THE DEFORMATION PROPERTIES OF CONCRETE WITH CLASSIFIED LETHABO FLY ASH.

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requirement for the degree of
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BY
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DECLARATION

The writer hereby declares that the work contained herein, with the exception of the quoted sources, is his own and has not been submitted to any other university.

Signed by candidate

Pierre Victor Mukheibir

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ABSTRACT

It has become necessary to determine the magnitude of creep, shrinkage, elastic and thermal deformations of concrete as these characteristics determine the loss of prestressing in prestressed concrete and affect the deflections with time of large concrete sections. Much of the literature available on this topic has conflicting conclusions.

In this research, the effect of fly ash was first investigated with regard to general concrete properties such as bleeding, early set, workability, mortar excess and compressive strength. Classified Lethabo fly ash and local Western Cape materials were used for this work.

With the increase in the percentage fly ash present in the concrete mix, the water requirement was reduced in order to get the same workability. This characteristic reduced the amount of water available for bleeding. For a given C/W ratio the inclusion of fly ash in a concrete mix had no effect on the mortar excess.

The early setting time was retarded for mixes with increasing percentages of fly ash. Higher cementitious material to water ratios were required for concrete with classified Lethabo fly ash than Ordinary Portland Cement mixes, to obtain the same 28 day compressive strength. The fly ash mixes had higher strength developments with time i.e. they have lower early strengths and higher long term strengths than OPC mixes for the same 28 day compressive strengths.

Having developed a wide range of concrete mixes, the main investigation was done on specific deformation properties of concrete such as the elasticity, shrinkage, creep and thermal movement. The effect of different wet curing durations and testing ages on these properties were investigated.

The elastic modulus was determined by both static and dynamic test methods. A relationship was established between the two methods to estimate the static modulus from the dynamic modulus, which was quicker to perform. In this thesis, the elastic modulus was not affected by the presence of fly ash. The elastic properties of the fly ash mixes was found to be similar to that of the OPC mixes of the same compressive strength.

Similarly, the drying shrinkage and thermal movement were not affected noticeably by the presence of fly ash. The volume of aggregate was not a variable as it did not change when fly ash was added to the mix. An attempt was made to develop a test to determine the plastic shrinkage of an unrestrained sample. The effect of fly ash on the plastic shrinkage was not investigated fully.

For the creep of concrete, it was established that mixes containing fly ash have lower creep factors than OPC concretes, although no clear trends were apparent for increasing percentages of fly ash. The effect of fly ash in pump mixes was also investigated and the same trends were apparent, although in general, the pump mixes had higher creep factors than the normal mixes.

The curing of concrete is critical if good quality concrete is to be obtained. For all deformation properties, the longer a specimen was wet cured, the lower were the deformations. With longer wet curing, a larger volume of hydrated gel developed which gave higher compressive strengths and more rigidity within the matrix.

The conclusion reached in this thesis was that the presence of classified Lethabo fly ash did not noticeably affect the deformation properties of the concrete for equivalent compressive strengths. Where some effects were noticed, the fly ash concretes displayed somewhat lower deformations.

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GLOSSARY

OPC - Ordinary Portland Cement

OPC concrete - Concrete made with OPC and no fly ash

Fly ash concrete - Concrete made with OPC and fly ash

Cementitious material - ("Binder") OPC + fly ash

Percentage fly ash - Percentage of the total cementitious content that the fly ash makes up

c/w ratio - OPC to water ratio

C/W ratio - Cementitious material to water ratio

Mortar - Concrete without any stone agregate

PCI - Portland Cement Institute

RH - Relative Humidity

E - Young's Modulus of Elasticity

1
INTRODUCTION

Concrete may be regarded as a two-phase material consisting of a mixture of naturally occurring aggregates bonded together by a hydrate formed during the reaction of cement with the mixing water. The combination of these materials allows the concrete to exhibit important deformation characteristics, viz.

- elasticity,
- creep,
- shrinkage.
- thermal movement

Engineers are particularly aware of these deformation characteristics of concrete in connection with the loss of prestressing found in prestressed concrete and the increased deflections with time of large span beams. It has thus become necessary to determine the magnitude of elastic, shrinkage, creep and thermal deformations of concrete.

At the University of Cape Town research has already been conducted on the fresh properties, durability and abrasion resistance of fly ash concretes. This thesis investigates the effect of classified Lethabo fly ash on the deformation properties of concrete.

Fly ash is a waste product of coal used in power stations and may be used as a pozzolan or a cement extender in the concrete mixes. The total cementitious material in the mix then consists of Ordinary Portland Cement (OPC) and a percentage of fly ash.

The materials used in this research (sand, stone, OPC and water) were locally available in the Western Cape. The fly ash used was obtained from the Lethabo power station and classified at the Matla classifier plant. Classified Lethabo fly ash will soon be available on the market and the investigation into the properties of this fly ash was therefore sponsored by the Foundation for Research Development.

It has been reported that the inclusion of fly ash in concrete improves many of the fresh and hardened properties of concrete. The relevant properties of fly ash are characterised largely by its fineness. The addition of fly ash to concrete mixes normally causes a reduction of bleeding due to the addition of further fines in the mix, a reduction of the water requirement for a given consistency due to the lubricating effect of the spherical fly ash particles and a lower heat of hydration due to the slower hydration of the fly ash.

However, there is a delay in the setting time due to the slower hydration of the fly ash and this is not always desirable. In hardened concrete, the presence of fly ash promotes a denser matrix and gives more long-term strength development.

The literature is somewhat contradictory with regard to the deformation properties of concrete mixes containing fly ash. There does not seem to be any specific trend with increasing percentages of fly ash present in the cementitious material regarding the elasticity and thermal movement of the concrete. There seems to be a general trend that fly ash reduces the shrinkage and creep of concrete mixes. At the very least the deformation properties of the fly ash concretes are similar to OPC concrete.

In this thesis the concrete properties that were investigated were: the water requirement, bleeding, mortar excess, setting time, compressive strength development, elasticity, shrinkage, creep and the thermal expansion. An attempt is made to establish trends regarding these properties and the effect of classified Lethabo fly ash.

Due to practical reasons and time constraints, no long term testing could be carried out. The work for this thesis was confined to practical mixes using local Western Cape materials. The variables were: percentage fly ash in the cementitious material, design strength, duration of wet curing and the age at testing. The concrete mixes were designed for chosen 28 day compressive strengths and a slump of 50mm.

2
MIX MATERIALS

2.1. INTRODUCTION

The research for this thesis was done on concrete using cement, stone, sand and water available locally in the Western Cape. The fly ash used for this research was obtained from the Lethabo power station.

The materials chosen are those most commonly used in the Western Cape. Cape Flats Dune sand was used as the fine aggregate, Malmesbury Shale as the coarse aggregate and the cement was De Hoek Ordinary Portland Cement.

In order to keep the material properties constant throughout the research period, the sand was dried and stored in water-free bins. The cement and fly ash were sealed in plastic bags and stored in air-tight drums.

2.2. FINE AGGREGATE

Cape Flats Dune sand is a wind blown sediment characterised by a well rounded particle shape. The sorting power of the wind results in a sand of uniform shape, size and relative density, i.e. it lacks both coarse and very fine particles.

The grading of this sand is very poor and the particle size distribution falls outside the recommended limits laid down by SABS 1083 (Ref.1). Fig.1 shows the typical grading curve for Cape Flats Dune sand against that recommended by SABS 1083.

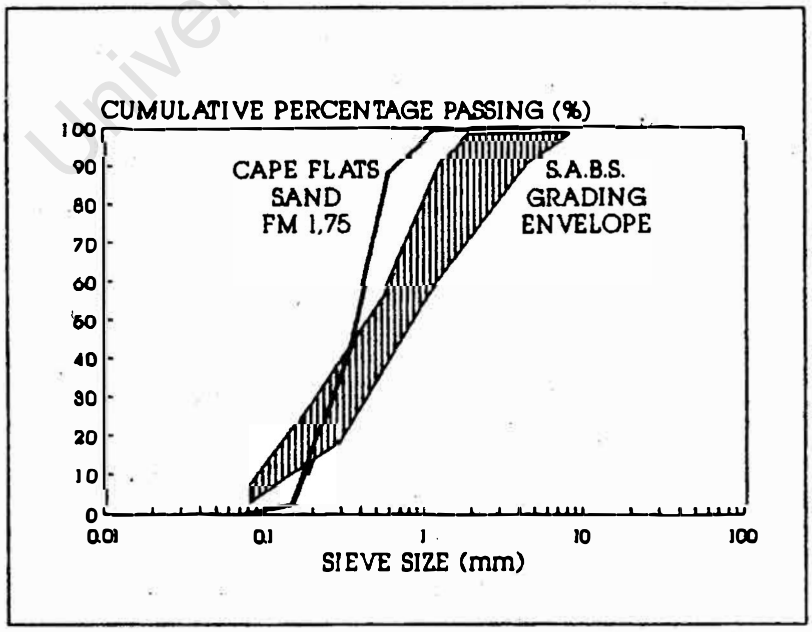

Fig 2.1. Typical grading curve for Cape Flats Dune sand used

The fineness modulus (FM) of Cape Flats Dune sand is dependent on its source and varies between 1.7 and 2.1. It may therefore be considered as a "fine" sand. However, the well rounded particles and the surface texture result in the relatively low water demand of the sand. The relative density of the Cape Flats Dune sand is 2.63.

2.3. COARSE AGGREGATE

Malmesbury shale is a Hornfels that developed by thermal metamorphism from argillaceous rocks. It is fine grained and owing to its glassy nature, the Hornfels tends to produce a somewhat flaky aggregate when crushed (Ref.2).

A nominal 13mm Malmesbury shale was used in this research. The grading falls well within the recommended limits laid down by SABS 1083 and is shown below. The relative density of the stone is 2.68.

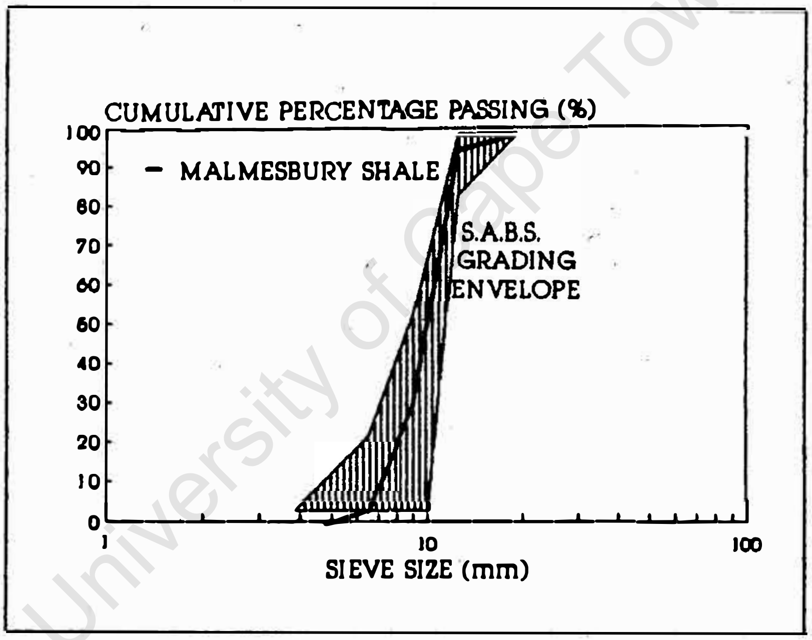

Fig 2.2. Grading curve of Malmesbury shale used

2.4. CEMENT

The cement used in this thesis was De Hoek OPC. Portland cement consists of a mixture of calcium silicates, calcium aluminates and other molecular compounds which have hydraulic properties. The proportions of the compounds present may vary from one plant to another and may even vary within a plant from day to day. These variations arise due to changes in the raw materials, production methods and production levels.

The De Hoek OPC was ordered from one production batch and stored in air-tight drums to minimise any deterioration of the cement over time. The chemical and physical properties of the cement used are listed below.

	De Hoek (%)	Usual SA Cement (%) (Ref.3)
CaO	64.00	63 - 68
SiO_2	21.50	19 - 24
Al_2O_3	3.90	4 - 7
Fe_2O_3	3.90	1 - 4
MgO	1.10	0.5 - 3.5
Na_2O	.22	0.2 - 0.8
K_2O	.53	0.2 - 0.8
SO_3	2.50	-
Loss on ignition	2.30	-
Alkali content	0.57	
Surface area -	2970 cm^2/g	(Modified Blaine)
Relative density	3.15	
Initial set	3hr 19min	
Final set	4hr 15min	

Table 2.1. Chemical and physical properties of De Hoek Ordinary Portland Cement used

2.5. FLY ASH

Fly ash is a waste product of coal that is burned in power stations. The finely ground coal dust, is injected into a furnace. The non-combustible material melts while in suspension and cools rapidly as it leaves the furnace. This rapid cooling causes the fly ash to form spherical particles which are combinations of glassy and crystalline phases.

Fly ash is a pozzolan, i.e. "a siliceous or siliceous and aluminous material which in itself possesses little or no cementitious value but will, in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties" (Ref.3). As cement and water react to form hydrates, calcium hydroxide, is produced. The highly reactive silica and alumina in fly ash react with the lime to form further hydrates and thereby contribute to the strength of the concrete.

At present fly ash is not yet commercially produced at the Lethabo power station. Commercial (classified) fly ash is sorted in an air classifier to produce a uniform product. The classified Lethabo fly ash used for this research was classified at the Matla plant.

2.5.1 Chemical and mineral composition

ELEMENT	COMPOUND	PERCENTAGE
Silicon	(SiO_2)	52.72%
Aluminium	(Al_2O_3)	32.70%
Calcium	(CaO)	5.30%
Iron	(Fe_2O_3)	3.62%
Titanium	(TiO_2)	1.72%
Magnesium	(MgO)	1.44%
Phosphorus	(P_2O_5)	0.66%
Potassium	(K_2O)	0.57%
Sodium	(Na_2O)	0.23%
Sulphate	(SO_3)	0.20%
Loss on ignition (1000 C)		0.17%
FINENESS (retention on the 45 micron sieve)		6.40%

Table 2.2. Chemical composition of Lethabo classified fly ash used

The three main constituents of fly ash are SiO_2, Al_2O_3 and Fe_2O_3 which together make up more than 80% of the Lethabo classified fly ash. The composition of the fly ash is largely dependent on the type of coal used. The carbon content, which is assumed to be roughly equal to the loss on ignition, depends largely on the efficiency of the power station. Modern power stations have more efficient operations than before and consequently the loss on ignition of the Lethabo fly ash is low. The carbon content also determines the colour of the fly ash.

Fly ash is mostly composed of non-crystalline glassy phases. The chemical (pozzolanic) reactivity of the fly ash is essentially dependent on the nature and amount of glassy phase material present (Ref.4). This is due to the nature of the source coal and the operating temperature of the furnace. The reactivity of this glassy phase within fly ash may also be affected by the amount of Portlandite formed by hydration.

2.5.2. Physical Properties

Fineness, particle size distribution, shape and physical composition of fly ash particles influence the properties of both fresh and hardened concrete in which the fly ash is used. Fineness and particle size distribution are probably the most important properties of fly ash governing the pozzolanic activity and it also greatly affects the workability of the concrete. The finer the ash the greater the surface area and the better its pozzolanic activity. Also the spherical shape of the fly ash particles result in better workability of most concretes made with it (Ref.1). Lethabo fly ash is finer than other fly ashes available in South Africa eg. the percentage of material retained on the 45 micron sieve is only 6.4%, whereas Matla classified fly ash is 9.6%.

This "fineness" should not be used in isolation to determine the quality of the fly ash as factors such as the presence of ultra-fines particles may change the characteristics of the fly ash. After all the particles range in size from about one millimeter to less than one micrometer.

Generally fly ash particles are spherically shaped, being either solid or hollow (Ref. 5). This compares strikingly with the angular shape of OPC particles. The round shape of the fly ash particles clearly has a lubricating effect on the concrete mix.

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3
CONCRETE MIX DESIGN

3.1. INTRODUCTION

The mix design procedures of concrete mixes with fly ash vary quite widely and the procedure chosen depends on the use of the concrete. When comparing concrete mixes with fly ash, either the total cementitious material is kept constant or the cementitious material/water ratio (C/W ratio) is held constant or equal compressive strengths are used to make comparisons.

The research in this thesis is a comparative study between concrete with and without fly ash present, using locally produced materials. Hence, all the concrete mixes were designed for chosen 28 day compressive strengths and a slump of 50mm for different percentages of fly ash present in the cementitious material.

3.2. DESIGN METHOD

The design of Ordinary Portland Cement (OPC) concrete mixes was done according to the PCI method (Ref.1). In this method, the cement/water ratio (c/w ratio) is chosen from a graph according to the required 28 day compressive strength. The water requirement of the mix is determined by trial mixes, although an estimate can be made from the known properties of the aggregates. The cement content can thus be determined using the c/w ratio. The stone content is obtained from the published tables and the sand content is found from the remaining volume required to make up a concrete mix of one cubic meter.

The design of fly ash mixes in this thesis was done according to the method outlined by Ash Resources (Ref.2). The amount of fly ash present in the mix is expressed as a percentage of the total volume of cementitious material (i.e. OPC + fly ash) in the mix. This method is very similar to the PCI method, but has adjustments in three areas.

a) the cementitious material/water (C/W) ratios are higher than those for OPC concrete for a given grade of concrete,
b) the water demands are significantly lower,
c) the stone contents are increased over the OPC mixes.

These adjustments are discussed in detail in the following section.

The design charts devised by Ash Resources are applicable to Transvaal materials and classified Matla fly ash. During our preliminary work, using classified Lethabo fly ash and Western Cape materials, the strengths obtained for the chosen C/W ratios did not differ greatly from those predicted by Ash Resources for Transvaal materials. However, a set of mix design curves for the work in this thesis was produced all the same (Fig.3.1.).

