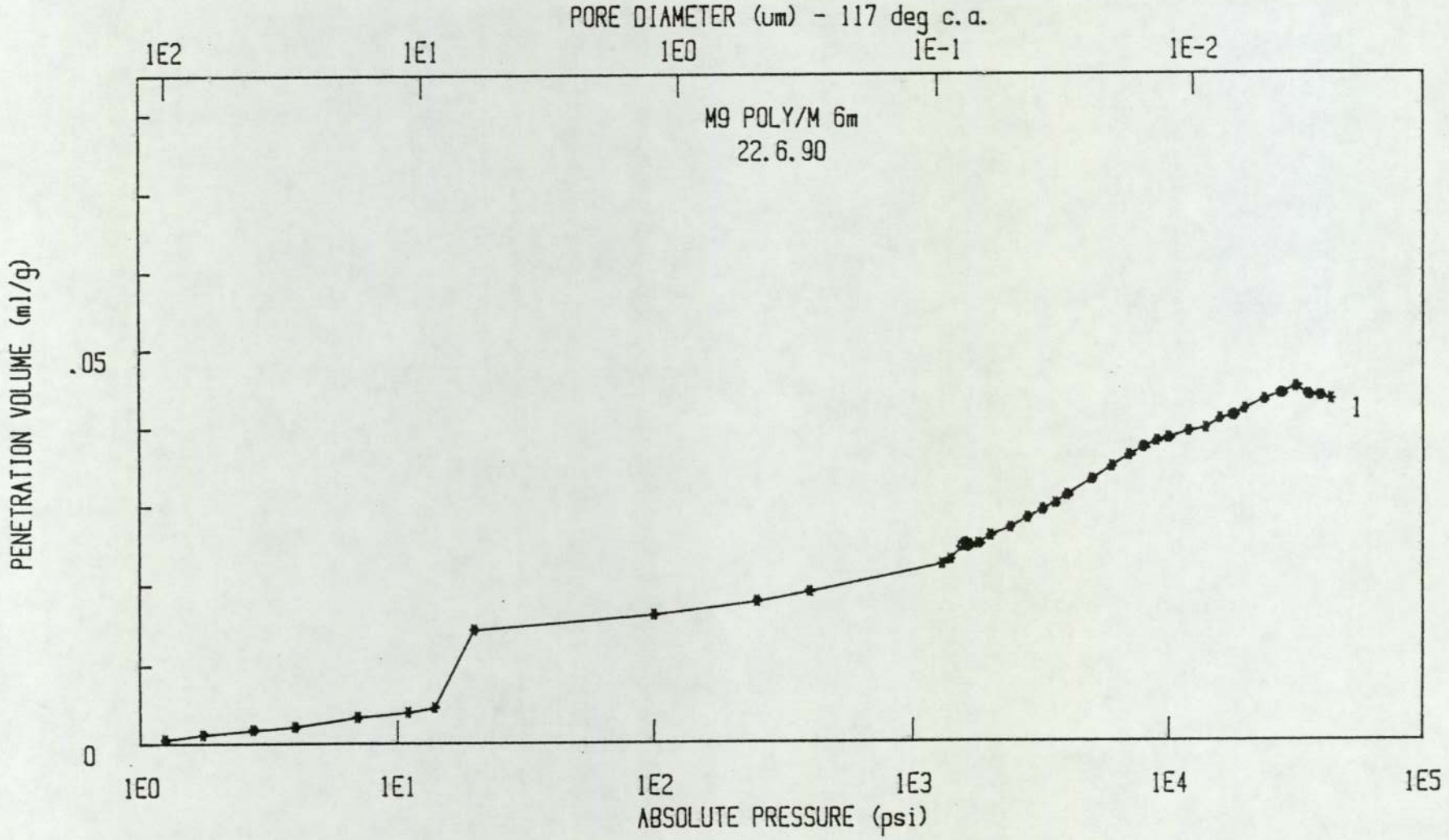

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M9 POLY/M 6m
22.6.90
PENETRATION VOLUME (ml/g)
.05
0
1
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K38

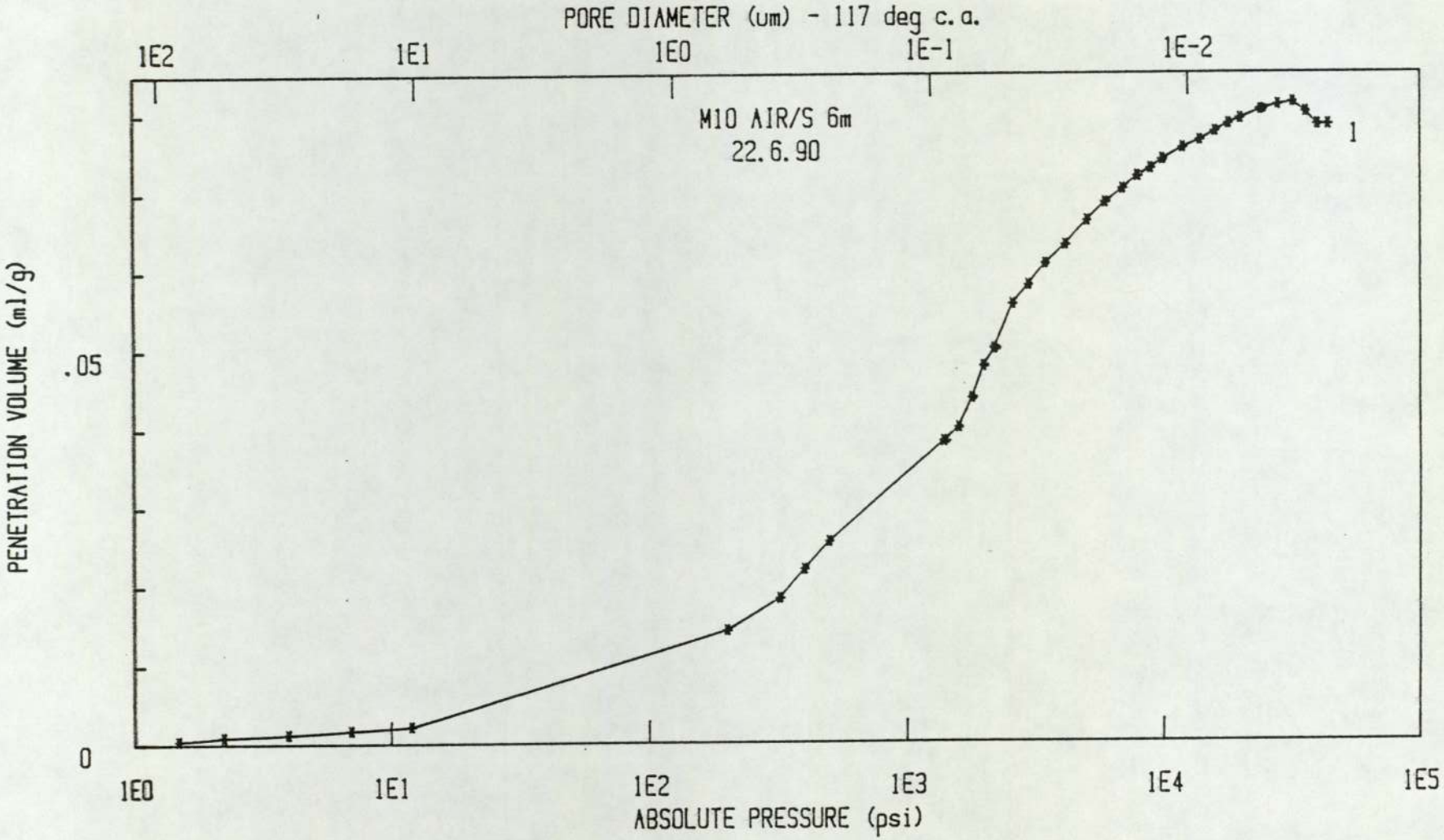

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M10 AIR/S 6m
22.6.90
1
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K39

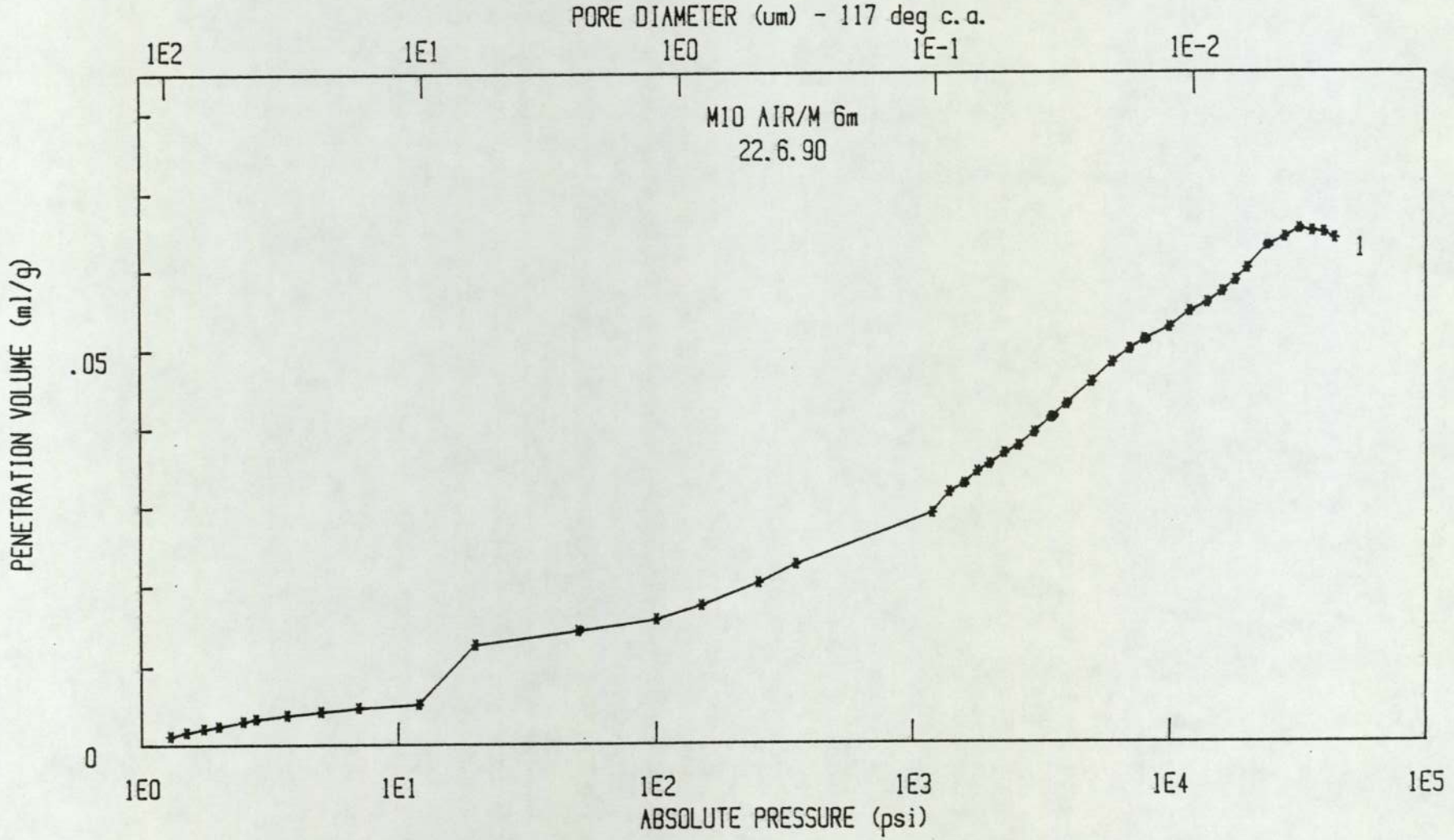

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M10 AIR/M 6m
22.6.90
1
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K4O