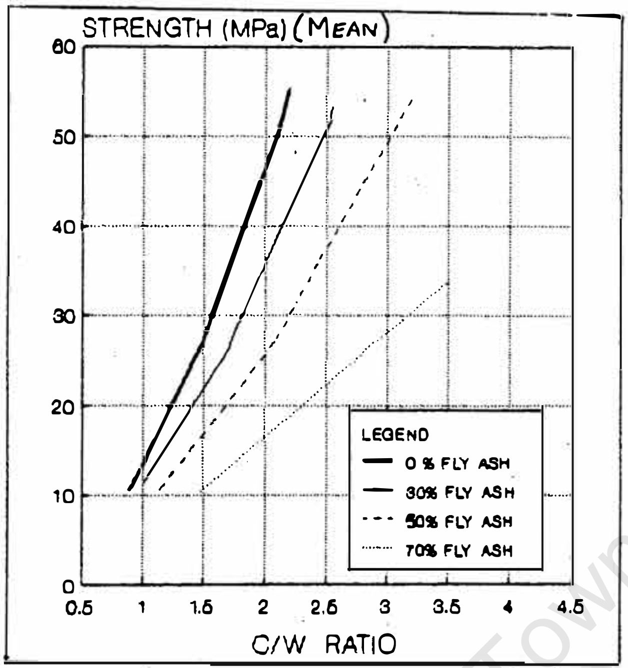

Fig.3.1. Revised design chart for classified Lethabo fly ash mixes used

3.3. DESIGN QUANTITIES

3.3.1. Total Cementitious Material Content:

It has been suggested that the cementitious content be expressed as follows: (Ref.3.)

$$C/W = \frac{c + 0.4\,F}{W}$$

where C/W = the cementitious material/water ratio required for a fly ash concrete to give it the same strength as that required for an OPC concrete
c = OPC content of the mix (kg)
F = fly ash content of the mix (kg)
W = Water content of the mix (kg)

This formula is based on a cementing efficiency factor for fly ash of 0.4 which was found to give an approximation for the marketed fly ash from the Matla power station.

Our research showed a variation in the cementing efficiency for different percentages of fly ash and also an increase in the cementing efficiency of the fly ash with age (see Table.3.1).

This thesis is therefore based on the total cementitious material comprising Ordinary Portland Cement and classified Lethabo fly ash. For any given strength and water demand, the C/W ratio from Fig.3.1. gives the total cementitious material content required. Therefore the "C/W ratio" means the the total cementitious material to water ratio throughout this thesis.

AGE	STRENGTH	CEMENTING EFFICIENCY OF CLASSIFIED LETHABO FLY ASH
7 days	30 MPa	10% to 20%
28 days	30 MPa	40% to 60%
90 days	30 MPa	80% to 100%

Table.3.1 Cementing efficiency for classified Lethabo fly ash with age.

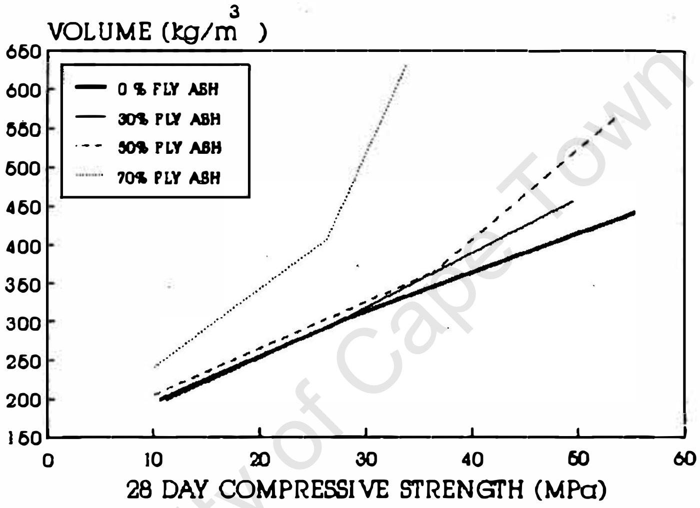

Fig.3.2. Total cementitious material required for classified Lethabo fly ash mixes used

For strengths below 30 MPa in Fig.3.2., the total cementitious material content is not affected by the percentage of fly ash present, despite the required increase in the C/W ratio for higher percentages of fly ash (see Fig.3.1.). This is due to the substantial reduction in the water requirement caused by the fly ash, resulting in a higher C/W ratio, which in turn compensates for the loss of strength due to the fly ash. The reduction in water content is not true for fly ash percentages greater than 50% as discussed in the following section and so the cementitious content of the mix is higher.

3.3.2. Water requirement:

One of the characteristics of fly ash is its effect on the water requirement of the concrete mixes. Fig.3.3. shows that with the increase in the percentage fly ash, the water requirement is reduced in order to get the same slump i.e. 50mm.

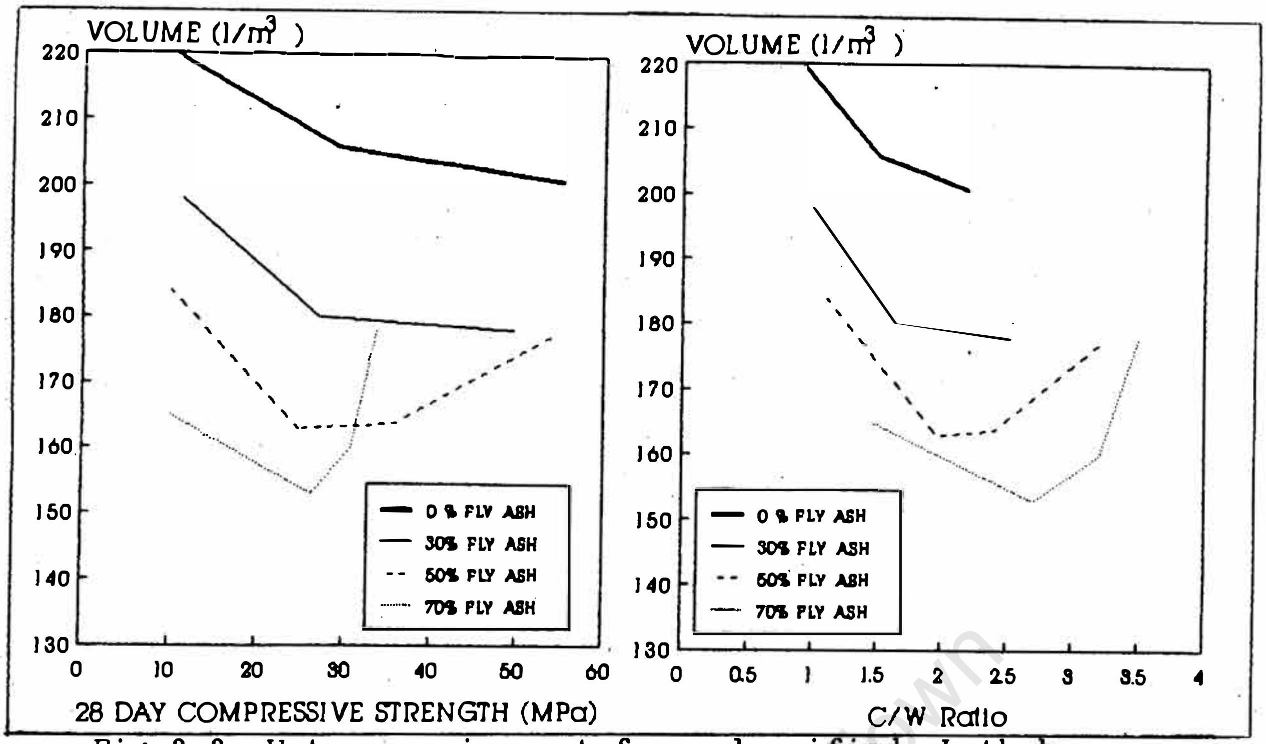

Fig.3.3. Water requirement for classified Lethabo fly ash mixes used

It is interesting to note that for high percentages of fly ash in high strength mixes, the water requirements increase however. For mixes with percentages of fly ash higher than 50%, larger quantities of cementitious material are needed to obtain the required strengths (Fig.3.2.). These mixes are rather sticky in nature and so the water content has to be increased to maintain the desired workability. For this range of mixes however, the slump test does not give a good indication of the concrete workability.

3.3.3. Stone content:

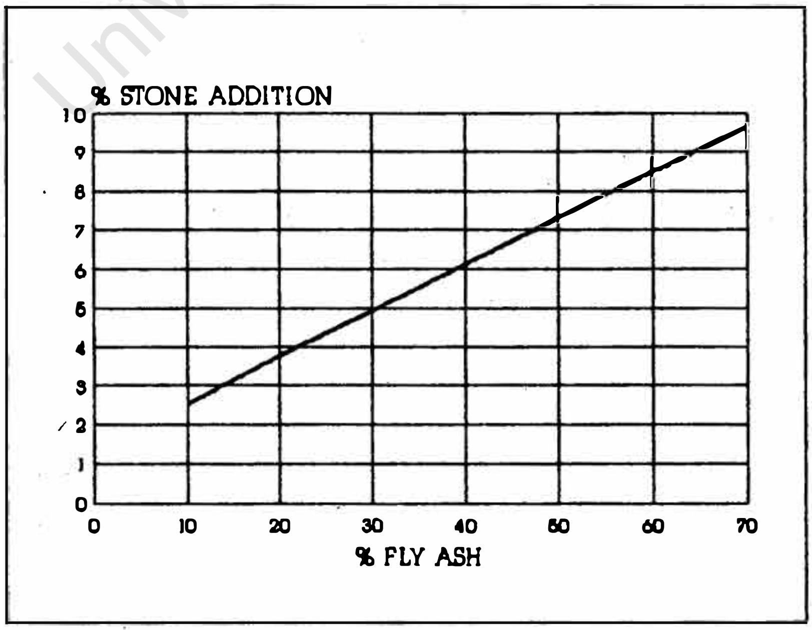

Fig.3.4. Stone adjustment for fly ash mixes used(Ref.2)

For mixes without fly ash present, the stone content based on previous work, was 1050kg/m^3. With the increase in the fly ash content of each mix, the stone content was increased as indicated in Fig.3.4., in accordance with the D&H Ash Resources recommendations (Ref.2). The lubricating effect of the spherical fly ash particles increases the workability of the mix and the extra stone compensates for this. The D&H Ash Resources recommendations effectively ensure that the coarse to fine aggregate ratio remains constant as the fly ash can be regarded as additional fine aggregate for the purposes of workability.

3.4. MIXING PROCEDURE

After designing the concrete mix, the dry materials for each mix were batched. The mixing of the concrete was done in either a 50 litre capacity pan mixer or a 100 litre capacity drum mixer, depending on the size of the batch. All the dry material was placed in the mixer and then the water was added while the mixer was in motion. A measured amount of water was added to the mixture until the desired slump of 50mm +/- 15mm was reached. When the concrete mix was accepted, the actual amount of water added to the mix was noted and the final mix proportions calculated.

Once the concrete mix was found to be within acceptable limits, the concrete was then placed in the various moulds required and compacted on a mechanical vibrating table.

3.5. CONCLUSIONS

From the above results and graphs the following can be concluded:

- higher cementitious material/water ratios are required for concrete with classified Lethabo fly ash present than mixes without fly ash,
- the classified Lethabo fly ash reduces the water demand of the concrete mixes for a given slump.

3.6. REFERENCES

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4
FRESH CONCRETE PROPERTIES

4.1. INTRODUCTION

The properties of the fresh concrete are of vital importance to the contractor involved in the mixing, placing and curing of the concrete. The fresh properties of importance include: the consistency (wetness); the workability; the mortar excess; the bleeding characteristics and the setting time of the concrete.

The concrete mixes used in this thesis were mixed in a laboratory and the above properties were examined using samples from the same batch. The ambient temperature of the laboratory was between 12°C and 20°C.

Although in most of the literature, fresh properties of concrete mixes have been plotted against strength, it was felt by the author that a better relationship exists between the C/W ratio and the fresh properties. So for completeness, both relationships have been considered where possible.

4.2. RANGE OF MIXES USED

Two variables were investigated - cementitious material/water ratio (which is related to strength) and fly ash content as a percentage of the total cementitious material. A constant slump of 50mm was used for the whole range of mixes. The mix contents are listed in Appendix A. The following range of mixes was investigated:

	10 MPa	30 MPa	50 MPa
0 % FLY ASH	X	X	X
30 % FLY ASH	X	X	X
50 % FLY ASH	X	X	X
70 % FLY ASH	X	X	X

Table.4.1. Range of mixes for the investigation of the fresh concrete properties

4.3. WORKABILITY

Concrete workability can be described as the property of fresh concrete that determines the ease with which it can be mixed, transported, placed, compacted and finished. The slump of concrete which is really a consistency test, is therefore not a true measure of workability, but is simple and useful in detecting variations in the uniformity of a mix. The slump test generally gives reliable results for most concretes of average workability.

Ordinary Portland Cement grains are prone to exhibit some coagulation or flocculation in fresh concrete, which tends to produce an inhomogeneous and non-uniform hydrate structure. The addition of fly ash , or any ultra-fine powder, can physically disperse these cement flocs, thus freeing more paste to lubricate the aggregates and improve the workability (Ref.1.). However, the improvement in workability of a mix by the addition of a pozzolan may not be reflected in the slump and in fact more water may have to be added to obtain the required slump (Ref.2). This is true for the high percentage fly ash concrete mixes because of the dominant effect of the stickiness of the mix on the slump.

It was decided to design all the mixes for a 50mm slump so as to have the same consistency for the whole range of mixes. Thus, it was difficult to make comparisons of workability for varying percentages of fly ash. The reduction in the water requirement with increasing percentages of fly ash to reach the desired slump is shown below.

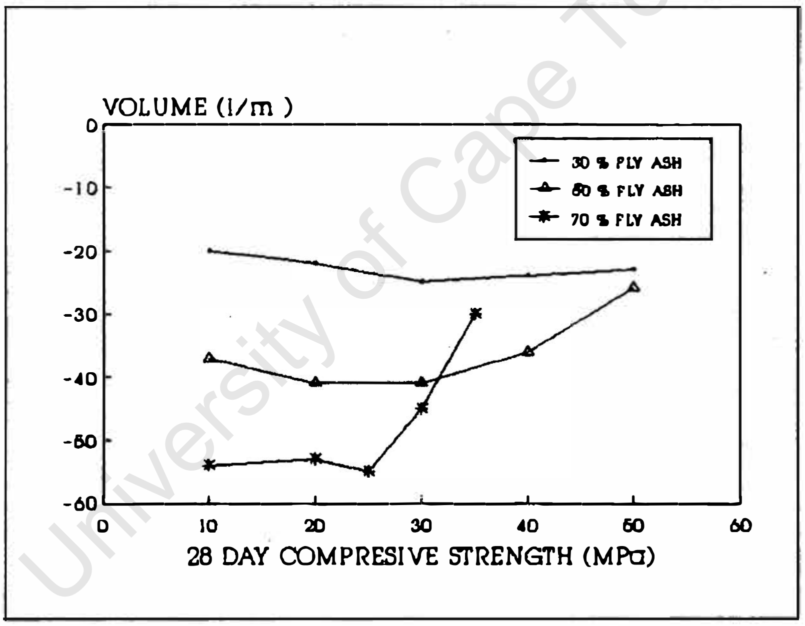

Fig.4.1 Reduction in water requirement

It can be seen that with the increase in the percentage fly ash, the water requirement is reduced in order to get the same slump. However, the water requirement increases for high strength mixes with high percentages of fly ash present. These mixes have a very high cementitious content and are rather sticky and thixotropic in nature. The water content has to be increased to obtain the desired 50mm slump. For this range of mixes, the slump test clearly does not give a good indication of the concrete workability.

4.4. MORTAR EXCESS

The excess volume of mortar forming a layer on top of a fully compacted concrete, is expressed as a percentage of the volume of the concrete. This gives some indication of the surface finish that may be achieved and the ease of acheiving it.

The mortar excess may be determined by poking a ruler as a dipstick into the top surface of the fully compacted fresh concrete till it comes in contact with the coarse aggregate. The depth of the mortar excess is expressed as percentage of the total depth of the sample. Fig 4.2. shows how the mortar excess is reduced with the increase in percentage of fly ash. So for a given strength of concrete, the concrete mix with fly ash will have less mortar excess. As only one type and size of stone was used, this is mainly due to the addition of extra stone to the mixes containing fly ash. The volume of stone is indicated in brackets in kilograms per cubic meter.

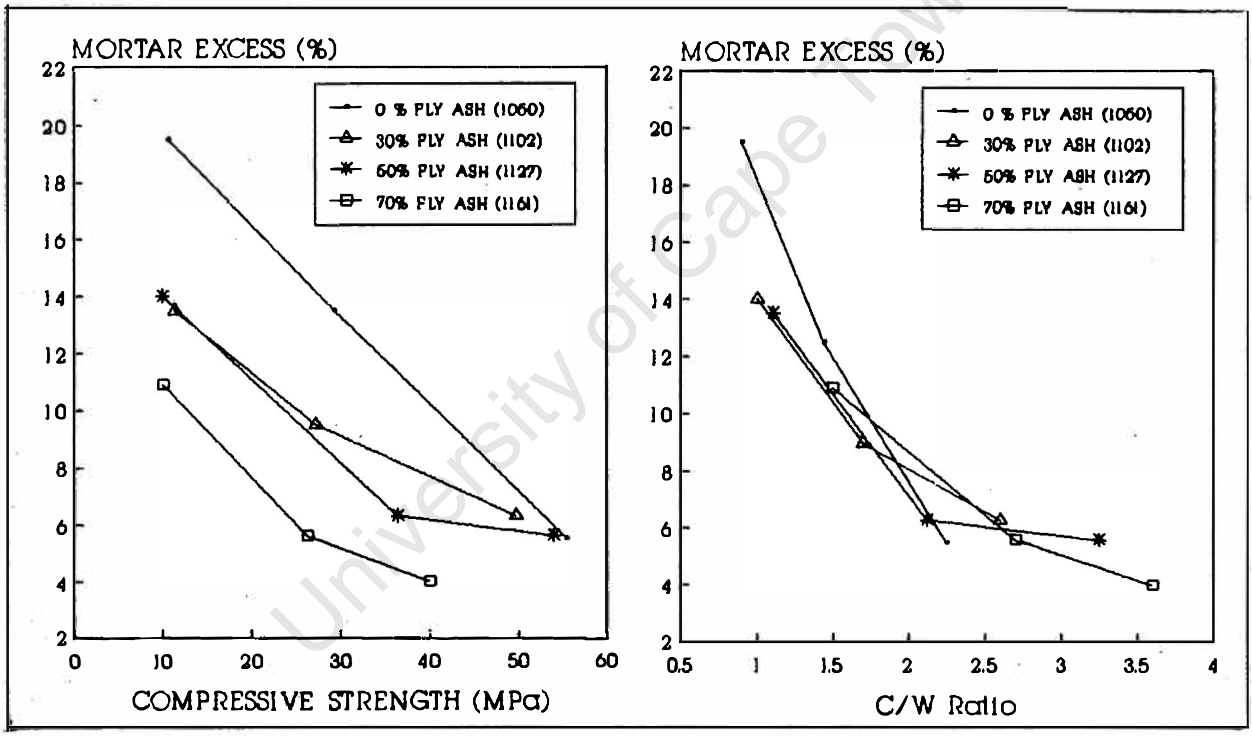

Fig.4.2. Mortar excess of fresh concrete for classified Lethabo fly ash mixes used

In Fig.4.2. it can also be observed that for increasing C/W ratios, the mortar excess decreases. This would possibly indicate better packing for concretes with high C/W ratios. They have more fine particles present in the mix.