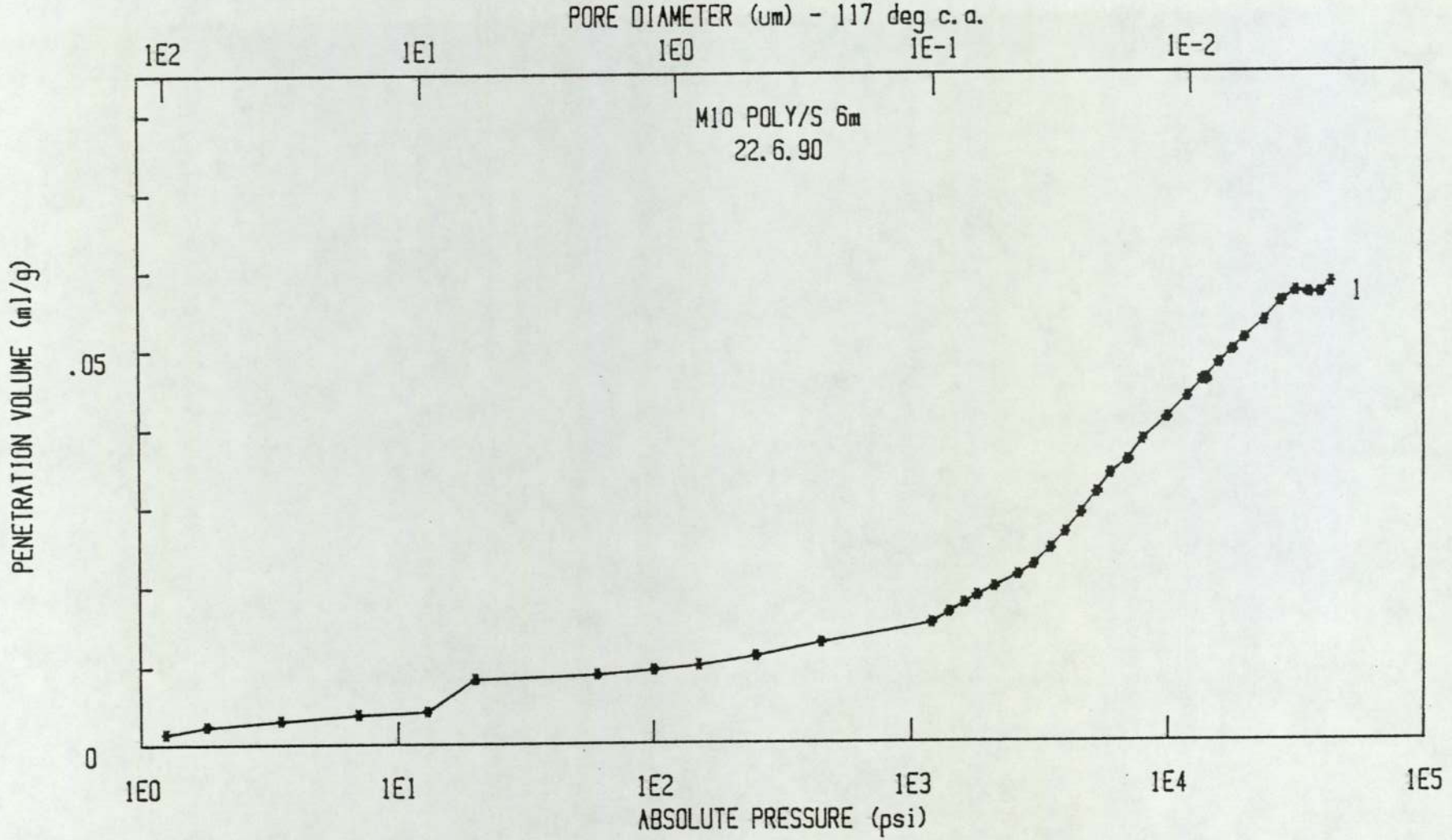

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M10 POLY/S 6m
22.6.90
1
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K41

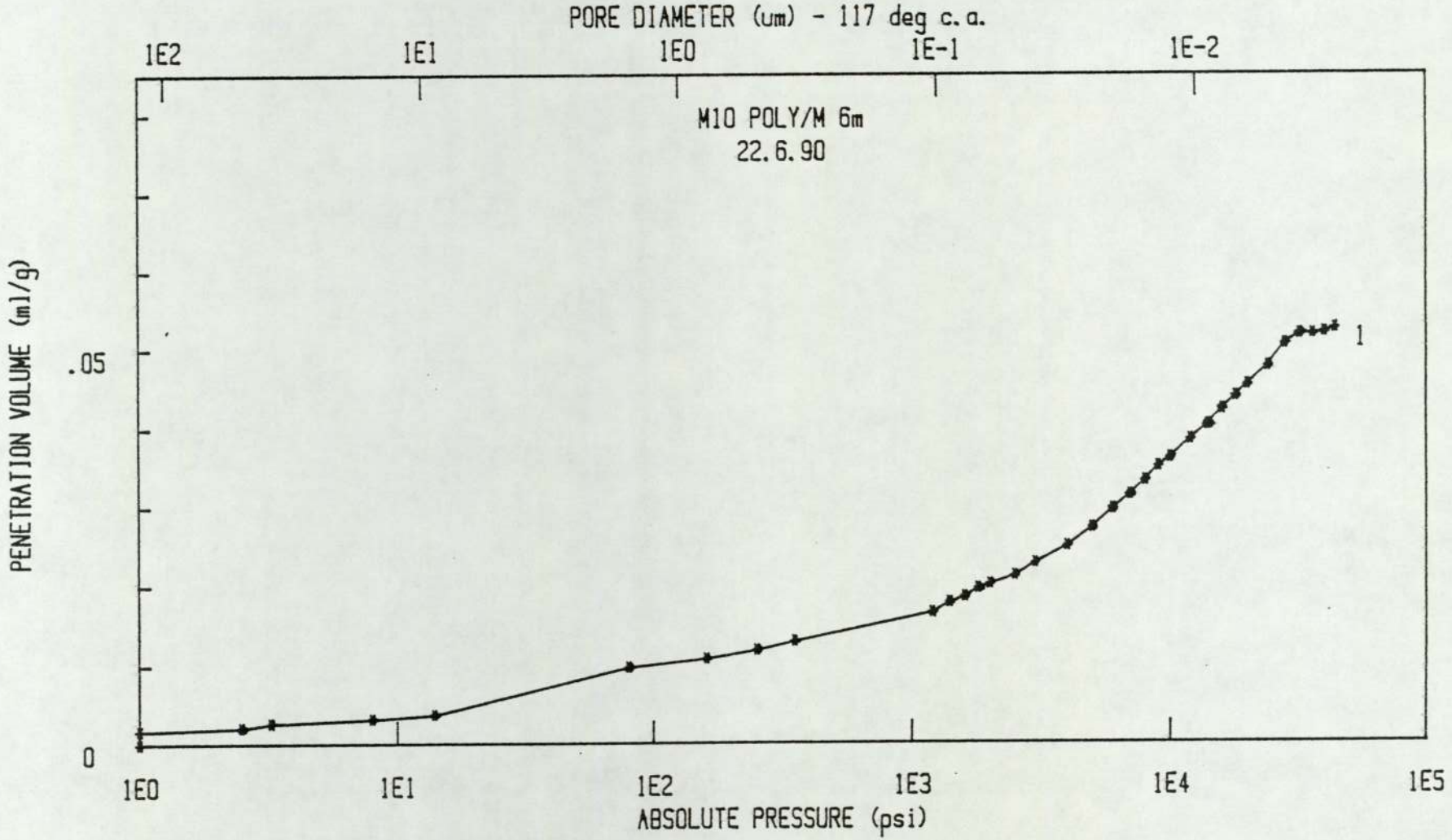

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M10 POLY/M 6m
22.6.90
PENETRATION VOLUME (ml/g)
.05
0
1
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K42