However, for a given C/W ratio the inclusion of fly ash in a concrete mix would appear to have no measurable effect on the mortar excess.

4.5. BLEEDING CHARACTERISTICS

After compaction and until the initial set, there is a natural tendency for the heavy fine particles in suspension to exhibit a downward movement. This settlement displaces the water, some of which is forced to the surface. This surface water produced by the ~~bleeding~~ Settlement, was measured by the pipette method defined in ASTM C232 (Ref.3).

The concrete mix was cast in a rigid steel cylindrical bucket with a diameter of 280mm. The pipette measurements were taken at 15 min intervals until the bleeding had stopped. The bleeding test was conducted at a constant temperature of 23° C and a relative humidity of 50%. The container was covered to prevent excessive evaporation.

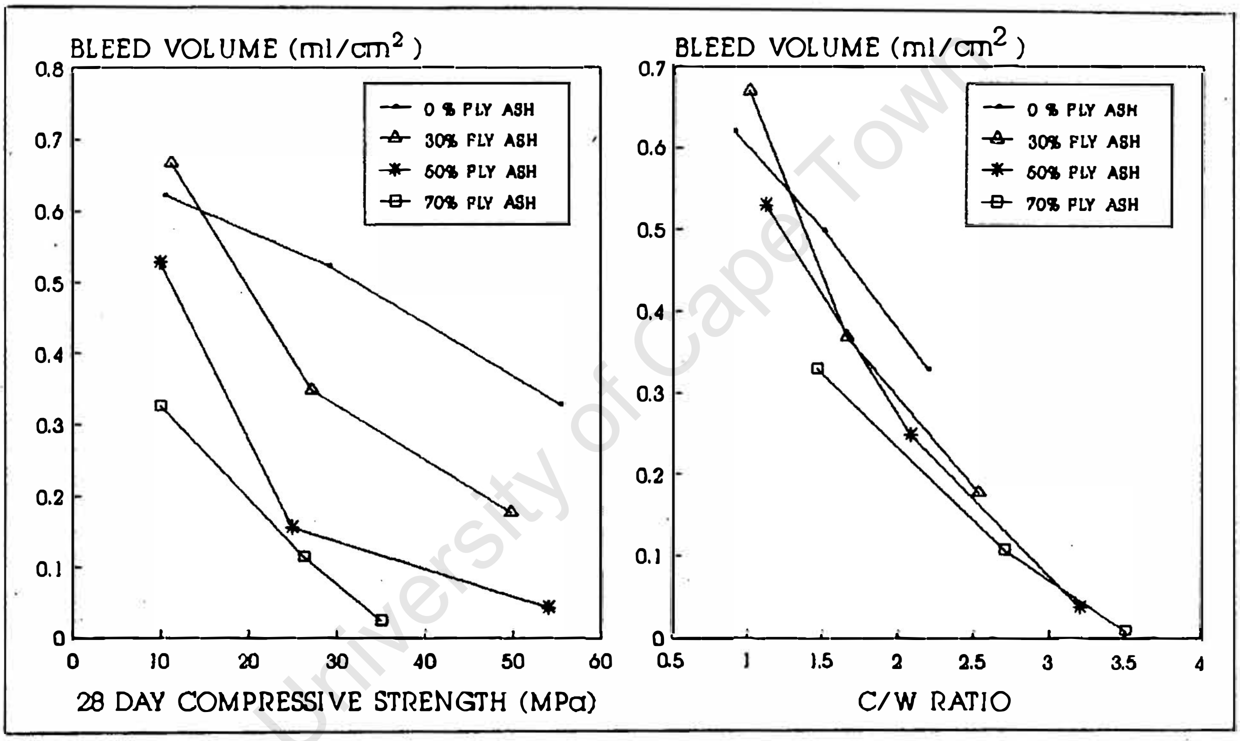

Fig.4.3. Bleeding volume for classified Lethabo fly ash concrete mixes used.

It can be expected that fly ash will reduce the bleeding capacity of concrete (Fig.4.3) and the bleeding rate (Fig.4.4) when plotted against the 28 day compressive strength. The fine particles of the fly ash are assumed to have filled many of the voids around the cement and aggregates promoting a denser matrix in the concrete mix, and so preventing the displacement of the mix water. Further, the presence of fly ash in a mix reduces the water requirement of the mix and so reduces the amount of water available for bleeding.

When compared against the C/W ratio (Fig.4.3. and Fig.4.4.), both the bleed rate and the bleed volume per area were also reduced with increasing percentages of fly ash. The magnitude of the reduction in bleeding volume and rate is not as emphasised as is the case when plotted against the 28 day compressive strength.

Bleeding is related directly to the make-up of the fresh concrete mix, whereas it is only indirectly related to strength.

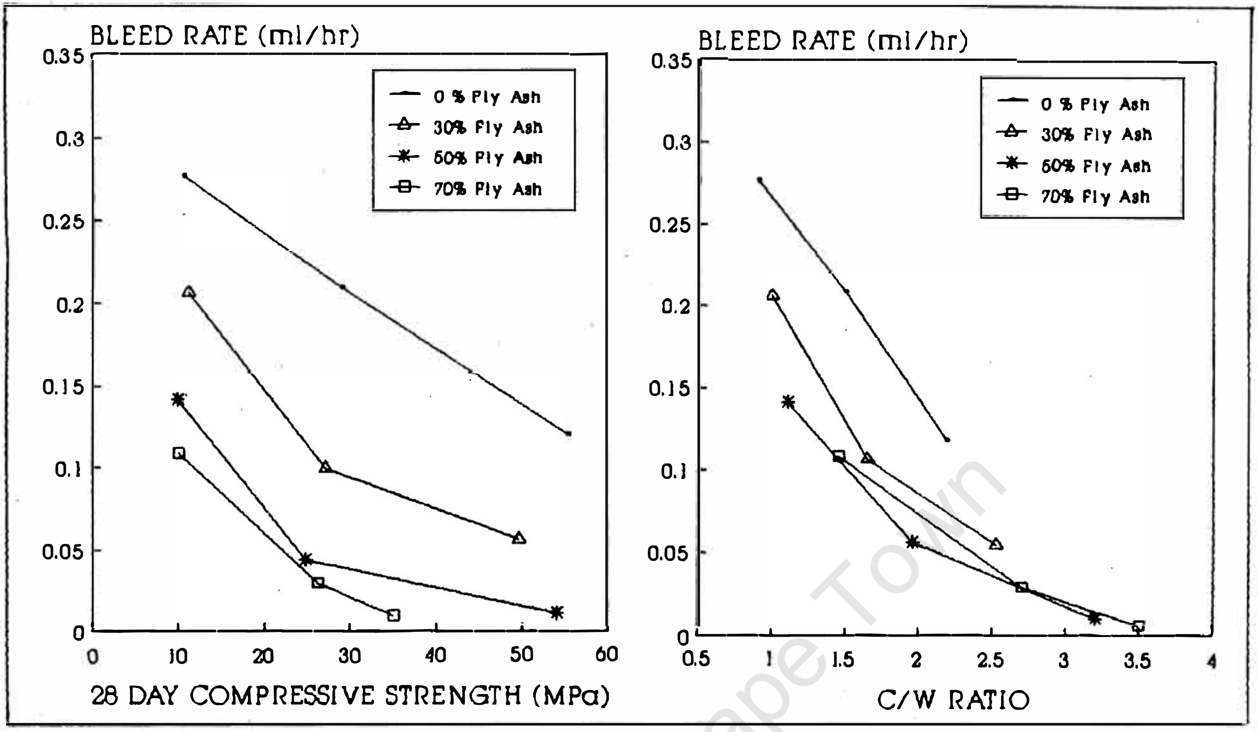

Fig.4.4. Bleeding rate for classified Lethabo fly ash concrete mixes used.

4.6. SETTING TIME

The determination of the setting characteristics of concrete is important when considering factors such as delays during placing, revibration, finishing of the concrete surface and stripping of formwork.

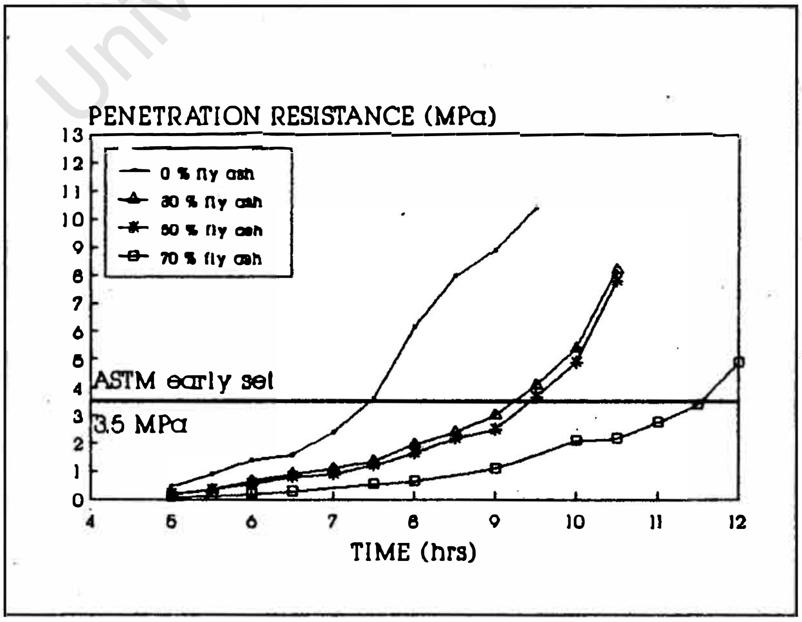

Fig.4.5. Penetration Resistance vs Time - grade 10 MPa

The setting time ("early set") for concrete mixes is defined in ASTM C403 as the time taken for the mortar to reach a penetration resistance of 3.5 MPa when tested with a standard penetrometer (Ref.4). The mortar is obtained by sieving out the stone from the concrete mixes with a 4.75 mm sieve.

All the testing took place in a controlled environment at a constant temperature of 23° C and 50% relative humidity. The cube moulds containing the mortar were kept covered to reduce moisture loss and the bleed water was removed just before the first penetration test.

Fig.4.5. gives a typical set of results for a given grade of concrete with varying percentages of fly ash present in the cementitious material.

It can clearly be seen that the early setting time is retarded for mixes with increasing percentages of fly ash present. This trend is due to the slow pozzolanic nature of the fly ash. The fly ash particles remain relatively inert during the setting process and tend to retard the initial hydration of the cementitious material (Ref.1.).

Concrete mixes with high C/W ratios (or high strengths) have quicker early setting times than those mixes with low C/W ratios (or low strengths). The large amount of cementitious material present in a concrete mix with high C/W ratios therefore reduces the delay in the setting.

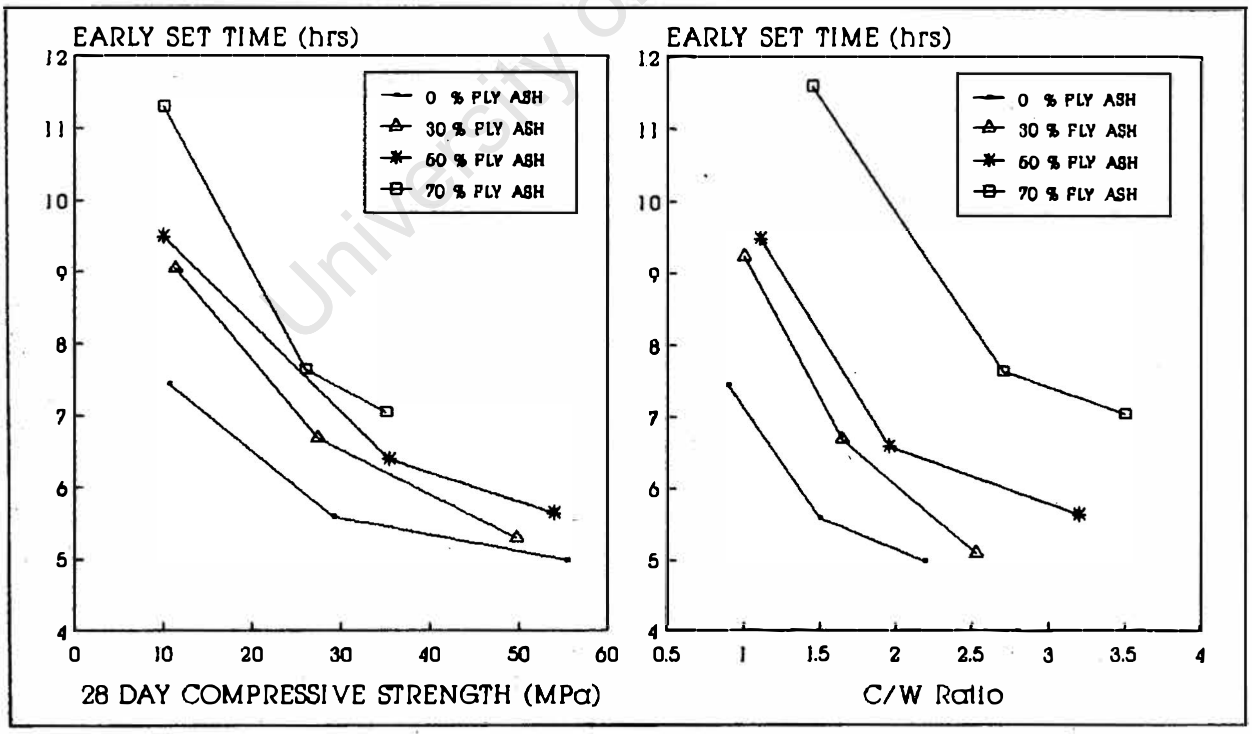

Fig.4.6. Early Set Time for the classified Lethabo fly ash mixes used

4.7. CONCLUSIONS

From the results and the graphs the following can be concluded:-

- the slump test does not give a good indication of the workability of concrete with more than 50% fly ash present in the cementitious material
- for a given 28 day compressive strength the mortar excess of a mix is reduced with the increase in the percentage fly ash present in the cementitious material;
- for a given C/W ratio the inclusion of fly ash in a concrete mix would appear to have no effect on the mortar excess;
- classified Lethabo fly ash has a reducing effect on the bleed volume and rate of concrete mixes at a given C/W ratio or strength;
- an increase in the C/W ratio or 28 day compressive strength results in a quicker early setting time;
- classified Lethabo fly ash concrete has a retarding effect on the early setting of the concrete mixes.

It should be noted that the above results and conclusions were derived from a limited number and range of mixes and the figures quoted should not be taken as applying generally.

4.8. REFERENCES

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5
COMPRESSIVE STRENGTH

5.1 INTRODUCTION

Compressive strength is one of the most important properties of hardend concrete and the most easily measured. It is commonly used as on overall measure of the quality of the concrete and also for the assessment of other properties such as shear, tensile strength, flexural strength and durability. However, compressive strength can be a deceptive property for specifying concrete quality as two types of concrete may have similar strengths but may have other properties that are quite different.

Specifying the 28 day compressive strength does not take into account the rate of strength development of the concrete. Fly ash concrete usually has a lower rate of strength development but carries on gaining strength longer than OPC concrete (Ref.1).

The effects of different percentages of fly ash present in concrete and the effects of different wet curing times on the compressive strength of the concrete were examined in this thesis.

5.2 TEST METHODS AND PROCEDURES

5.2.1 Making and curing of specimens

Twelve 100 mm test cubes from the same design mix were cast and cured in accordance with BS 1881 Part 3 (Ref 2). The moulds were filled in three layers and each layer compacted using a vibrating table until all the air pockets had been removed. The specimens were first stored for 24 hours at a constant temperature of 23°C +- 1° C and 50% relative humidity. Then the specimens were demoulded and stored under the various curing conditions:

a) air cured - the specimens were stored in a temperature room at 23°C +- 1°C and 50% RH until tested,

b) 7 days wet - the specimens were stored in water at 23°C +- 1°C for 7 days and then removed and stored in the temperature room until tested,

c) 28 days wet - the specimens were stored in water at 23°C +- 1°C for 28 days and then removed and stored in the temperature room until tested.

5.2.2 Test for the compressive strength of concrete cubes

The specimens were tested at ages after mixing of 3, 7, 28 and 90 days. Three cubes were tested at each of the ages in accordance with SABS method 863 (Ref 3). The test cubes were placed in the Amsler compressive machine in such a manner that the load was applied to the side faces as cast. The load was applied without shock and increased continuously at a rate of 15 MPa per minute until no greater load could be sustained. The compressive strength of each cube is calculated by dividing the maximum load sustained by the cube by the cross-sectional area of the cube. The average of the three cube results was recorded.

5.3 THE ACCURACY OF THE COMPRESSIVE STRENGTH TESTING

A batch of concrete was made for the exclusive purpose of obtaining statistical data on the accuracy of the compressive strength testing. The mix was a grade 35 MPa without any fly ash present.

Twenty cubes were cast and crushed after 28 days curing in water according to condition c).

The average strength of the twenty samples was 34.7 MPa with a standard deviation of 1.2 MPa and a coefficient of variation of 2.3%.

The level of control exercised is determined by the standard deviation of the results. The above test is regarded as "excellent" control as the standard deviation for the sample is less than 1.4 MPa (Ref 4).

5.4 RANGE OF MIXES USED

	CURING REGIMES		
FLY ASH	a)0 DAYS WET	b)7 DAYS WET	c)28 DAYS WET
0%	X #	X #	* X #
15%	X	X	X
30%	X #	X #	* X #
50%	#	#	* X #
70%			* X #

X) Grade 50 MPa design strength
#) Grade 30 MPa design strength
*) Grade 10 MPa design strength

Table.5.1. Range of mixes used for compressive strength testing

5.5 RESULTS AND DISCUSSIONS

5.5.1 Strength development with time

A higher C/W ratio is needed with the increase of fly ash as a percentage of the total cementitious material, to obtain the same 28 day strength as a concrete mix with no fly ash present. The same is true for the compressive strengths at 7 days and at 90 days. Fig.5.1 illustrates this trend for concrete specimens that have been cured for 28 days in water at 23° C.