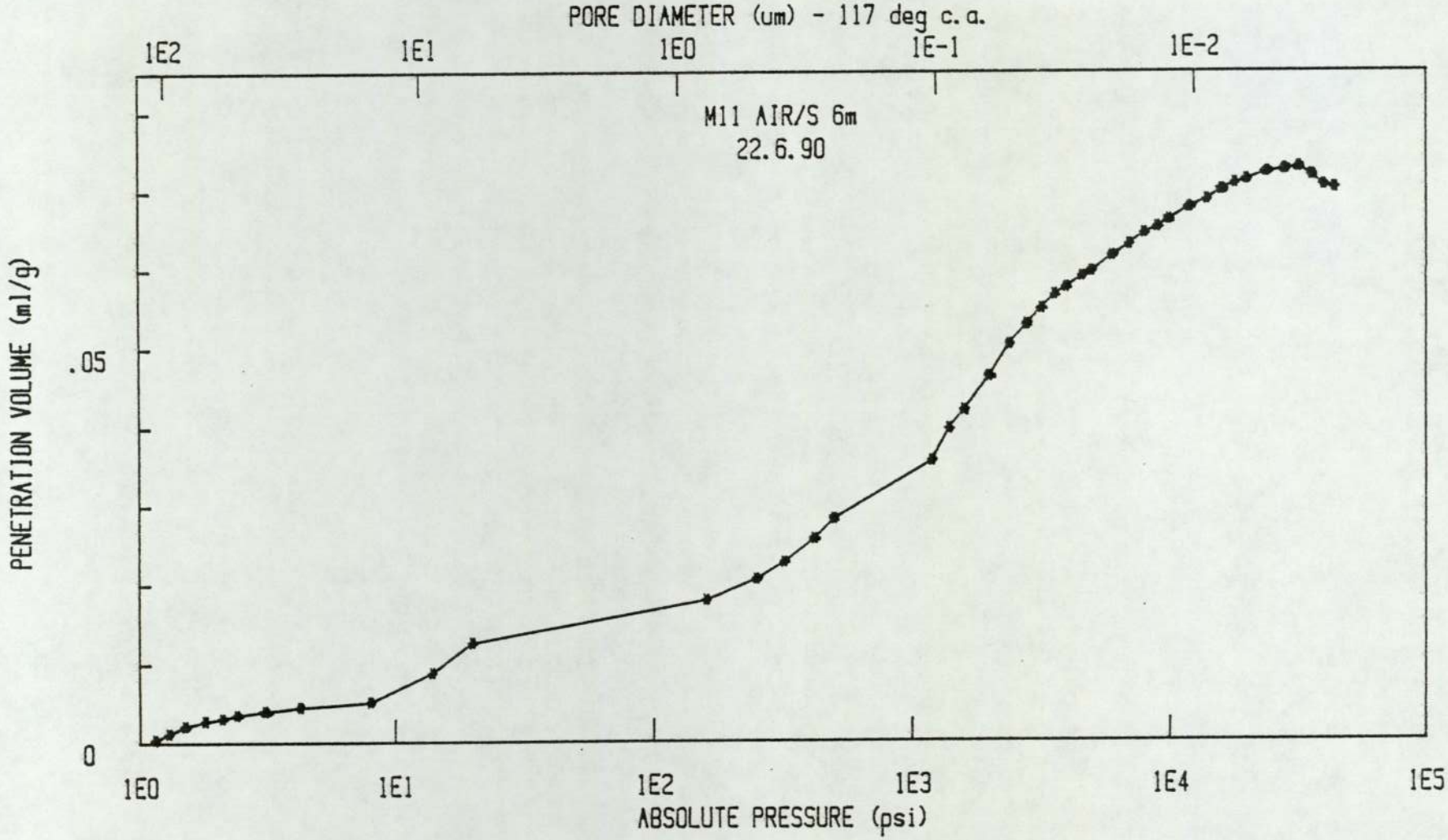

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M11 AIR/S 6m
22.6.90
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K43