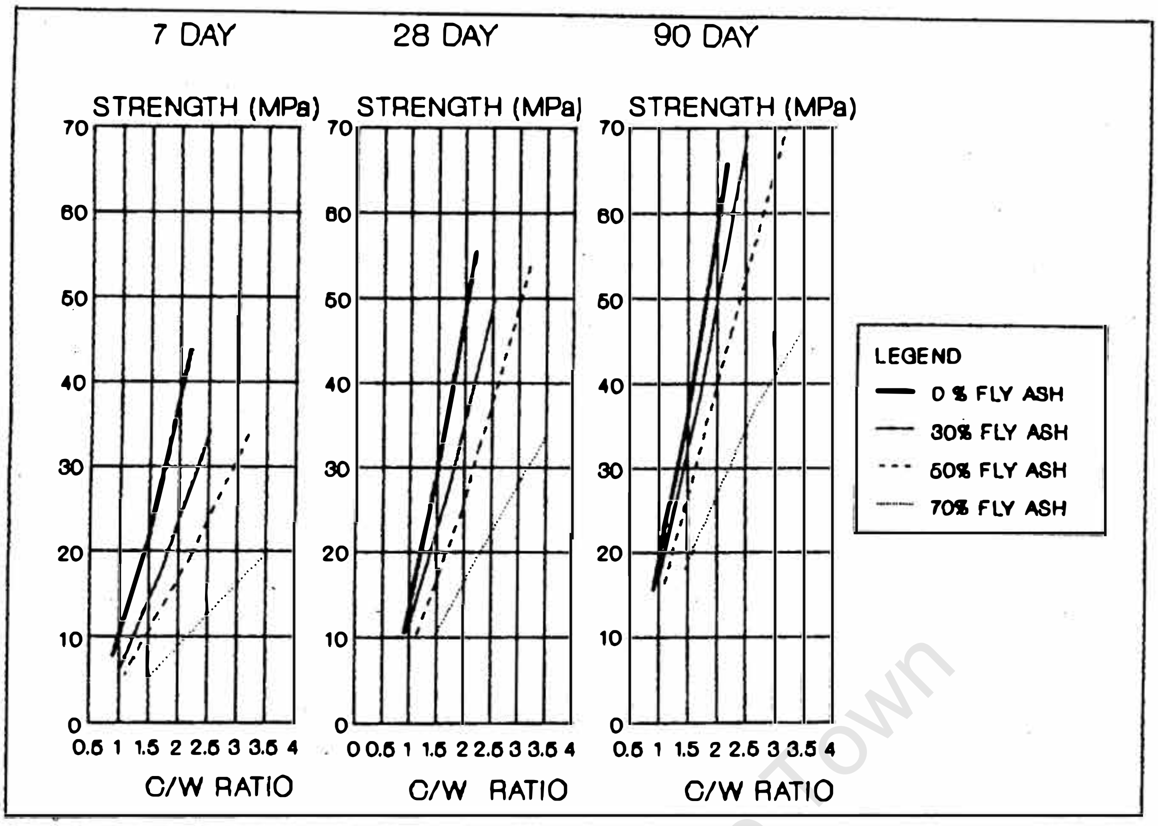

Fig.5.1. Compressive strengths of mixes used with classified Lethabo fly ash at 7, 28 and 90 day ages after casting according to curing regime c)

The strength development was found to be dependent on the percentage fly ash in the cementitious material and on the age, for similar curing. At the early age (i.e. 7 days) a lower strength resulted from increasing the percentage of fly ash. At an age of 90 days, a higher strength development was apparent from increasing the percentage of fly ash.

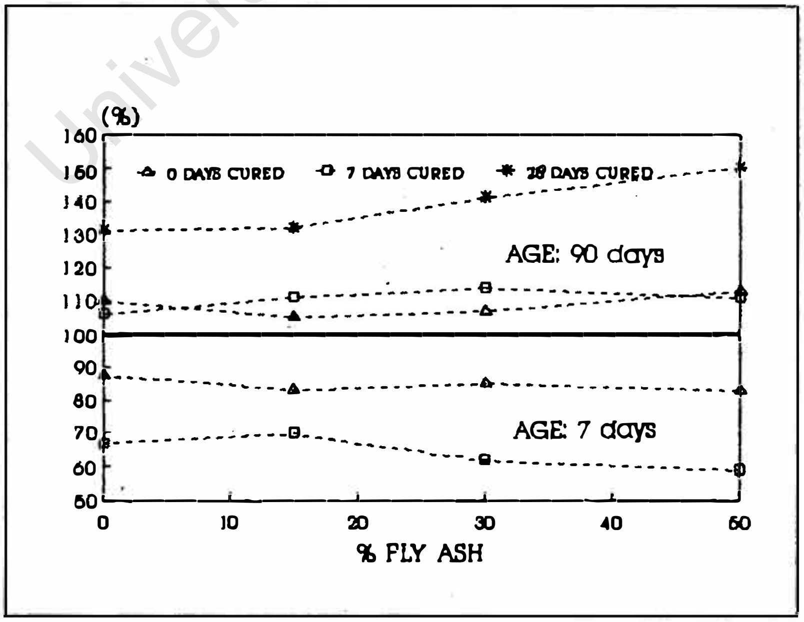

Fig.5.2 Strength development of classified Lethabo fly ash with age for various curing times expressed as percentages of the 28 day compressive strengths.

Early and long term strengths are usually expressed as a percentage of the 28 day strengths for the corresponding C/W ratios. The graph (Fig.5.2) for early and long term strength development was obtained by taking the average of the percentage of 28 day compressive strength across the entire strength range for each percentage fly ash and curing regime. It can be seen that concrete mixes containing large percentages of fly ash, initially achieve a lower percentage of their 28 day compressive strength but reach higher percentages of the 28 day compressive strength in the long term, than mixes without fly ash.

Considering the early strength development, it is clear that fly ash concretes hydrate slower and so gain strength more slowly than similar OPC concrete. Beyond 28 days, the benefits that accrue from the pozzolanic reaction of the fly ash become more apparent (Ref 5) (as also shown by an increase in the cementing efficiency factor in Table 3.1).

5.5.2 Curing of concrete specimens

Adequate curing is a key factor in achieving quality concrete and much of the subsequent deterioration should be attributed to inadequate curing. The American Concrete Institute recommended practice for curing concrete (Ref 6) suggests 7 days of moist curing for structural concrete, or the necessary time to attain 70% of the required strength, whichever is the lesser. The curing times are expected to be longer if fly ash is used to allow for the slower strength development.

No attempt was made in this thesis to model any real-life curing regime but the extreme cases were rather used.

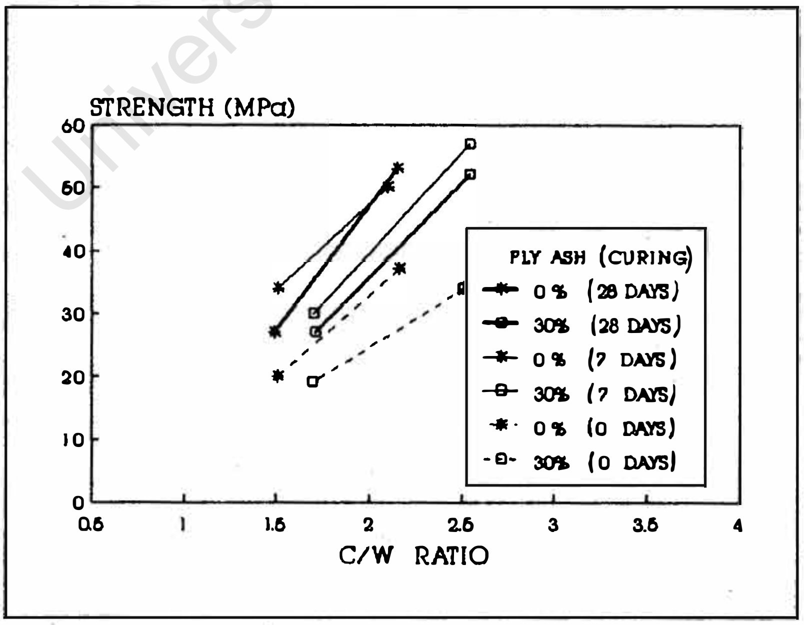

Fig.5.3. Compressive strengths at age 28 days for concrete specimens cured for different periods in water (as indicated in the brackets)

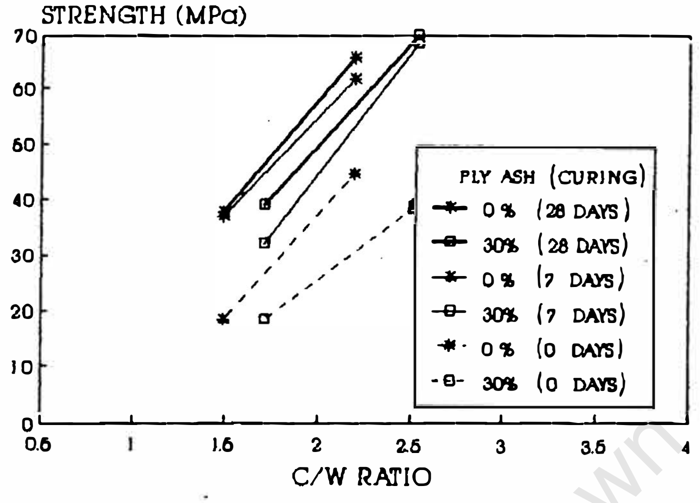

Fig.5.4. Compressive strengths at age 90 days for concrete specimens cured for different periods in water (as indicated in brackets)

It can be seen from Fig.5.3 and Fig.5.4 that moist curing gives better compressive strengths for concrete with any percentage fly ash. The longer the specimen was cured in water at 23°C the higher was the compressive strength obtained at both 28 and 90 day ages.

In the graph for 28 day compressive strength, the specimens cured for 28 days in water had lower strengths than those cured for 7 days. This anomaly could be attributed to the fact that the 28 day cured specimens were still wet when they were crushed.

The strength development for the compressive strength for the various curing times is illustrated in Fig.5.2. It can be seen that the concretes cured in air do not increase much in strength after 7 days. Whereas the concretes cured in water for 28 days have a higher strength development with time. In the fly ash concretes, the fly ash only begins to be chemically active after about 7 days. It can be seen in Fig 5.2 that the longer the fly ash concretes are cured in water the higher will be the strength development. So on average the fly ash concretes are affected to a larger extent than OPC concrete, by the duration of the wet curing that it is exposed to.

The concretes exposed to wet curing reached higher strengths because the hydration was able to continue, there being a no lack of water. After about 7 days the specimens were able to seal themselves, thereby trapping water in the pores of the concrete for further hydration.

Concrete will hydrate even if it is not in a fully saturated condition. This is because below 100% relative humidity the water is held in capillary pores by surface tension forces. The cement draws on these water reserves for further hydration, but the rate of hydration will become slower. When internal relative humidity drops below 80%, hydration will stop and the strength development will cease.

The effect of curing on fly ash concrete has also been investigated recently by several researchers - with slightly conflicting conclusions.

Research done by the C.S.I.R. showed that fly ash concrete needs to be carefully cured to ensure satisfactory properties. This work lead to the recommendations for longer curing of fly ash concrete than those for OPC concrete (Ref 7).

Ash Resources have also done extensive work locally on the effect of wet and dry curing on compressive strength. They stated that up to 30% fly ash in concrete does not increase the susceptibility to poor curing when considering the compressive strength (Ref.8). This conclusion is in contradiction to most of the previous work done on this subject and with the results obtained in this thesis. In an attempt to model real life conditions, Ash Resources initially wet cured their dry cured specimens to simulate the likely site curing conditions. This method may be somewhat optimistic when there is poor curing on site. Modeling of site curing is however somewhat subjective and makes comparisons with other work difficult. In practice, concrete in most structures seldom get adequate moist curing.

5.6 CONCLUSIONS

From the results and graphs above the following can be concluded:

- higher cementitious material to water ratios are required for concrete with classified Lethabo fly ash than mixes without fly ash, to obtain the same 28 day compressive strengths;
- the compressive strengths at early ages (7 days) of concrete containing classified Lethabo fly ash are lower than the concrete mixes without any fly ash, for the same C/W ratio;
- ~~the compressive strengths at 90 days of concrete containing classified Lethabo fly ash are higher than the concrete mixes without any fly ash, for the same C/W ratio;~~
- the compressive strength development over long periods ie. 90 days, for concrete with classified Lethabo fly ash is higher than for concrete mixes without fly ash;
- concrete cured in water at 23°C for 7 days or more, have higher compressive strengths than the same concrete cured in air, at both 28 and 90 day ages;

- the compressive strength development is highest for concrete cured for 28 days in water at 23° C;

- the compressive strength development increases for fly ash concrete with the increase of the percentage of classified Lethabo fly ash present in the cementitious material, when cured for 28 days in water at 23° C;

- good curing is of importance to all types of concrete mixes if good quality control is to be achieved.

It should be noted that the above results and conclusions were derived from a limited number and range of mixes and the figures quoted should not be taken as applying generally.

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6
ELASTIC MODULUS

6.1. INTRODUCTION

When a load is applied to a structural material it deforms. If on removal of the load the recovery is both complete and immediate the material is considered to be perfectly elastic. The elasticity of concrete is usually only of interest to design engineers who are concerned with deformations and deflections of structural elements.

The ratio of the applied compressive stress to the longitudinal strain produced is called the "Modulus of Elasticity". The stress-strain relationship for concrete is however not linear, mainly due to creep or plastic deformation, particularly at slow rates of loading. A portion of the curve may however, be regarded as effectively linear and at stresses within this range the elastic modulus may be taken as the slope of this linear portion and is referred to as the "initial tangent modulus". If the stress is above that at which the stress-strain relationship deviates from linearity, two further forms of elastic modulus may be considered, namely the "tangent modulus" as represented by the slope of the tangent to the curve at a particular stress, and the "secant modulus" represented by the slope of the line connecting the origin to the point of the curve corresponding to the stress selected as shown in Fig.6.1. (Ref 1.).

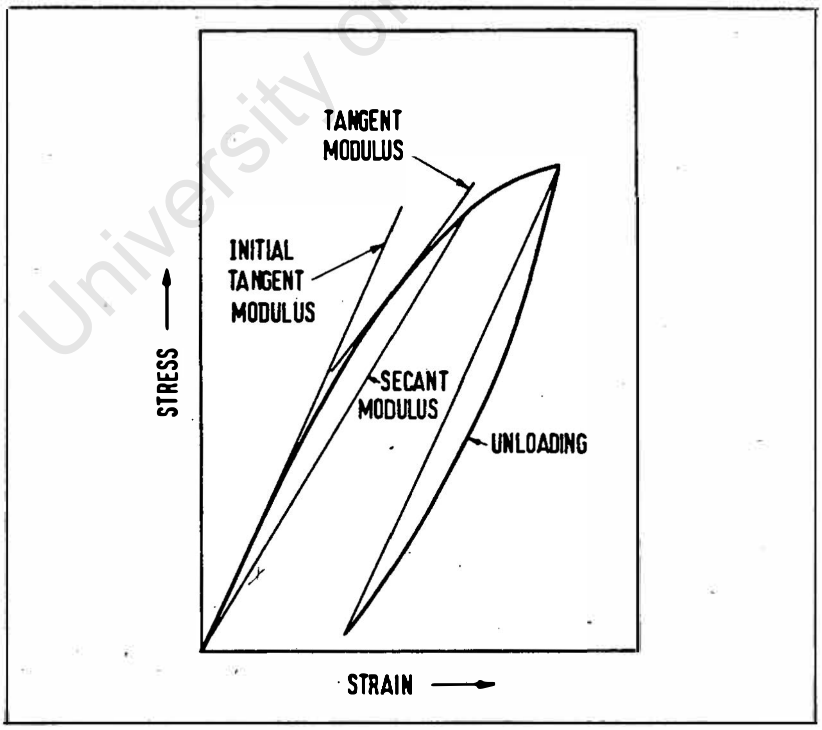

Fig 6.1. Three forms of Elastic Modulus (Ref.1.)

6.2 METHODS OF TESTING

6.2.1. Making and curing of specimens

Three 150 mm diameter by 300 mm long test cylinders from the same design mix were cast and cured in accordance with BS 1881 Part 3 (Ref 2). The moulds were filled in three layers and each layer compacted using a vibrating table until all the air pockets had been removed. The specimens were first stored in air for 24 hours at a constant temperature of 23° C +- 1° C and 50% relative humidity.

Then each specimen was capped with a sand/cement mortar and a capping plate pressed down and left in place for a further 24 hours under the same conditions. This was to give the specimens a smooth top surface.

The following day the specimens were demoulded and stored under the various curing conditions:

a) 0 days wet cured - the specimens were stored in a temperature room at 23°C +- 1°C and 50% RH until tested,

b) 7 days wet cured - the specimens were stored in water at 23°C +- 1°C for 7 days and then removed and stored in the temperature room until tested,

c) 28 days wet cured - the specimens were stored in water at 23°C +- 1°C for 28 days and then removed and stored in the temperature room until tested.

6.2.2. Static testing method:

The static modulus of elasticity was determined according to the standard BS 1881: Part 121 : 1983 (Ref.3).

The specimens were always tested when air dried for at least one day. A wet specimen has a higher modulus of elasticity than a dry one, while the compressive strength varies in the opposite sense (Ref.4.).

Three pairs of targets, equally spaced around the cylinder perimeter, were attached to the specimens. The targets were made of brass discs with stainless steel balls fixed on. Each pair of targets was positioned 100mmm apart, placed symmetrically around the mid-length of the specimen.

The concrete test cylinders were loaded in compression and the longitudinal strain measured with a Pfender precision strain gauge with a gauge length of 100 mm. A direct read out accuracy of 1 μm represents a strain of 10 X 10^{-6} . This gauge was kept in the same room with the test specimens to eliminate temperature effects on the gauge.

In carrying out the test, the specimens were first loaded to about 40% of their ultimate compressive strength at a constant rate of 15 MPa per minute. The load was maintained for about 1 minute and then the stress was reduced to 1 MPa. This process was repeated for a second time. This "exercising" of the test specimen reduces the creep and on the third or fourth loading the curvature of the stress-strain relationship is generally very small for compressive stresses which are less than half the ultimate stress.

The load was then applied again at the same rate and strain gauge readings taken at a lower and upper value not exceeding 40% of the ultimate compressive stress. When the strain observed at each pair of targets differed by more than 5% from the average strain, the specimen was unloaded and realigned on the platten. The procedure was then repeated until the difference was less than 5%.

The static modulus of elasticity is taken to be the slope of the straight line drawn through the plotted stress-strain points. The slope of the lines for the three sets of targets were determined and the average value found. This average value is then the static modulus of elasticity of concrete, expressed in GPa.