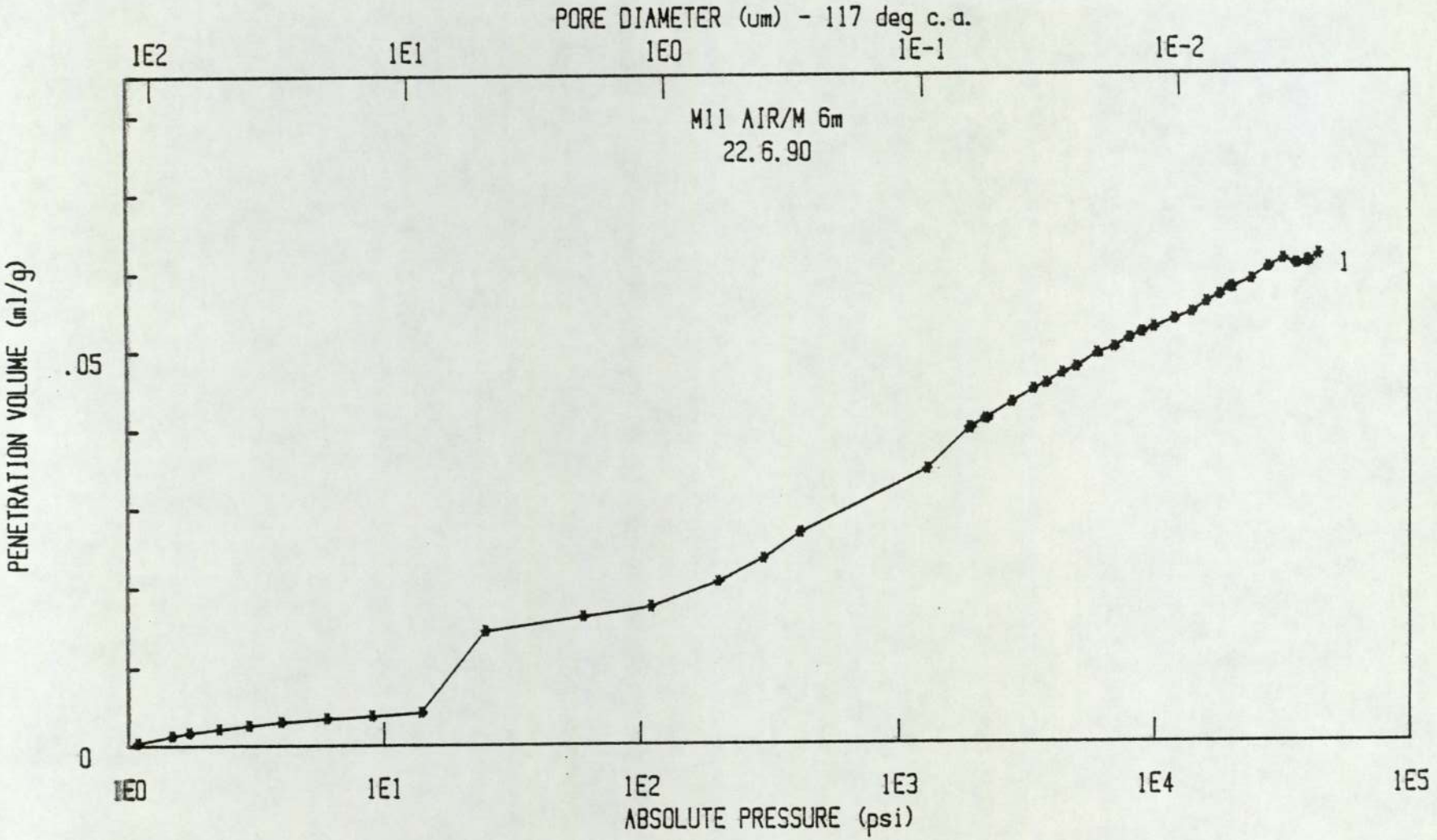

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M11 AIR/M 6m
22.6.90
1
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K44

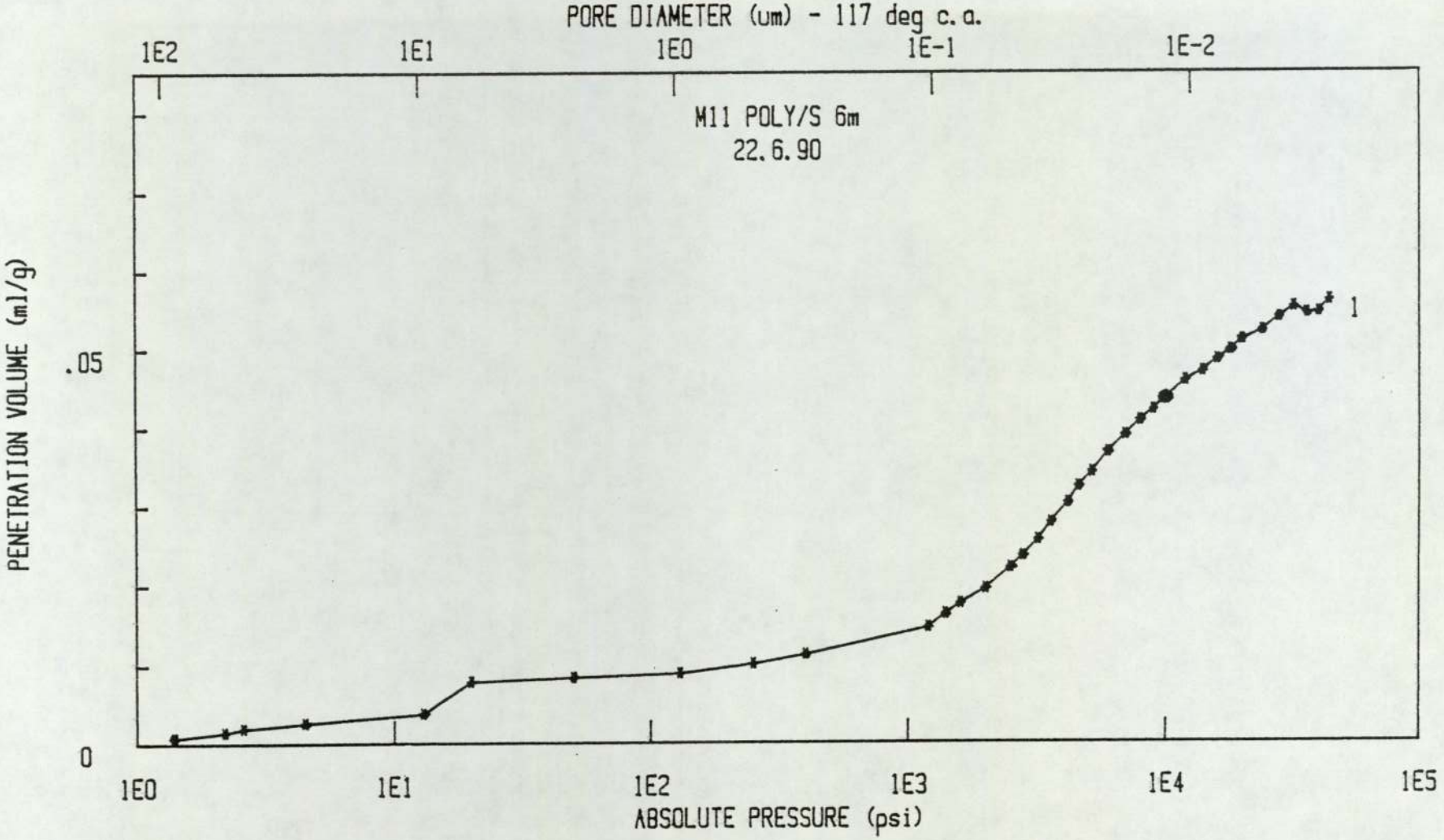

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M11 POLY/S 6m
22.6.90
1
PENETRATION VOLUME (ml/g)
.05
0
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K45