6.2.3. Dynamic testing method

Dynamic methods have been developed for determining the modulus of elasticity of concrete. In these methods the applied loads are very small and the rates of application and release of the loads are rapid, so the effects of creep are negligible. For this reason, the dynamic modulus is approximately equal to the initial tangent modulus determined in the static test and is therefore appreciably higher than the secant modulus.

The dynamic modulus of elasticity was determined according to the standard BS 1881 :Part 5 (Ref.5).

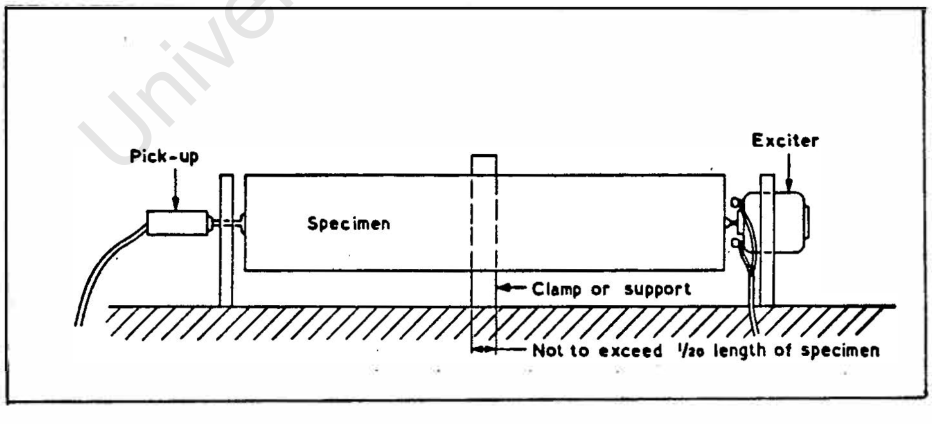

Fig.6.2. Arrangement of the specimen and apparatus for determining the dynamic elastic modulus (Ref.5.)

The same specimens that were used for the static test were used for the dynamic testing. The testing was performed on the same day as the static testing. The specimens were surface dry when tested as wet specimens generally have lower dynamic modulus of elasticity than dry ones (Ref.4.).

The apparatus used for the testing consisted of a variable frequency oscillator, an electromagnetic exciter unit, a vibration pick-up, an audio-frequency amplifier, an amplitude indicator and a clamp to hold the specimen. The apparatus was arranged as illustrated in Fig.6.2.

The sample was placed in the apparatus as shown above so that the clamp was in the middle of the specimen. The pick-up unit and the exciter unit were fixed so that they lightly touched the specimen on the two end faces respectively. To improve the transfer of the vibration through the specimen a piece of tin foil can be fixed between the specimen and the exciter unit using grease, but this was not found to be necessary.

The test specimen was exited by the exciter unit which was driven by a variable-frequency oscillator. the oscillations were received by the pick-up unit, amplified and applied to an amplitude indicator. The frequency of excitation was varied until resonance was obtained in the fundamental mode of vibration. The dynamic modulus of elasticity was calculated from the formula -

$$Ed = 4\ n^2 l^2 w \times 10^{-12}$$

where Ed = dynamic modulus of elasticity (GPa)
n = natural frequency of the fundamental mode of longitudinal vibration of the specimen (Hz)
l = length of specimen (mm)
w = density of specimen (kilograms per cubic meter)

6.3. RANGE OF MIXES USED

	CURING REGIMES		
FLY ASH	a)0 DAYS WET	b)7 DAYS WET	c)28 DAYS WET
0%	X #	X #	X #
15%	X	X	X
30%	X #	X #	X #
50%	#	#	#

X) Grade 50 MPa design strength
#) Grade 30 MPa design strength

Table.6.1. Range of mixes used for Elastic Modulus testing

6.4. DISCUSSION OF RESULTS

6.4.1. Comparison of static and dynamic moduli

The dynamic modulus refers to almost purely elastic effects and is unaffected by creep as the vibration of the specimen causes a negligible applied stress. The dynamic modulus is appreciably higher than the static modulus, as discussed above.

The dynamic modulus results may be used to estimate the static modulus, the tests is quick and the specimen is not likely to get damaged in any way. Various relationships between static and dynamic moduli have been suggested but the proposal by SABS 0100 is probably the most suitable and is generally correct within +-4 GPa (Ref.1.):

$$Es = 1.25\ Ed - 19 \quad \text{(in GPa)}$$

where Es = the static modulus
Ed = the dynamic modulus

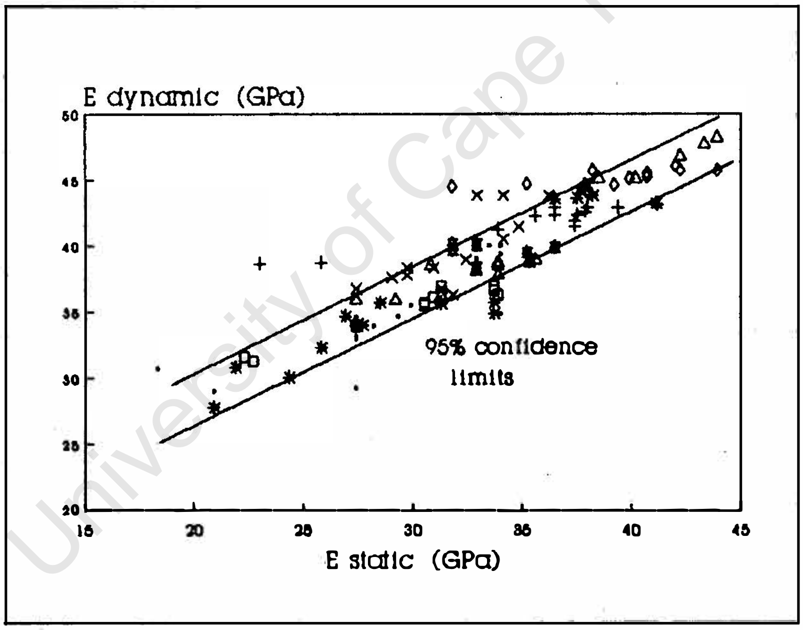

Fig.6.3. The relationship between the static and dynamic elastic moduli for the mixes used

Fig.6.3. illustrates that for all the data obtained in this thesis lumped together, there were no significant trends for concretes with differing curing regimes or percentages fly ash, when plotted on a graph of Ed vs Es. The relationship between the static and dynamic moduli for the data obtained in this research can be expressed by the equation:-

$$Es = 1.25\ Ed - 15.6 \quad \text{(in GPa)}$$

where Es = the static modulus
Ed = the dynamic modulus

This is not really a departure from the SABS formula as it has been suggested that the relationship between static and dynamic moduli may vary when different types of aggregates are used (Ref.6.). It can be safely assumed that this is the equation for the concrete with the types of aggregates used in this thesis. The 95% confidence limit has a width of 3 GPa.

6.4.2. Static modulus of elasticity

The two major components of concrete, cement paste and aggregate, when individually subjected to stress both exhibit a linear stress-strain relation. The reason for the curved relation in the composite material (concrete) lies in the presence of interfaces between the cement paste and the aggregate and in the development of micro cracking at those interfaces (Ref.7.). (See Fig.6.4.)

In the past attempts have been made to relate the static modulus of elasticity to the compressive strength of the concrete. Such correlations can be misleading as the most important factor influencing the elasticity is the type of aggregate used (Ref.1).

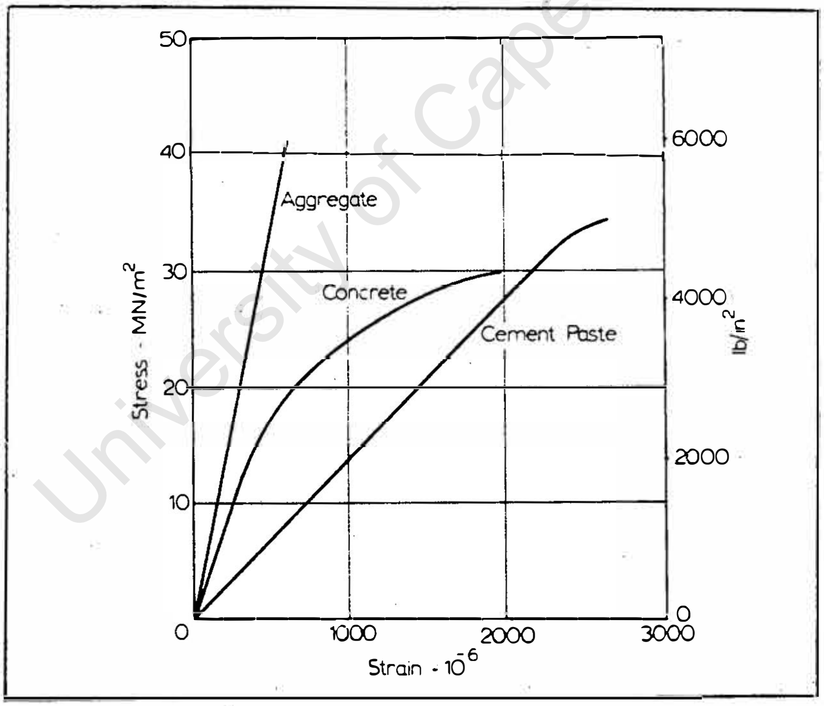

Fig.6.4. Stress-strain relations for cement, aggregate and concrete (Ref.4.)

The stiffer the aggregate used, the higher the elasticity of the concrete. For a given type of aggregate, the elasticity of the concrete will increase with the strength of the concrete. The age of the concrete and its composition also influence the value of Es but not to the same extent as the aggregate properties and concrete strength.

The shape and surface characteristics of the coarse aggregate affect the entire shape of the stress-strain relation through their influence on the development of micro-cracking (Ref.4.). Although these properties of the aggregates influence the modulus of elasticity, they generally do not affect the compressive strength of the concrete much.

The formula below has been developed (Ref.8.) to estimate the static modulus of elasticity. It takes into consideration the aggregate properties as well as the strength of the concrete. This formula is not accurate for strengths less than 20 MPa.

$$Es = Ko + \alpha \, fcu$$

where Es = the static modulus of elasticity for a particular age of concrete being considered;
Ko = constant related to the stiffness of the aggregate (GPa)
α = strength factor related to the aggregate characteristics (GPa/MPa)
fcu= cube strength at the same age matching that of Es (MPa)

age	Ko	α	
3 to 28 days	24	0.25	
1 to 6 months	27	0.23	(interpolated)
older than 6 months	31	0.20	

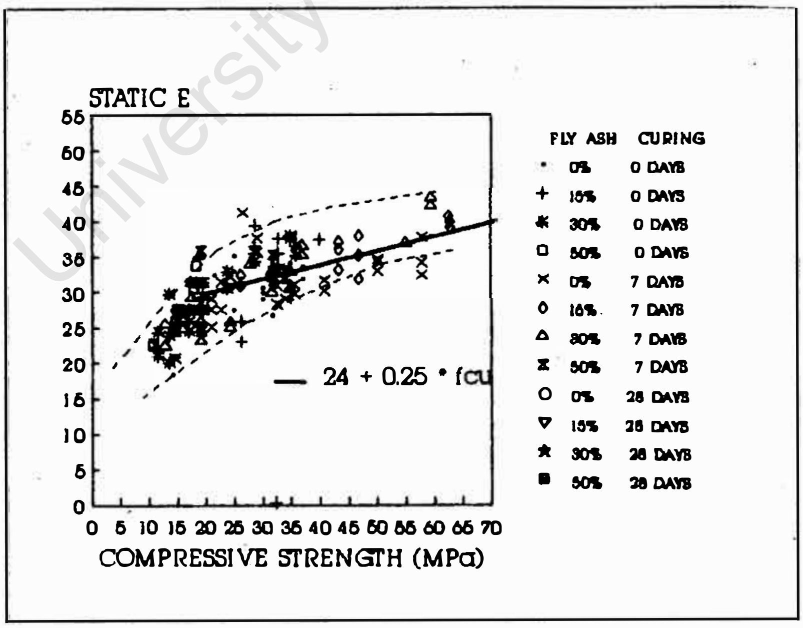

Fig.6.5. Static modulus of elasticity vs compressive strength (for 3 to 28 day old concrete) for all the concrete mixes used.

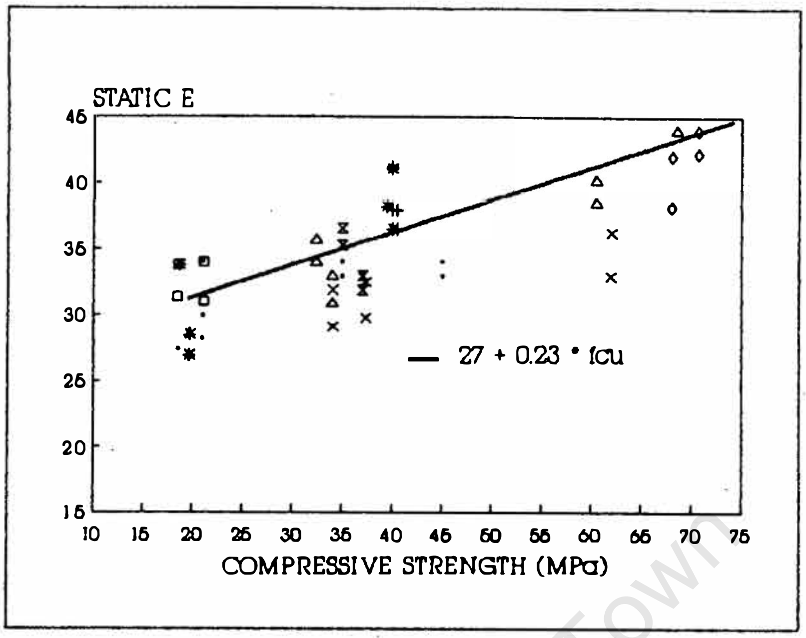

Fig.6.6. Static modulus of elasticity vs compressive strength (90 day old concrete) for all the concrete mixes used.

In Fig.6.5. the equation complies with the results obtained in this thesis for the compressive strengths greater than 35 MPa but deviates for compressive strengths below 35 MPa. The results plotted on the graph do not give a linear relationship but rather a curved relationship as suggested by BS 1881: Part 5 (Ref.5.).

In Fig.6.6. the results do illustrate a linear trend when observed by eye. The line plotted by the equation shown above is a bit high for the results obtained in this thesis. A lower Ko-value would bring the line down to agree with results obtained.

Both Fig.6.5. and Fig.6.6 show that the presence of fly ash and the types of curing regimes have virtually no significant effect on the elastic properties of concrete. The same conclusion was made by PCI (Ref.9.) on the work they conducted on concrete made with OPC and various blends of OPC and fly ash (See Fig.6.7.).

An interesting aspect of the increase in the elastic modulus with strength, is that the changes observed cannot be accounted for in terms of the elasticity of the aggregate nor by strength gains in the matrix. The explanation lies in some form of on-going interfacial bond development between the aggregate and the matrix. (Ref.1.).

Hansen suggests that the relationship between the modulus of elasticity and strength is not a fundamental one since the modulus of elasticity of concrete depends on the modulus of elasticity of the aggregate (as discussed above) and on the aggregate content, while the strength is only slightly affected by these two factors (Ref.10.).

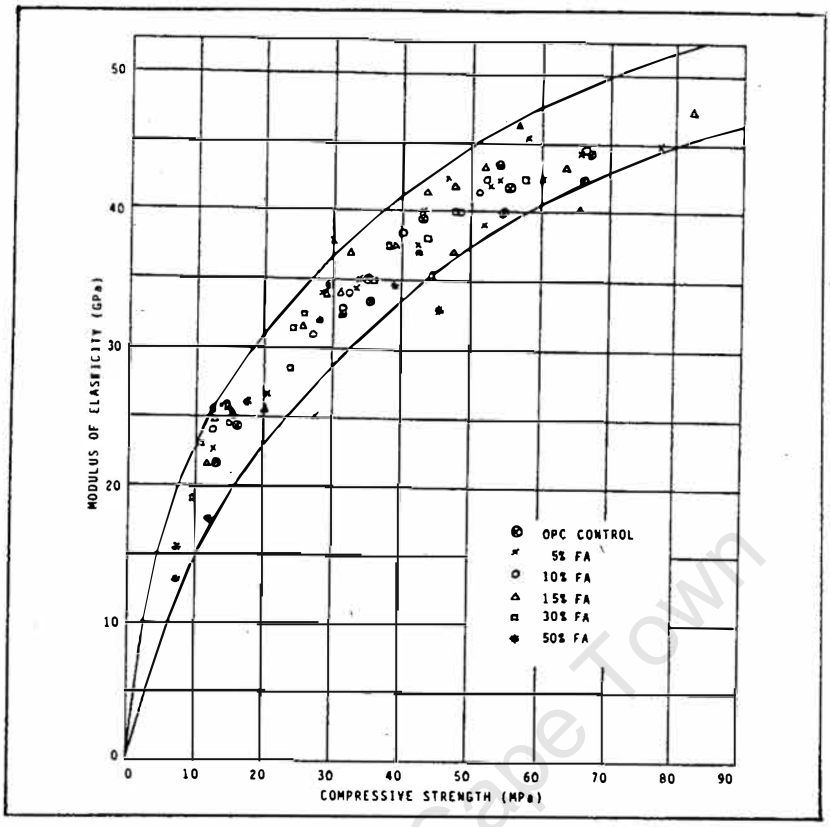

Fig.6.7. "Modulus of elasticity vs compressive strength for concretes with various percentages of cement replacement by fly ash" (Ref.9.).

Design strength	30 MPa			50 MPa		
% fly ash	0	30	50	0	15	30
Actual strength	35	31	33	58	62	60
Static E	31	33	33	35	40	43
Stone content	1050	1102	1127	1050	1083	1102
Total Aggregates	1850	1896	1893	1773	1788	1770

Table.6.2. Static elasticity at 28 days compared with the volume of stone and total aggregates for mixes cured in regime b).

The stone content of the concrete mixes was increased with the increase in the percentage of fly ash, as discussed in chapter 3. In Table 6.2. it can be seen that a higher modulus of elasticity was obtained when the stone content was increased. The total volume of aggregates present does not appear to correlate with the modulus of elasticity of the concrete.

6.4.3. Dynamic modulus of elasticity

The dynamic testing apparatus gives better repeatability than the static testing method, as can be seen from the graphs in Fig.6.5. and Fig.6.6.