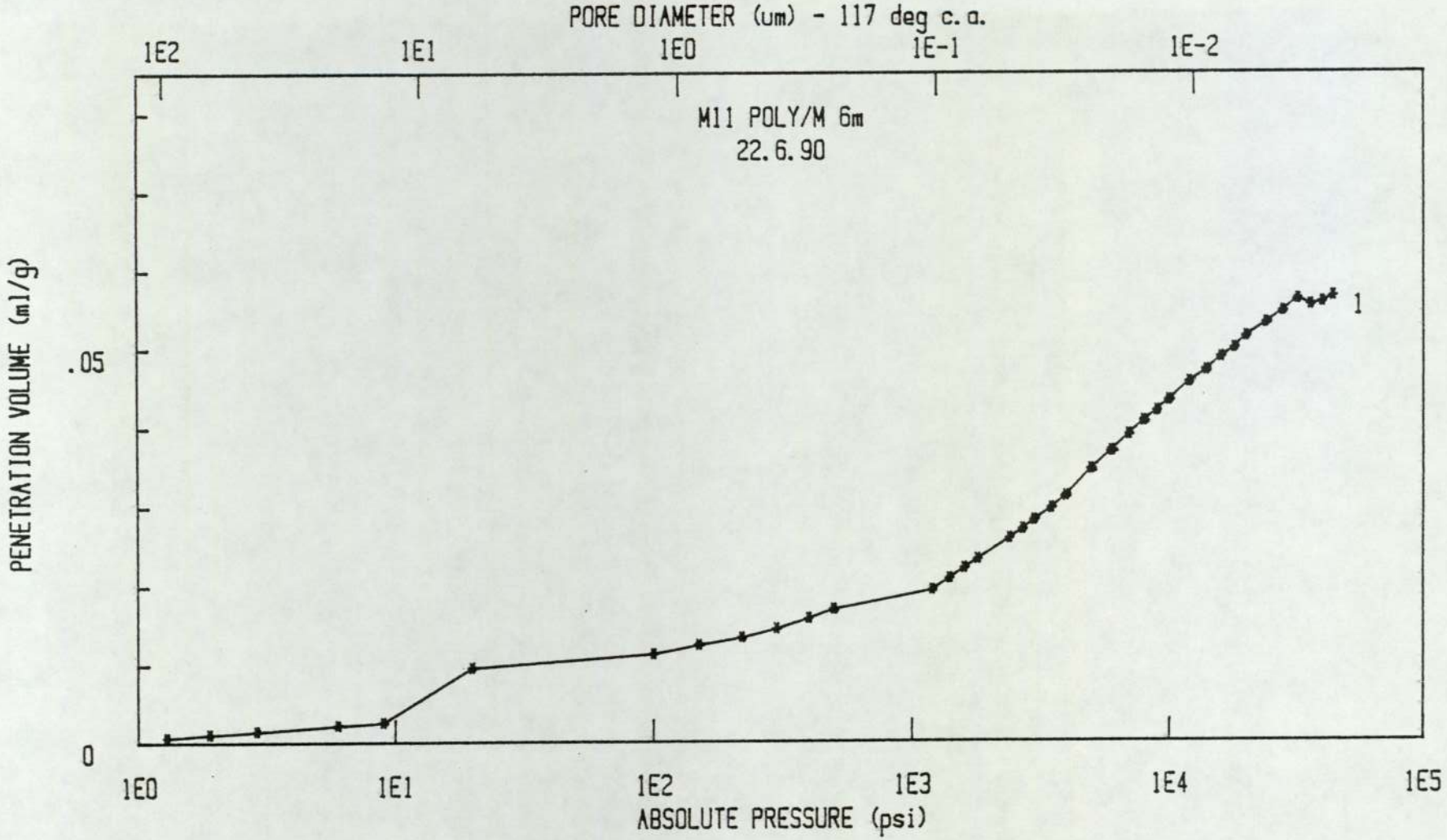

PORE DIAMETER (um) - 117 deg c.a.
1E2
1E1
1E0
1E-1
1E-2
M11 POLY/M 6m
22.6.90
PENETRATION VOLUME (ml/g)
.05
0
1
1E0
1E1
1E2
1E3
1E4
1E5
ABSOLUTE PRESSURE (psi)

FIGURE K46

APPENDIX L

TABLE: L1 SUMMARY OF MICROHARDNESS RESULTS

Specimen Number/ Curing regime	Vickers Hardness Number (Kg/Sq mm)					
	TOP			MIDDLE		
	0 mm	mm	mm	50 mm	mm	mm
8 Polythene sheeting	75	67	64	69	65	67
8 Air curing	72	68	64	65	65	66
9 Polythene sheeting	84	79	75	77	78	75
9 Air curing	100	86	83	77	77	74
10 Polythene sheeting	71	65	65	64	64	64
10 Air curing	65	65	65	67	67	65
11 Polythene sheeting	75	70	69	65	65	64
11 Air curing	65	64	64	64	64	64

Specimen No. 8 Polythene curing/surface matrix Age 6 months Load: 100 gm

Determination Number	Top			Middle			Bottom		
	X	Y	Mean	X	Y	Mean	X	Y	Mean
1	390	386	388	383	388	386	412	409	410
2	372	375	374	382	395	394	400	402	401
3	382	376	379	390	392	391	415	419	417
4	355	362	358	375	373		411	408	409
5	358	364	361	402	408	405	418	420	419
6	380	376	378	349	355		415	415	415
7	369	365	367	395	396	396	405	407	406
8	384	380	382	392	388	390	389	394	392
9	381	377	379	398	396	397	386	389	
10	355	357		386	383		380	374	
11	340	344		399	402	400	396	398	397
12	354	359		402	405	404	377	379	
13	360	365	362	395	386	390	399	402	401
Average of 10 Readings	373			395			407		
Vicker's Hardness No. (Mean Value) (Kg/mm^2)	75			67			64		

Specimen No. 8 Polythene curing/middle matrix Age 6 months Load: 100 gm

Determination Number	Top			Middle			Bottom		
	X	Y	Mean	X	Y	Mean	X	Y	Mean
1	368	365		412	420	416	392	390	391
2	360	363	361	400	405	402	398	390	394
3	393	395	394	398	396	397	395	396	396
4	400	400	400	396	395	396	390	395	392
5	408	410	409	385	388		350	356	
6	348	349		385	285		360	363	
7	389	396	392	392	391	392	348	342	
8	400	395	398	368	372		395	398	396
9	396	392	394	410	414	412	384	385	384
10	355	358		408	406	407	390	396	393
11	348	346	347	400	404	402	400	392	396
12	386	390	388	398	394	391	396	399	398
13	382	380	381	400	396	398	395	390	392
Average of 10 Readings	388			401			393		
Vicker's Hardness No. (Mean Value) Kg/mm^2	69			65			67		

Specimen No. 8 Air curing/surface matrix Age 6 months Load: 100 gm

Determination Number	Top			Middle			Bottom		
	X	Y	Mean	X	Y	Mean	X	Y	Mean
1	368	376	372	386	370	378	400	405	402
2	350	354		380	386	383	398	396	397
3	366	370	368	363	370		410	415	412
4	388	390	389	390	395	392	406	410	408
5	354	359		389	392	390	420	427	424
6	389	390	389	370	375		408	415	411
7	380	384	382	382	380	381	428	426	427
8	364	374	371	374	375		414	412	413
9	385	382	384	388	386	387	389	396	
10	345	349		396	398	397	380	374	
11	378	384	381	400	400	400	408	408	408
12	380	385	382	405	408	406	388	398	
13	380	380	380	395	390	392	405	405	405
Average of 10 Readings	380			391			411		
Vicker's Hardness No. (Mean Value) (Kg/mm^2)	72			68			64		

Specimen No. 8 Air curing/middle matrix Age 6 months Load: 100 gm

Determination Number	Top			Middle			Bottom		
	X	Y	Mean	X	Y	Mean	X	Y	Mean
1	402	400	401	400	405	402	393	395	394
2	408	410	409	388	394	391	395	397	396
3	376	388		376	379		398	390	394
4	400	406	403	396	394	395	390	395	392
5	390	395	392	399	410	404	390	394	392
6	412	406	409	400	408	404	364	377	
7	366	379		406	405	370	370		406
8	414	419	416	412	419	416	395	393	394
9	390	393	391	406	406	406	400	410	405
10	398	396	397	375	377		392	396	394
11	377	380		366	363	364	370	357	
12	392	395	394	379	386	388	400	404	402
13	393	397	395	392	399	396	398	392	395
Average of 10 Readings	401			401			396		
Vicker's Hardness No. (Mean Value) (Kg/mm^2)	65			65			66		

Specimen No. 9 Polythene curing/surface matrix Age 6 months Load: 100 gm

Determination Number	Top			Middle			Bottom		
	X	Y	Mean	X	Y	Mean	X	Y	Mean
1	310	315		370	368	369	395	393	394
2	368	365	366	352	356	354	386	394	390
3	360	363	362	356	350	353	370	374	372
4	348	350	349	344	348		366	364	365
5	345	346	345	326	335	405	355	352	354
6	333	336	334	338	340		388	384	386
7	358	350	354	362	366	364	372	375	374
8	360	363	361	380	382	381	348	344	
9	348	344	346	364	365	364	338	340	
10	328	330		385	380	382	380	376	378
11	320	324		350	352	351	354	355	354
12	350	354	352	360	358	359	330	325	
13	345	348	346	360	355	358	370	360	365
Average of 10 Readings	352			364			373		
Vicker's Hardness No. (Mean Value) (Kg/mm^2)	84			79			75		

Specimen No. 9 Polythene curing/middle matrix Age 6 months Load: 100 gm

Determination Number	Top			Middle			Bottom		
	X	Y	Mean	X	Y	Mean	X	Y	Mean
1	335	340	338	398	395	396	366	370	368
2	392	395	393	334	340	337	404	402	403
3	382	380	381	392	391	391	377	372	374
4	390	393	391	366	368	367	352	355	354
5	325	328		348	355	351	348	348	
6	383	386	384	344	339	342	392	398	395
7	320	324	322	368	369	368	345	346	345
8	316	314		330	336		362	364	363
9	386	388	387	328	325		357	355	356
10	330	326		345	340		386	385	385
11	358	355	356	350	338	344	356	358	357
12	330	334	332	400	396	398	348	340	
13	390	396	393	360	354	357	377	379	378
Average of 10 Readings	368			365			373		
Vicker's Hardness No. (Mean Value) (Kg/mm^2)	77			78			75		

Specimen No. 9 Air curing/surface matrix Age 6 months Load: 100 gm

Determination Number	Top			Middle			Bottom		
	X	Y	Mean	X	Y	Mean	X	Y	Mean
1	315	320	318	358	354	356	334	330	
2	319	326	322	335	331	333	340	342	341
3	305	307	306	330	325	328	366	372	369
4	300	299		358	350	354	316	320	
5	310	305	308	342	345	344	334	333	
6	305	302		352	350	351	359	355	357
7	300	305		330	328		384	383	383
8	315	318	316	318	320	319	362	358	360
9	336	330	333	345	342	344	338	335	336
10	330	325	328	360	355	358	355	339	347
11	338	340	339	355	352	354	350	352	351
12	350	345	348	354	350	352	342	354	348
13	309	323	316	345	340	342	350	346	348
Average of 10 Readings	323			349			354		
Vicker's Hardness No. (Mean Value) (Kg/mm^2)	100			86			83		

Specimen No. 9 Air curing/middle matrix Age 6 months Load: 100 gm

Determination Number	Top			Middle			Bottom		
	X	Y	Mean	X	Y	Mean	X	Y	Mean
1	356	365	360	370	376	373	372	374	373
2	344	342		362	365	364	380	382	381
3	350	354	352	344	350	347	370	366	368
4	368	370	369	394	390	392	386	388	387
5	342	340		360	362	361	372	375	374
6	338	340		338	344		367	365	366
7	368	372	370	329	335		360	362	
8	388	383	381	388	383	385	376	373	374
9	370	377	372	348	354	351	384	386	385
10	374	372	373	340	336		350	356	
11	350	353	352	389	394	392	362	366	
12	376	378	377	366	374	370	365	367	366
13	370	365	367	360	354	357	380	370	375
Average of 10 Readings	367			369			375		
Vicker's Hardness No. (Mean Value) (Kg/mm^2)	77			77			74		

Specimen No. 10 Polythene curing/surface matrix Age 6 months Load: 100 gm

Determination Number	Top			Middle			Bottom		
	X	Y	Mean	X	Y	Mean	X	Y	Mean
1	382	385	384	390	388		415	412	414
2	388	386	387	398	395	396	395	398	396
3	378	380	379	368	369		398	395	396
4	348	345		400	405	402	390	392	391
5	350	352		390	396	393	374	378	
6	390	396	393	402	406	404	394	398	396
7	372	370	371	410	414	412	386	390	388
8	368	365		418	422	420	390	395	392
9	400	394	397	410	415	412	397	398	397
10	396	395	395	422	430	426	375	380	378
11	380	368	374	388	394		368	372	370
12	388	384	386	400	400	400	399	399	394
13	380	378	379	400	398	399	403	408	406
Average of 10 Readings	384			406			398		
Vicker's Hardness No. (Mean Value) (Kg/mm^2)	71			65			65		