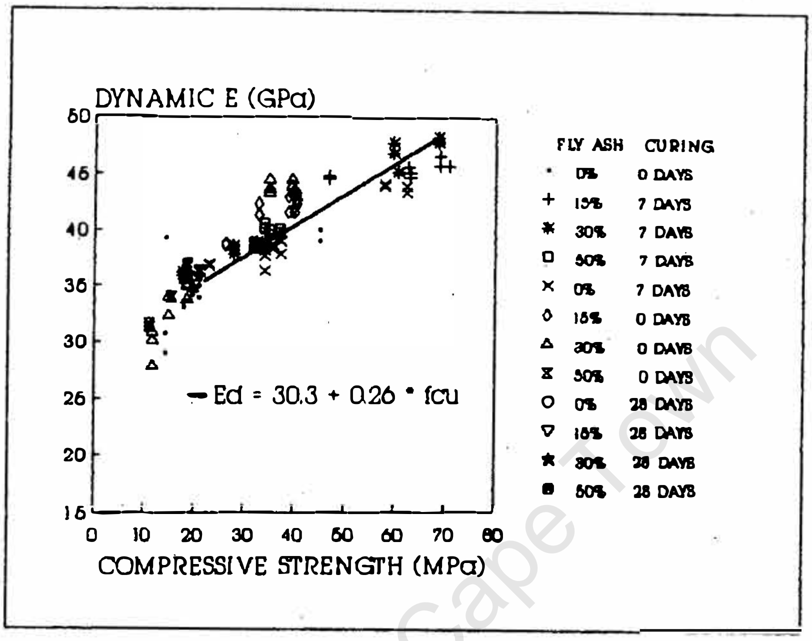

Fig.6.8. Dynamic modulus of elasticity vs compressive strength (3-90 day old concrete) for all the concrete mixes used.

The results plotted in Fig.6.8. tend to have a linear relationship. The equation of the linear line for the results obtained in this thesis is :

$$Ed = 30.3 + 0.26\ fcu$$

where Ed = the dynamic modulus (GPa)
fcu= cube strength at the same age matching that of Es (MPa)

Fig.6.8 shows that the percentage of fly ash present in a mix does not visibly affect the dynamic elastic modulus of the concrete. The relationship between elastic modulus determined by longitudinal vibration of cylinders and their compressive strength is not affected by air entrainment, method of curing or the type of cement used (Ref.11.).

The stone content of the concrete mixes was increased with the increase in the percentage of fly ash, as discussed in chapter 3. No apparent trends can be observed when Ed is related to the stone content and aggregate content. One can deduce that the dynamic modulus of elasticity is related to the properties of the aggregates but not to the volume present in the mix.

Design strength	30 MPa			50 MPa		
% fly ash	0	30	50	0	15	30
Actual strength	35	31	33	58	62	60
Dynamic E	39	38	39	44	45	46
Stone content	1050	1102	1127	1050	1083	1102
Total Aggregates	1850	1896	1893	1773	1788	1770

Table.6.3. Dynamic elasticity at 28 days compared with the volume of stone and total aggregates for mixes cured in regime b).

An on-going interfacial bond development between the aggregate and the matrix would account for the increase in the dynamic elastic modulus with time. With time, the concrete matrix gets stiffer and so exhibits a higher elastic modulus.

6.5. CONCLUSIONS

From the results and graphs above the following can be concluded:

- the dynamic testing method gives better repeatability than the static testing method;

- when plotted on a graph of Ed vs Es, concretes with widely different percentages fly ash content exhibited no significant trends;

- both the static and the dynamic moduli were unaffected by the type of curing that the concrete was exposed to;

- on a graph of Ed vs strength, the presence of fly ash has no significant effect on the static elastic properties of concrete;

- on a graph of Es vs strength, the presence of classified Lethabo fly ash has no significant effect on the dynamic elastic properties of concrete;

- the stiffer the aggregate used, the higher the elasticity of the concrete;

- a higher static modulus of elasticity was obtained when the stone content was increased;

- no apparent trends could be observed when the dynamic elasticity was related to the stone content;

- the total volume of aggregates present did not appear to have any affect on the modulus of elasticity of the concrete.

It should be noted that the above results and conclusions were derived from a limited number and range of mixes and the figures quoted should not be taken as applying generally.

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7
SHRINKAGE

7.1. INTRODUCTION

Shrinkage is the decrease in the dimensions of unstressed concrete caused by the withdrawal of water. If the withdrawal of water takes place while the concrete is still fresh it is known as plastic shrinkage. Plastic shrinkage does not cause stresses in the structure. The withdrawal of water of hardened concrete is known as drying shrinkage and causes stresses in the structure if it cannot move freely (Ref.1).

Of the potential shrinkage that can occur from the time of casting to 3 years later, 20% occurs while the concrete is still plastic (plastic shrinkage) - 80% occurs after setting and is due to the drying of the concrete (drying shrinkage) (Ref.2.).

7.2. PLASTIC SHRINKAGE

Plastic shrinkage cracking of concrete occurs after the concrete has stiffened but while the concrete is still very weak. This type of cracking is due to tensions caused by the water in the capillaries after the level of the bleed water has, due to evaporation, dropped to a level below the concrete surface (Ref.3).

Menisci are formed between the particles close to the surface and as a consequence all the pore water is under negative capillary pressure. If the process is not excessive this mechanism leads to a contraction of the fresh concrete (Ref.4). It is thus understandable that water demand, bleeding and stiffening characteristics have an influence on the development of plastic shrinkage cracking.

7.2.1. Method of testing

An attempt was made to develop a new testing method for evaluating the amount of plastic shrinkage. Unfortunately the testing conditions were not consistent (viz. temperature and humidity) and there was concern on the safety of working with mercury, so this method was not pursued further. This is briefly outlined below but is discussed in more detail in Appendix B.

A small mortar prism was cast in a mould, vibrated and it was slipped out of the mold and floated on mercury. Two targets were placed on the prism and the relative movement was measured with a travelling microscope until no further movement was apparent. This procedure was carried out in a fume cupboard with a constant flow of air over the testing apparatus.

7.3. DRYING SHRINKAGE

When concrete is exposed to the normal atmosphere (i.e. when the formwork is removed from concrete) the exposed surface of the concrete immediately starts to lose water. The rate of evaporation initially depends on the temperature, relative humidity, C/W ratio and the exposed surface area of the concrete.

Water in the cement paste is removed progressively by evaporation from the menisci in the larger capillary pores. The capillary tension that develops in the residual water induces compressive stresses in the concrete and as a result the concrete shrinks. As drying continues, the menisci recede away from the concrete surface and the water held to the internal surface by physical forces is lost. Removal of this absorbed water causes further shrinkage (Ref.4.).

Drying shrinkage can account for a substantial part of the long term movements that occur in structures (Ref.5.).

7.3.1. Method of testing

The test method selected to establish the ultimate drying potential of the range of concrete mixes was SABS method 1085 (Ref.6.).

The test required the casting of prisms (280 X 50 X 50mm), with a brass anvil at each end for the accurate measurement of length. Nine prisms were cast for each mix investigated. The concrete prisms were cured in the moulds for 24 hours in a fog room with a relative humidity of 90% and then demoulded.

The prisms were cured as specified in Table.7.1. The wet curing was done in water with a temperature of 23° C +- 1° C. After the specified curing, the prisms were surface dried (where necessary) before being measured with a 300 mm micrometer screw gauge.

The prisms were then dried out in an oven at 55 degrees celsius. The relative humidity of the oven was maintained at less than 25% using silica gel crystals.

The prisms were removed from the oven every second day and allowed to cool for two hours in the temperature room, regulated at 23° C. After two hours the prisms had reached room temperature and therefore were no longer changing length due to cooling. They were then measured using the same micrometer screw gauge and returned to the oven for further drying. These measurements were continued until a change of less than 10 microns in two successive measurements was observed.

The ultimate drying shrinkage was calculated as the overall change in the length divided by the distance between the inner ends of the anvils, expressed as a percentage. Shrinkage measured on small-sized laboratory specimens may be taken as the upper bound of shrinkage to be expected in members of practical dimensions (Ref.7.).

7.3.2. Range of mixes used

	CURING REGIMES		
FLY ASH	a)0 DAYS WET	b)7 DAYS WET	c)28 DAYS WET
0%	X #	X #	X #
15%	X	X	X
30%	X #	X #	X #
50%	#	#	#

X) Grade 50 MPa design strength
#) Grade 30 MPa design strength

Table.7.1. Range of mixes used for Drying Shrinkage

Due to the increased stone content with increasing percentages of fly ash (see Fig.4.1.) it was decided to do drying shrinkage tests on both mortar and concrete prisms.

7.4. DISCUSSION OF RESULTS

7.4.1. Plastic Shrinkage

Unfortunately not enough samples were tested in order to get a idea of the plastic shrinkage trends for the various concrete mixes and for various percentages of fly ash.

According to the NBRI of the CSIR, fly ash influences the water demand of the concrete in which it is used, and the bleeding and stiffening characteristics of the fly ash concrete also differ from those of OPC concrete. These characteristics may counteract each other such that their influence on plastic shrinkage cracking cancel out. It is however also possible that they may supplement each other such that plastic shrinkage is aggravated (Ref.3.).

It may be concluded that the effect of fly ash concrete on plastic shrinkage during drying has no clear trends (Ref.8.).

7.4.2. Drying Shrinkage

From the figures below (7.1., 7.2. and 7.3.) it can be seen that for all mixes (ie OPC and fly ash mixes), an increase in the C/W ratio results in a higher drying shrinkage. For samples that have undergone longer wet curing lower overall shrinkage values were obtained. It has however also been argued that wet curing increases the volume of cement gel formed and can lead to increased shrinkage of the concrete (Ref.3.).

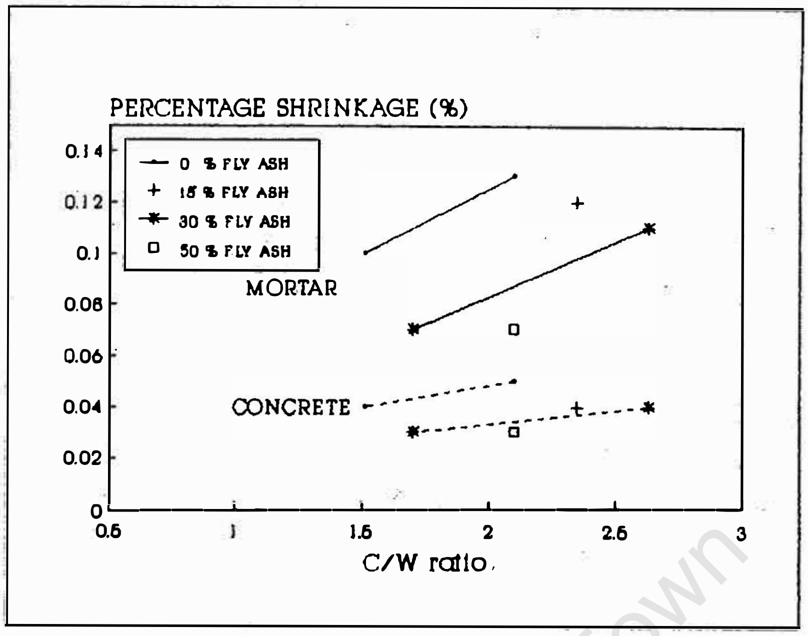

Fig.7.1. Drying shrinkage of mortar and concrete prisms tested after 0 days wet curing vs C/W ratio.

A general trend of decreasing drying shrinkage with increasing percentages of fly ash can be observed for mixes with no wet curing and for 28 days wet cured (Fig.7.1. and Fig.7.3.). For mixes wet cured for 7 days (Fig.7.2.), the mix with 30% fly ash had a higher drying shrinkage than the 0% fly ash mix. Yet, the 15% and 50% fly ash mixes shrank less than the OPC mixes. These trends are true for both the mortar and the concrete prisms.

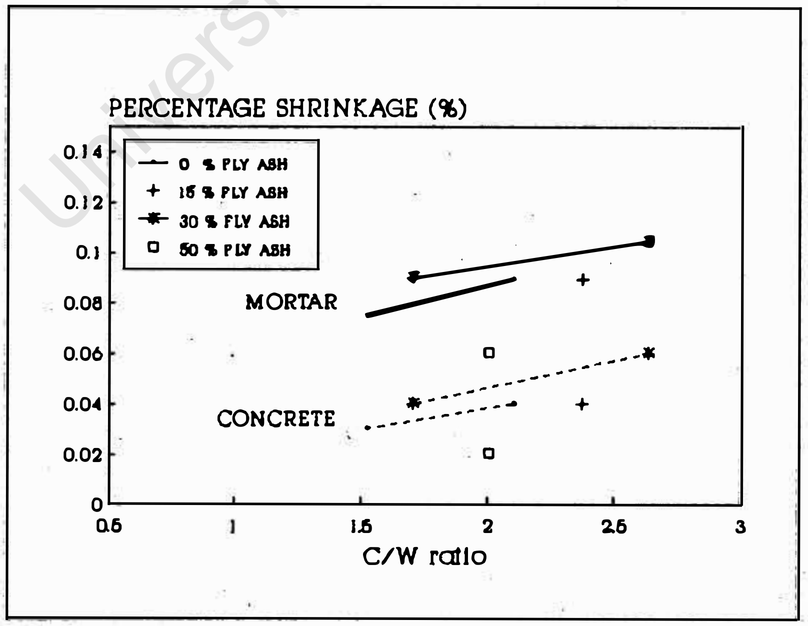

Fig.7.2. Drying shrinkage of mortar and concrete prisms tested after 7 days wet curing vs the C/W ratio.

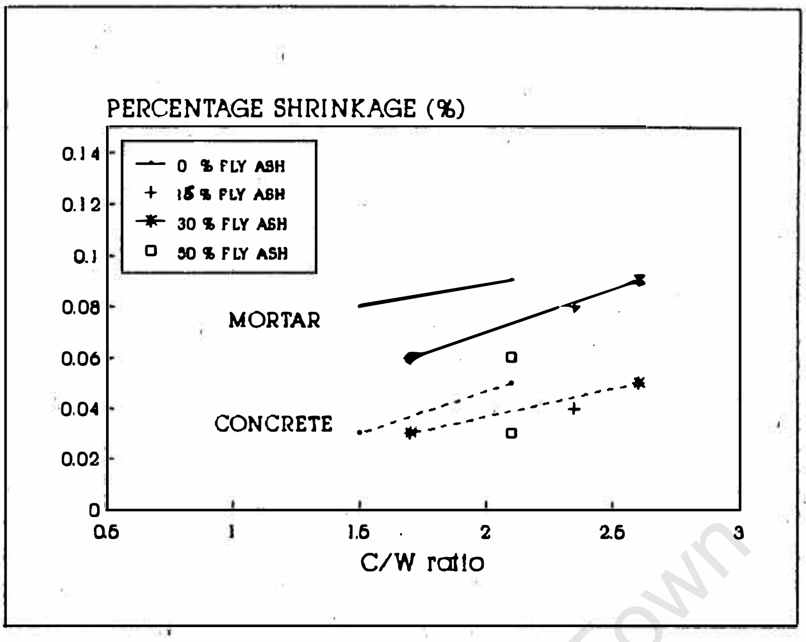

Fig.7.3. Drying shrinkage of mortar and concrete prisms tested after 28 days wet curing vs the C/W ratio.

The literature contains conflicting opinions on the effect of fly ash on shrinkage.

The results of shrinkage done by PCI indicate that fly ash tends to reduce shrinkage (Ref.9) (see Fig.7.4.).

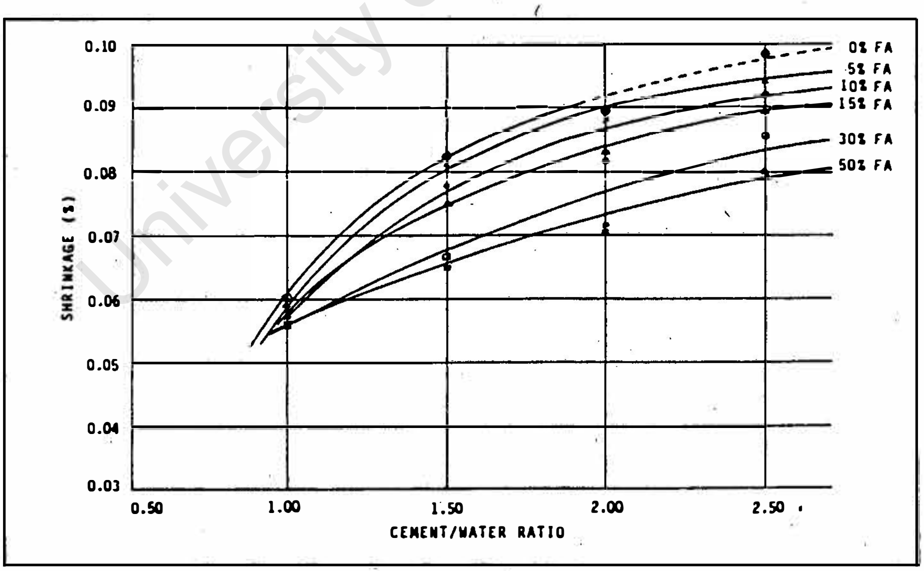

Fig.7.4. Drying shrinkage of mortars vs C/W ratio for different fly ash contents (Ref.9).

Mills observed that the shrinkage of pastes containing blastfurnace slag was appreciably greater than that containing only OPC (Ref.7.). This differs from the general trend of decreasing shrinkage with increasing percentages of fly ash.

Yet some researchers believe that fly ash, used in practical proportions, does not influence the drying shrinkage of concrete. Gebler and Klieger showed that drying shrinkage for concretes containing fly ash was essentially the same as for the control concretes with the same cementitious content without fly ash (Ref.10.).

This was confirmed by research conducted by van Dijk, as the shrinkage of the fly ash concrete was similar to that of the OPC concrete, only a small difference existed (Ref.11.). It has been suggested that this small difference may explain the finding of several investigators who report either decreases or increases in the shrinkage of different fly ash concretes

It is fairly obvious from the results obtained that concrete shrinks less than mortar. The influence of the aggregate upon the concrete shrinkage is substantial. Concrete normally contains between 55% and 80% by volume of aggregate and if the aggregate shrinks far less than the paste then the aggregate restrains the amount of overall shrinkage that can occur (Ref.12.).

Aggregates have two effects on paste shrinkage, viz "restraint" and "dilution". The former term refers to the fact that concrete shrinkage will reduce with increasing stiffness, while the latter refers to the fact that shrinkage of concrete will decrease with decreasing ~~shrinkage~~ paste contents (Ref.13). Fig.7.5. shows that the increase in stone content for increasing percentages of fly ash, did not really affect the drying shrinkage of the mixes. A graph of drying shrinkage vs total aggregate volume would essentially give the same conclusions, as the total volume of aggregate does not greatly differ when the percentage of fly ash is increased for a given grade of concrete (see the mix proportions in Appendix A).