Specimen No. 10 Polythene curing/middle matrix Age 6 months Load: 100 gm

Determination Number	Top			Middle			Bottom		
	X	Y	Mean	X	Y	Mean	X	Y	Mean
1	376	373		415	420	418	404	400	402
2	404	403	430	428	429	388	398	393	401
3	390	394		389	395		408	419	414
4	402	400	401	360	366		390	396	
5	380	380		405	404	398	395	396	419
6	408	415	412	400	400	400	404	402	403
7	400	403	402	388	394		420	418	419
8	415	419	417	425	422	424	390	395	
9	424	428	426	400	405	402	389	394	
10	400	405	402	404	406	405	403	405	404
11	405	405	405	400	400	400	408	405	406
12	410	414	412	410	415	412	400	400	400
13	405	403	404	410	404	407	400	402	401
Average of 10 Readings	408			410			404		
Vicker's Hardness No. (Mean Value) (Kg/mm^2)	64			64			64		

Specimen No. 10 Air curing/surface matrix Age 6 months Load: 100 gm

Determination Number	Top			Middle			Bottom		
	X	Y	Mean	X	Y	Mean	X	Y	Mean
1	400	406	403	385	396		380	375	
2	390	393		410	415	412	408	408	408
3	388	395		405	405	405	415	418	416
4	402	408	405	408	405	406	408	410	409
5	396	399		395	398	396	399	404	402
6	405	410	408	389	390		395	398	
7	408	403	406	408	415	412	400	410	405
8	396	399	398	394	396	395	386	389	
9	398	410	404	400	406	403	418	411	414
10	400	405	402	385	384		405	410	408
11	399	404	402	404	402	403	399	396	397
12	396	399	398	398	400	399	402	406	404
13	400	400	400	404	396	400	405	401	403
Average of 10 Readings		403			403			407	
Vicker's Hardness No. (Mean Value) (Kg/mm^2)		65			65			65	

Specimen No. 10 Air curing/middle matrix Age 6 months Load: 100 gm

Determination Number	Top			Middle			Bottom		
	X	Y	Mean	X	Y	Mean	X	Y	Mean
1	404	404	404	370	373		399	396	398
2	412	415	413	410	416	413	410	411	401
3	410	411	410	408	415	412	396	398	397
4	400	400	400	405	404	404	400	402	401
5	402	405	403	385	388	386	418	415	416
6	405	396	400	408	412	410	390	386	
7	380	374	377	370	376	373	377	369	
8	366	370		380	385	382	390	396	393
9	369	363		395	400	398	400	404	402
10	374	377	375	366	362		392	396	394
11	358	364		359	365		413	308	410
12	366	374	370	380	388	384	380	388	
13	390	392	391	385	389	387	399	401	400
Average of 10 Readings	394			395			402		
Vicker's Hardness No. (Mean Value) (Kg/mm^2)	67			67			65		

Specimen No. 11 Polythene curing/surface matrix Age 6 months Load: 100 gm

Determination Number	Top			Middle			Bottom		
	X	Y	Mean	X	Y	Mean	X	Y	Mean
1	380	375	378	360	364	362	388	394	391
2	388	392	390	360	378	369	354	352	
3	370	365	368	393	392	392	395	397	376
4	360	363	361	390	385	388	386	392	389
5	355	360		355	370		365	368	
6	366	360	363	348	350		395	396	396
7	359	355		393	397	395	385	382	383
8	380	377	378	380	375	378	392	398	395
9	360	348		378	365	372	385	392	388
10	372	366	369	370	377	374	390	375	382
11	388	395	391	380	375	378	393	390	391
12	380	372	376	360	354		393	390	391
13	365	371	368	395	397	396	389	395	392
Average of 10 Readings	374			380			390		
Vicker's Hardness No. (Mean Value) (Kg/mm^2)	75			72			69		

! RES;EXIT;

Specimen No. 11 Polythene curing/middle matrix Age 6 months Load: 100 gm

Determination Number	Top			Middle			Bottom		
	X	Y	Mean	X	Y	Mean	X	Y	Mean
1	385	382		377	384		415	420	418
2	380	375		410	418	414	396	400	398
3	403	401	402	400	404	402	372	375	
4	380	383		390	396	393	415	418	416
5	390	399	394	380	373		425	430	428
6	405	408	406	396	394	395	400	402	401
7	408	410	409	395	392	394	410	418	414
8	390	392	391	390	388	389	400	402	401
9	404	410	407	410	418	414	393	399	
10	392	400	396	420	418	419	405	408	406
11	390	402	396	380	383		410	402	406
12	400	394	397	388	390	389	396	380	
13	391	400	395	400	402	401	410	400	405
Average of 10 Readings	399			400			409		
Vicker's Hardness No. (Mean Value) (Kg/mm^2)	65			65			64		

Specimen No. 11 Air curing/surface matrix Age 6 months Load: 100 gm

Determination Number	Top			Middle			Bottom		
	X	Y	Mean	X	Y	Mean	X	Y	Mean
1	404	407	405	408	405	406	414	418	416
2	405	402	404	410	412	411	428	435	432
3	368	374		420	425	422	415	420	418
4	375	370		408	415	411	410	415	412
5	377	372	374	402	404	403	430	435	428
6	417	413	410	408	410	409	406	405	405
7	378	365		416	412	414	389	395	
8	400	396	398	428	430	429	365	370	
9	392	394	393	380	368		410	420	415
10	422	415	418	377	380		400	408	
11	405	412	408	400	404		425	418	422
12	405	392	398	408	419	414	415	411	413
13	400	390	395	410	404	407	420	408	414
Average of 10 Readings	400			413			418		
Vicker's Hardness No. (Mean Value) (Kg/mm^2)	65			64			64		

Specimen No. 11 Air curing/middle matrix Age 6 months Load: 100 gm

Determination Number	Top			Middle			Bottom		
	X	Y	Mean	X	Y	Mean	X	Y	Mean
1	410	420	415	418	415	416	385	390	
2	402	400	401	408	405	406	394	396	395
3	430	425	428	404	402	403	410	415	412
4	389	395	392	410	415	412	412	405	408
5	405	409	407	418	420	419	396	385	
6	380	385		380	389		388	399	
7	372	380		401	410	406	400	415	408
8	403	405	404	388	399	393	415	420	418
9	375	372		410	405	402	393	399	
10	408	410	409	420	410	415	407	410	408
11	410	410	410	396	390		405	420	412
12	406	405	405	389	400		418	422	420
13	400	404	402	406	402	404	410	402	406
Average of 10 Readings	407			408			409		
Vicker's Hardness No. (Mean Value) (Kg/mm^2)	64			64			64		