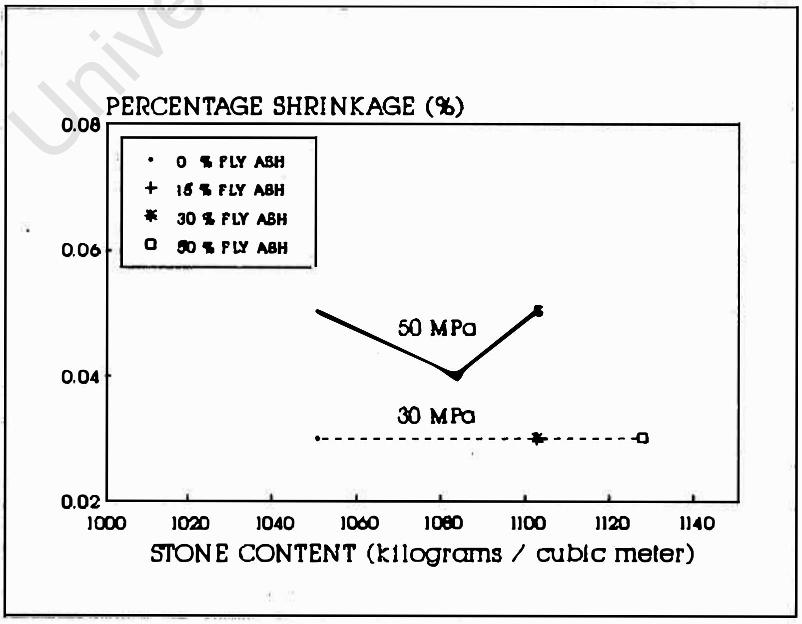

Fig.7.5. Drying shrinkage of concrete cured for 28 days in water vs the stone content.

Aggregate properties such as size and grading affect shrinkage of concrete indirectly through their effect on the water requirement of a mix. The fineness of the cementitious material is only a factor in so far as the particles coarser than say 0.074 mm, which hydrate incompletely, have a restraining effect similar to that of the aggregate.

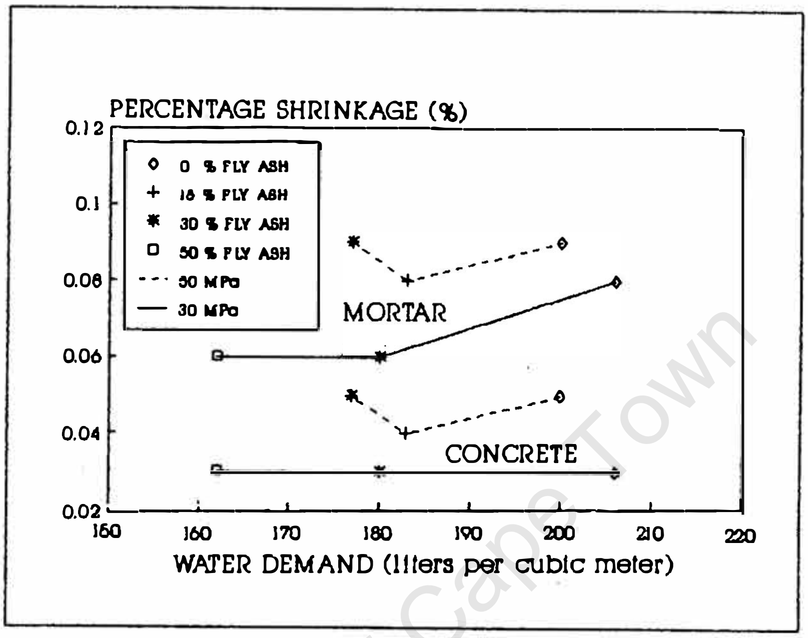

Fig.7.6. Drying shrinkage of concrete and mortar cured for 28 days in water vs the stone content

The water content of concrete affects shrinkage in so far as it reduces the volume of restraining aggregate and at the same time it increases the volume of evapourable water. Due to the reduction in the water demand of the fly ash mixes (see Fig.4.1.), the fly ash concretes and mortars should have lower drying shrinkage values than the OPC mixes (Ref.11). With reference to Fig.7.6. it can not confidently be confirmed, although a slight trend does exist for the 30 MPa ~~concrete~~ mortar, that a reduction in the water demand of the fly ash mixes contributes to the decrease in the drying shrinkage.

In attempting to explain the reduction of drying shrinkage with increasing percentages of fly ash, Dhir (Ref.14) notes that the reason for the reduction has not been fully explained by many other researchers. He suggests that with the addition of fly ash and the reduction of the water requirement, a finer paste structure is produced. As a result of this, the loss of pore water within the paste system is restricted and consequently the drying shrinkage is reduced.

7.5. CONCLUSIONS

From the results, graphs and references above the following can be concluded:

- from the point of view of plastic shrinkage, fly ash concrete is similar to OPC concrete;

- an increase in the C/W ratio results in higher drying shrinkage for all concretes;

- lower overall shrinkage values were obtained with longer wet curing for all concretes;

- concrete shrinks less than mortar due to the influence of the aggregate present in the mix;

- the small increase in stone content for increasing percentages of fly ash, did not affect the drying shrinkage of the mixes;

- it can not be confidently confirmed that a reduction in the water demand of the mixes with classified Lethabo fly ash contributes to the decrease in the drying shrinkage;

- it can however be safely assumed that drying shrinkage for concretes containing classified Lethabo fly ash is essentially the same as for concretes without fly ash, or possibly even less.

It should be noted that the above results and conclusions were derived from a limited number and range of mixes and the figures quoted should not be taken as applying generally.

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8
CREEP

8.1. INTRODUCTION

Creep is defined as the time-dependent strain in a concrete specimen, under sustained load, in excess of the strain in an unloaded companion specimen. A full knowledge of the potential creep that concrete will develop with time is of importance for calculating the long tèrm stresses and estimating deflections.

The role of research on creep generally has been to determine the degree of influence of various parameters on the time dependent behavior of concrete. This thesis investigates only the effect of the inclusion of fly ash in the concrete mix on its creep characteristics.

Creep is generally a desirable material property from the point of view of structural behavior, and without it concrete would simply be too brittle for use in the majority of structures. Creep also gives relief to restrained shrinkage. Detrimental effects of creep include increased deflections, loss of prestress, and creep buckling of long columns (Ref.1.).

An idealized creep curve for concrete under uniform sustained load is shown in Fig.8.1. Upon application of a load, an instantaneous strain which for practical purposes may be regarded as elastic is experienced by the concrete. Shrinkage due to the drying of the concrete is time dependent and irrecoverable. The remaining deformation is due to the total creep.

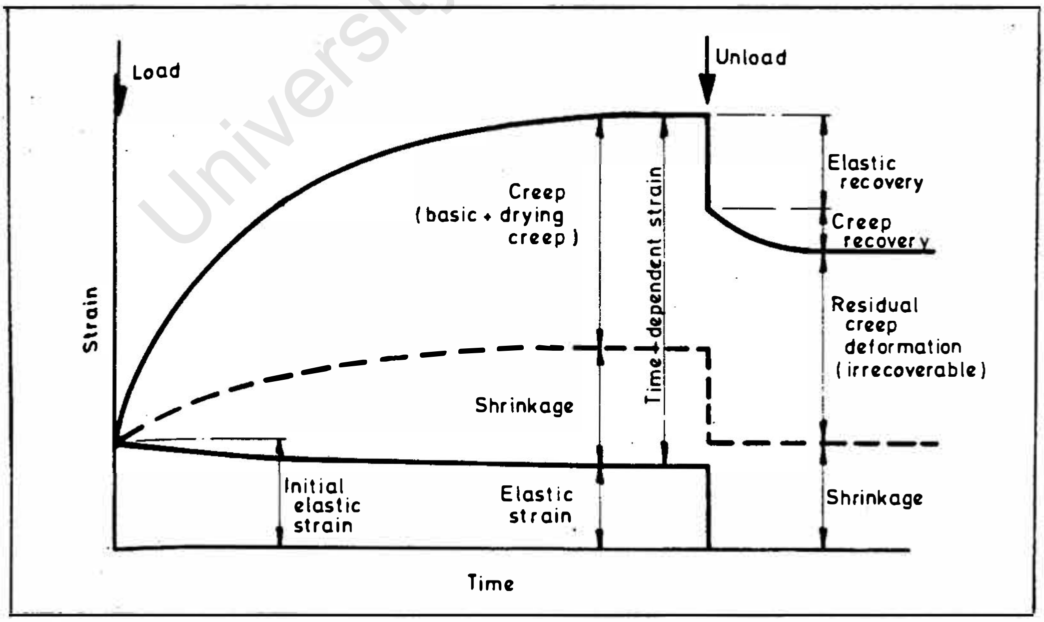

Fig.8.1. Components of deformation of concrete subjected to a compressive load in a drying environment (Ref.1.)

Total creep is the sum of the basic creep and drying creep. A distinction is drawn between basic creep and drying creep. If drying occurs while the concrete is under stress, the strain is likely to be much greater than the corresponding basic creep and the additional strain is called drying creep. Basic creep is the creep that occurs due to an applied load with no drying taking place eg a sealed specimen.

8.2. METHOD OF TESTING

8.2.1. Making and curing of creep specimens

Five 105 mm diameter by 300 mm long test cylinders from the same design mix were cast and cured in accordance with BS 1881 Part 3 (Ref.2.). The moulds were filled in three layers and each layer compacted using a vibrating table until all the air pockets had been removed. The specimens were first stored in air for 24 hours at a constant temperature of 23° C +- 1° C and 50% relative humidity.

Then each specimen was capped with a sand/cement mortar and a capping plate pressed down and left in place for a further 24 hours under the same conditions. This was to give the specimens a smooth top surface.

The following day the specimens were demoulded and stored under some of the various curing conditions :

a) 0 days wet cured - the specimens were stored in a temperature room at 23°C +- 1°C and 50% RH until tested,
b) 3 days wet cured - the specimens were stored in water at 23°C +- 1° C for 3 days and then removed and stored in the temperature room until tested,
c) 7 days wet cured - the specimens were stored in water at 23°C +- 1° C for 7 days and then removed and stored in the temperature room until tested,
d) 28 days wet cured - the specimens were stored in water at 23°C +- 1° C for 28 days and then removed and stored in the temperature room until tested.

Three of the cylinders were used as creep test specimens and the other two cylinders were used to measure the drying shrinkage.

8.2.2. Creep testing method:

The creep strain was determined according to the ASTM C512 - 66T (Ref.3.).

The specimens were always air dried for at least one day before testing. Three pairs of targets, equally spaced around the cylinder perimeter, were attached to the specimens. The targets were made of brass discs with stainless steel balls fixed on. Each pair of targets was positioned 100mm apart, placed equidistant from the ends of the specimen.

The diameter of the pressure plate placed at the ends of the cylinders was 5mm smaller than the cylinders and in some cases resulted in crumbling of the edges (Fig.8.2.). The effect of this on the readings was negligible as the targets were placed in the middle third of the specimen so as to avoid the end effects of the load on the cylinders.

Fig.8.2. Demonstration of the cracking due to the pressure plate being smaller than the cylinder.

Fig.8.3. Each creep rig was loaded with two cylinders from two different mixes.

In order that the exposed surface area of each companion cylinder was the same as that of the loaded specimens, the ends of the companion cylinders were covered with discs made of rhinoboard.

Load calibration of each test rig was carried out before the tests were begun. A 100 kN load cell was inserted in each rig in turn and the rig loaded to various pressures with the hydraulic hand pump. A graph was plotted of the applied pressure vs the reading on the dial gauge (see Appendix C).

On the day of loading, three cubes from the same mix batch were crushed to establish the compressive strength of the concrete. An average of 80% of the cube strength was taken to be the cylinder compressive strength for the same mix.

The longitudinal strain of the loaded cylinders was measured with a Pfender precision strain gauge with a gauge length of 100 mm. A direct read out accuracy of 1 μm represents a strain of 1 X 10^{-5}. This gauge was kept in the same room with the test specimens to eliminate temperature effects on the gauge. The strain due to the drying shrinkage was measured on the companion cylinders with the same gauge.

Initial measurements for each of the cylinders (including companion cylinders) were taken immediately before the cylinders in the test rigs were loaded to no more than 40% of the compressive strength of the cylinders (Ref.3.). A second set of measurements were taken immediately after the loading to determine the elastic strain. Although these values did not conform to the standard test for Young's modulus (see chapter 6) in that the specimens were not loaded and unloaded in the standard way, they do however give some indication of the relative values of E for individual specimens.

After this the strains were measured every day for the first week, every week for the first month and then at two week intervals until the concrete cylinders had been under constant load for three months. Unfortunately due to time constraints, each test had to be terminated after 90 days of sustained load. The final creep results are therefore 90 day values throughout.

The creep strain was obtained by subtracting the strain (due to shrinkage) of the companion cylinder from the strain of the loaded specimen. In addition to excluding that portion of the total strain due to shrinkage of the concrete, this procedure also eliminated the effects of any temperature variations. The total creep strain is the sum of the creep strains for each measurement interval, less the initial elastic strain. The specific creep is calculated for each loaded specimen by dividing the total creep strain (basic + drying) by the stress applied on the concrete specimen.

The creep factor is calculated by multiplying the specific creep by the Young's modulus of the concrete at the age of loading.

8.3. RANGE OF MIXES USED

GRADE 30 MPa CONCRETE	DAYS WET CURED							
	0			3	7			28
AGE AT LOADING	7	28	90	3	7	28	90	28
0 % fly ash	X	X	X		X	X	X	X
30 % fly ash	X	X	X		X	X	X	X
50 % fly ash	X	X	X		X	X	X	X

Table.8.1. Range of low strength mixes used.

GRADE 50 MPa CONCRETE	DAYS WET CURED							
	0			3	7			28
AGE AT LOADING	7	28	90	3	7	28	90	28
0 % fly ash	X	X	X	X	X	X	X	X
15 % fly ash	X	X	X	X	X	X	X	X
30 % fly ash	X	X	X	X	X	X	X	X

Table.8.2. Range of high strength mixes used.

The contents for concrete mixes with 50mm slumps are listed in Appendix A.

8.4. DISCUSSION OF RESULTS

Concrete may be regarded as a two-phase material consisting of hardened paste and aggregate. The structure of the hardened cementitious paste is complex and it is this component which gives rise to concrete creep as it responds to changes in load and environment in a time-dependent way. The aggregate imparts bulk and rigidity to the mix. Movement properties of the concrete will therefore then depend on the properties of the paste modified by the presence of the aggregate.

It should be noted that increasing the cementitious content of the mix at a constant water content leads not only to increased cement paste but also to a higher strength of the mix. The latter effect resists creep for the same stress/strength ratio and may offset or even exceed the increase in creep due to the increased cement content.

The specific creep is inversely proportional to the strength of concrete. Thus strength is a convenient, but approximate, measure of the state of the cementitious paste i.e. its composition and degree of hydration (Ref.4.).

The average creep factor of the three cylinders tested for each loading case listed in Table 8.1. and Table 8.2. has been plotted with respect to time in Appendix E. The final creep factors have been plotted against the compressive strengths (average of three cubes) at the age of loading (Fig.8.4.). The lines drawn indicate the mean average for each percentage fly ash present in each mix. All the results were plotted on this graph regardless of curing or age of loading in order to reduce the number of parameters and to establish if there were any trends related specifically to the strength of the concrete.

There is a definite trend of decreasing creep factor with increasing compressive strength of concrete, irrespective of age at loading for all percentages fly ash. It can also be observed that mixes with fly ash have lower creep factors than OPC mixes, however further than that, no other trends were displayed for increasing percentages of fly ash.

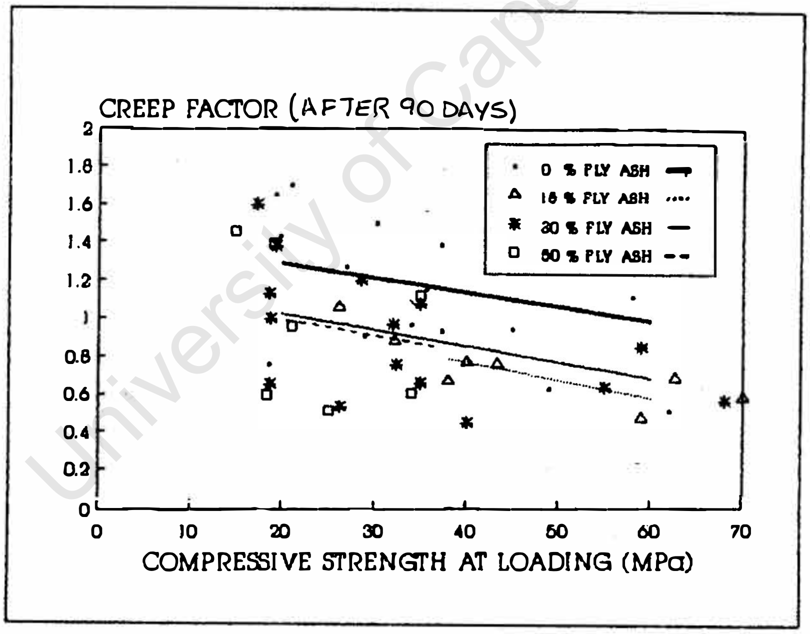

Fig.8.4. Creep factor vs the compressive strength at loading for all mixes investigated in Table 8.1. and 8.2.

Fly ash concrete subjected to a certain sustained loading (stress/strength ratio) has been shown by Dhir (Ref.5.) to exhibit lower creep strains than the corresponding OPC concrete. The NBRI stated that after 18 months of loading, the specific creep strain of the fly ash concrete was lower (19% to 39%) than the OPC concretes (Ref.6.). The Agrement Board of S.A. support this observation by stating that fly ash concrete had a lower creep factor than OPC concrete. (Ref.7.)

This reduction in creep can be up to 50%, depending upon the mix proportions and the age of the concrete when the load is applied and is usually explained as the consequence of the greater gain in strength with time of the fly ash concrete (Ref.5.). This gain in strength with time of the fly ash concrete was discussed in Chapter 5.

A more recent study by Dhir (Ref.5.) reported lower creep values for fly ash for which there was little gain in strength during the loading period. The explanation put forward related to the higher C/W ratio in the case of fly ash concrete mixes. The reduction in creep was shown to be dependent on mix design strength, which in turn is linked to C/W ratio.

Dhir suggests that the mechanism for this creep reduction is the reduction in water demand that fly ash allows. Since creep is linked to the relocation of water within the cementitious paste, the reduction of water in the paste and the higher C/W ratio mean that there is less potential for creep.

Although it is the hardened cement paste that creeps as the aggregate is usually inert, the aggregates have two effects on paste shrinkage, viz "restraint" and "dilution". The former term refers to the fact that concrete shrinkage will reduce with increasing stiffness. The stiffness of the aggregate restrains the potential creep by offering rigidity. The latter term refers to the fact that shrinkage of concrete will decrease with decreasing paste contents. The relative volume of the creeping material, the hardened cementitious paste, is reduced by the presence of the aggregate, ie dilution. (Ref.8. and Ref.9.).

It was reasonable to assume that the size, grading and stiffness of the aggregates would not affect the creep comparisons in this thesis as all the testing was done with the same aggregates. The real factor is the quantity ("dilution") of the aggregates. Although the volume of stone was increased with the increase in the percentage of fly ash present in a mix, the total volume of the aggregate did not change much from mix to mix. In Table 8.3. it can be seen that the variation in aggregate content is small and therefore the effect of changing volumes of aggregate on the creep of the mixes in this thesis is minimal.

	30MPa	50MPa
0 %	69.6%	67.0%
15 %		67.0%
30 %	71.0%	66.5%
50 %	71.0%	

Table.8.3. Percentage volume of total aggregate present in each mix.

The aggregate content and the content of the hydrated cement paste are complementary so that considering the effect of the one or the other is strictly equivalent. Hence, an investigation of the creep factor verses the volume of the cementitious material is not necessary, as the volume of cementitious material does not vary much with the increase in the percentage of fly ash..

Since the principal part of creep of concrete is considered by most investigators to be occurring in the hydrated gel, degree of hydration, curing and age at loading are relevant only in so far as they affect the amount and quality of the hydrated gel (Ref.10.).

The effect of hydration is to decrease both the porosity and the moisture content and hence the amount of irrecoverable creep. Water is held in the paste in essentially 3 ways (Ref.8.),
1)as water of hydration of the cement gel, which can be termed non-evaporable water,
2)as gel pore water adsorbed into the pores of the cement gel, this being evaporable over the range from 40% to 0% relative humidity,
3)as capillary pore water held outside the cement gel in the larger cavities. This water is more easily evaporable and will migrate out of the cement paste at a relative humidity of greater than 40%.

Moisture content is a relevant parameter in so far as the rate of moisture loss from a specimen of a concrete is a function of its moisture content. Therefore the rate and magnitude of creep will be dependent on the specimen's moisture content at the time the specimen is loaded. Part of the total creep is believed to be due to the migration of water within the voids of the specimen caused by the action of the loads and it is known that creep diminishes as the free water diminishes (Ref.10.).

It was established in Chapter 3 that fly ash mixes require less water to obtain the same workability. One would expect a lower creep factor for fly ash concrete because of this characteristic.

Coupled to the original volume of water added to the mix, the volume of moisture present in the concrete at the time of loading is obviously dependent on the type of curing prior to the loading.

When considering the graph for high strength concretes (Fig.8.5.) it is obvious that the length of wet curing has made an impact on the creep factor, resulting in a downward trend for increased wet curing. It can not be confidently said that the curing had an effect on the creep factor of the low strength mixes viz. the mixes with 0% and 50% fly ash present in the cementitious material. But the mix with 30% fly ash did show a downward trend. Once again it can be observed from the graphs that the inclusion of fly ash in the concrete mixes results in similar if not less creep than OPC concrete.

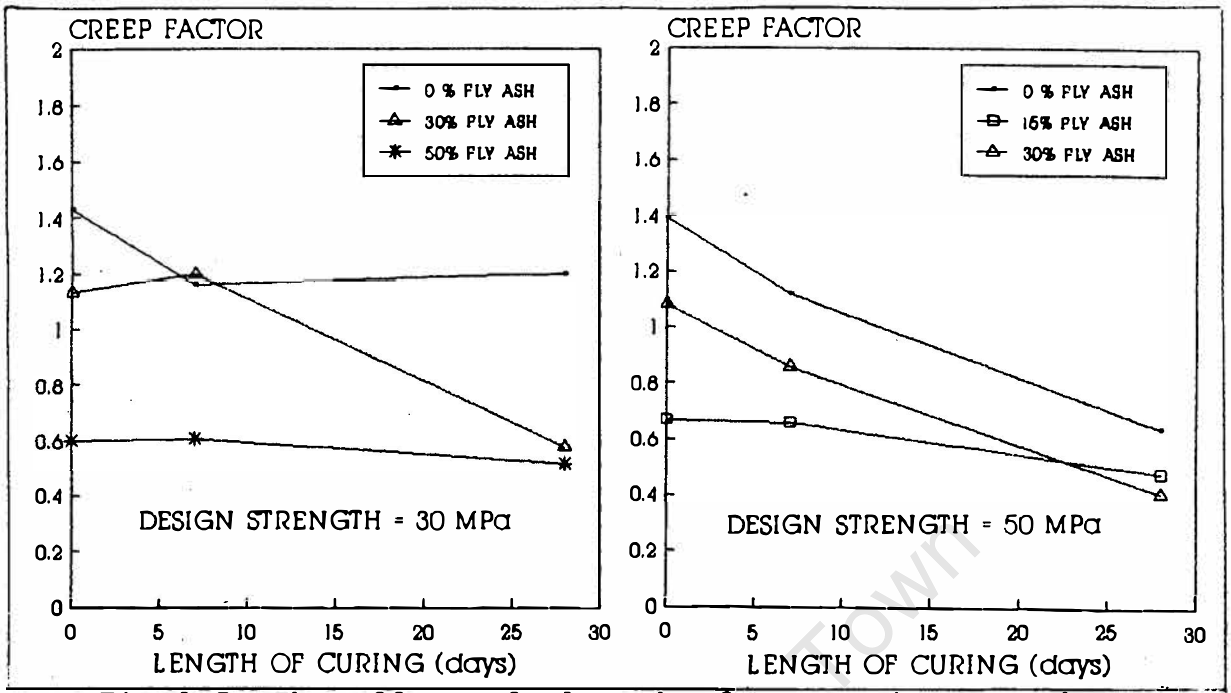

Fig.8.5. The effect of length of wet curing on the creep factor for mixes with various percentages of fly ash loaded at 28 days.

The length of time for wet curing has a three-fold effect. Firstly with no wet curing before loading, the specimens will contain less moisture and will consequently creep less (Ref.1.). However, they also have lower strengths as discussed in Chapter 5 and may, as discussed above, cause higher creep. The latter effect may offset or even exceed the decrease in creep due to the reduction in moisture.

Secondly, concretes that are loaded after a day of drying and allowed to dry under the compressive load, will experience greater creep than had they remained saturated, due to the additional component of drying creep (Ref.1.). This could offer some explanation for the fact that the high strength mixes had a reduction in creep when cured longer in water compared to the fairly similar creep factors of the lower strength concretes. The high strength concrete may have been able to seal themselves off fully by being cured in water for 28 days. They did not lose much moisture when exposed to the atmosphere when loaded and hence did not have much drying creep.

Thirdly, the water required for long term hydration of the cementitious paste may be lost when the specimens are dry cured resulting in an increase in the basic creep.

With reference to Fig.8.6. concrete loaded when 3 days old exhibit higher creep factors than those loaded at 28 days after being cured in water until loaded. Perhaps the younger specimens were experiencing the additional component of drying creep. The older specimens had undergone almost full hydration. One can observe that the mixes containing fly ash exhibit lower creep factors than the mixes with only OPC. The fly ash mixes do not show increasingly lower creep values with increasing loading ages relative to the OPC mixes.

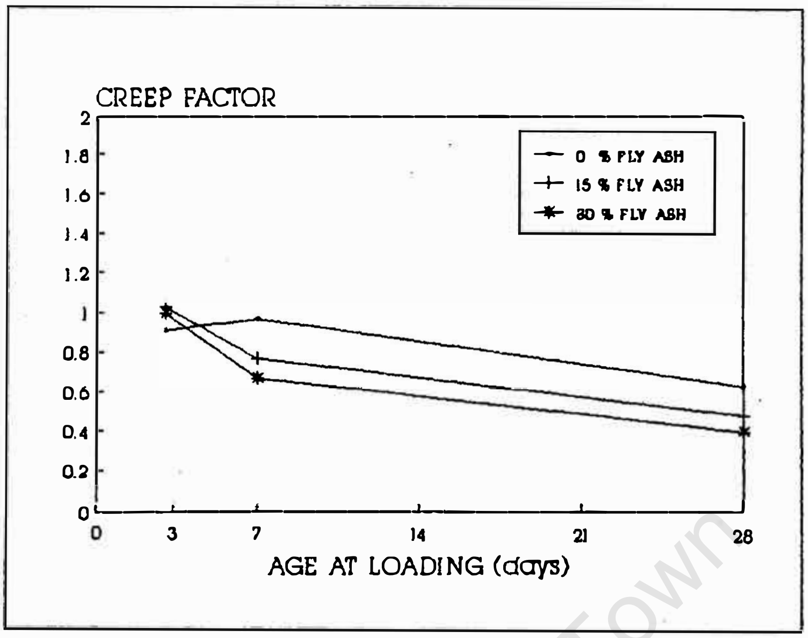

Fig.8.6. The creep factor of high strength concrete samples wet cured until loaded for various percentages of fly ash.

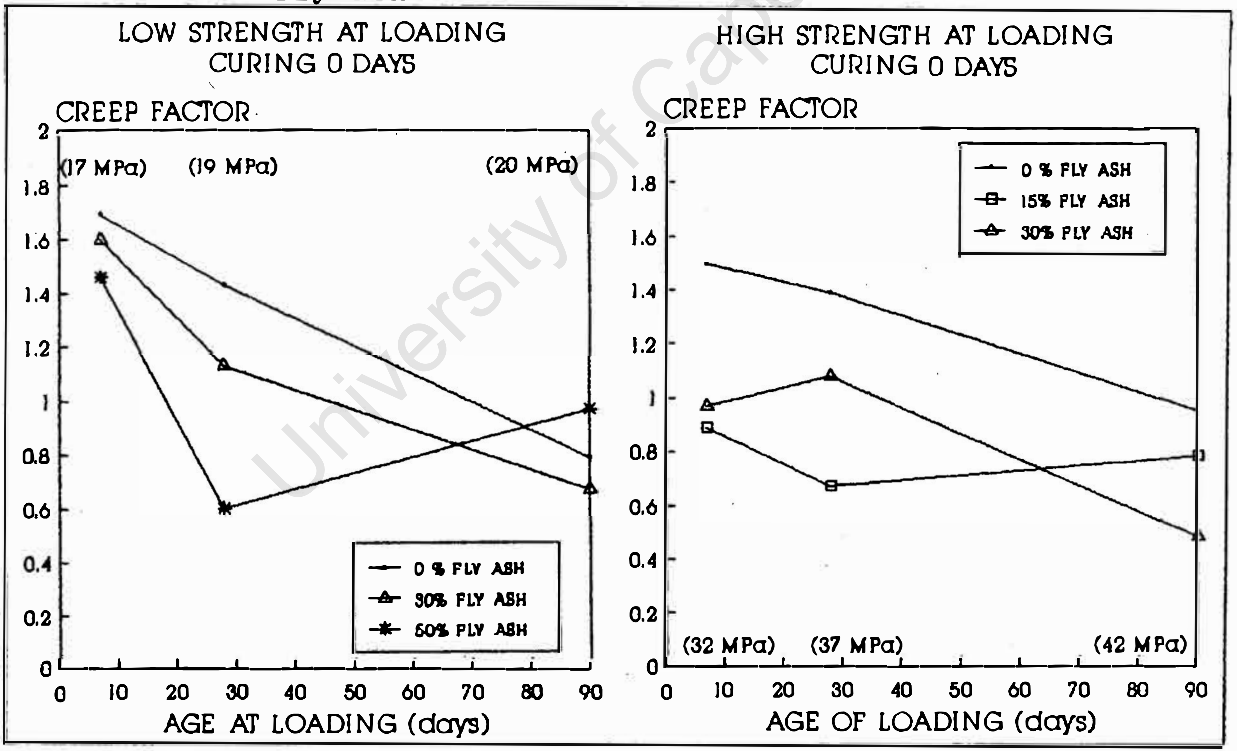

Fig.8.7. Creep factor vs age at loading for 0 days wet curing. The average strength at loading is in brackets.

The age of the concrete is a factor in creep in so far as the age influences the degree of hydration and the development of strength. Wallo and Kesler observed that the same concrete loaded at early age yields larger creep strains for a given time under load compared to the same concrete loaded at a later stage (Ref.10.).

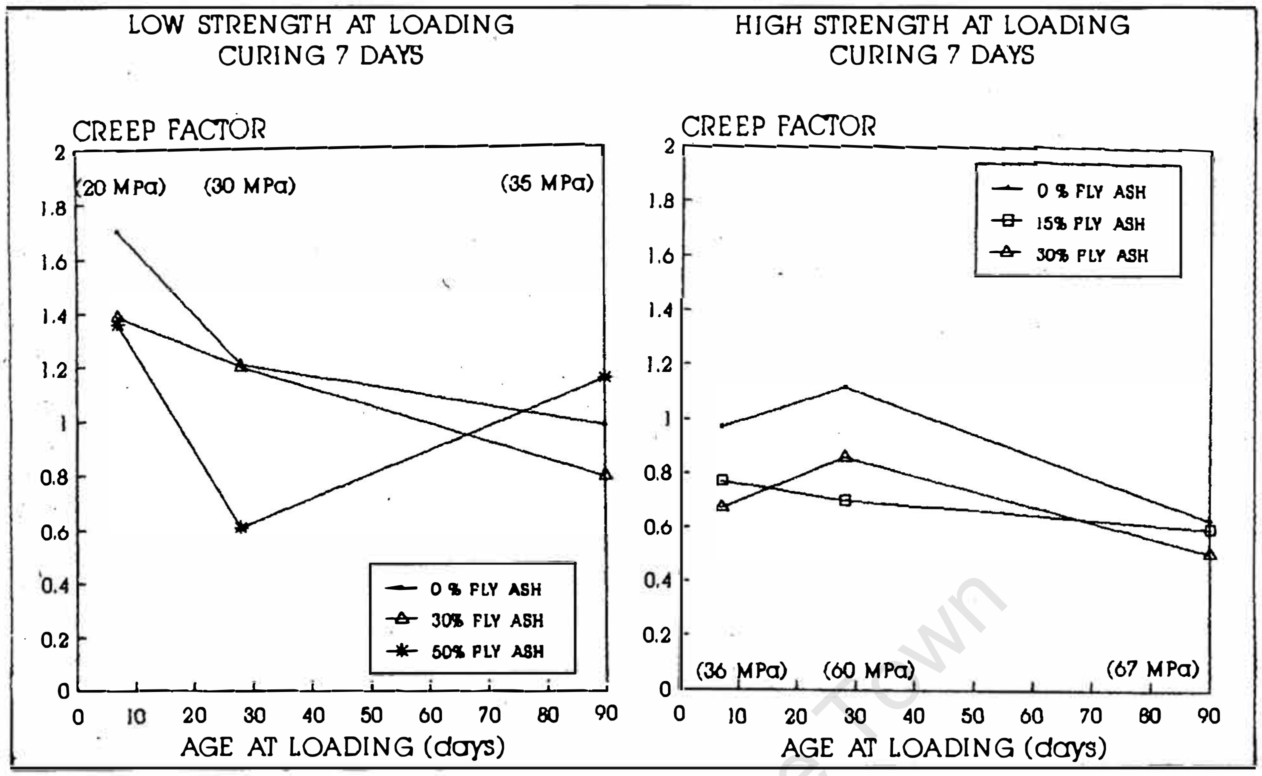

Fig.8.8. Creep factor vs age at loading for 7 days wet curing. The average strength at loading is in brackets.

The foregoing observation is also evident in the results plotted in Fig.8.7. and Fig.8.8. For all ranges of curing and strengths, specimens loaded at 90 days exhibited lower creep values than the specimens at 7 days. The older the concrete specimens the more mature the concrete which results in higher strength and as stated previously. the less the creep will be (see Fig.8.4.).

Where tests were performed by Owens (Ref.11.), the creep strain of the concrete containing fly ash has been found to reduce proportionately with the amount of fly ash used. Marked reductions in creep were observed at later ages as the amount of fly ash increased to 30%.

It can once again be observed in Fig.8.7. and Fig.8.8. that concrete containing fly ash creeps less than OPC concrete. The 30% and 15% fly ash mixes displayed lower creep factors than OPC mixes but the 50% fly ash concrete specimens did not display the same general trend when loaded at 90 days. A definite trend for concrete with high percentages of fly ash loaded at older ages is not possible to observe. The fly ash mixes then do not show increasingly lower creep values with increasing loading ages relative to the OPC mixes.

8.4.1. The influence of the size of the specimen on the creep.

A simple investigation into the effect of the size of the test specimen was conducted. The large (150mm diameter) cylinders that were originally used to determine the Young's modulus of the concrete mix were loaded at 90 days in a spring loaded rig. The stress imposed on these cylinders was equivalent to the stress imposed on the normal 105mm diameter creep cylinders.

WET CURING	0 DAYS		7 DAYS	
DIAMETER OF CYLINDER	105mm	150mm	105mm	150mm
0% FLY ASH	0.76	0.87	0.94	0.85
30% FLY ASH	0.66	0.79	0.76	0.66

Table.8.4. The creep factors for different size cylinders loaded at age 90 days.

The larger specimens also show the trend that concrete with fly ash creeps less than OPC concrete. Further, for the 7 day wet cured specimens, the larger specimens show a tendency to creep less than the smaller specimens when loaded at an age of 90 days. This characteristic is not evident for the specimens not cured in water but then the largest difference between the creep factors of the large and small cylinders is 0.13, which is hardly significant.

The explanation of the size effect in terms of the water loss to the ambient air can only apply if drying creep takes place, because in basic creep no loss of water to the outside is involved. In practical cases however, creep and shrinkage operate simultaneously. Thus in a small specimen a greater part of the concrete is subjected to drying creep while drying takes place and a larger creep is therefore recorded. Neville (Ref.12.) suggests that a greater degree of hydration will have taken place and a higher strength will have developed in the core of the larger specimen so that the creep response to the creep-while-drying condition will be small.

Several investigators have indicated an influence of the size of the specimen on creep. The measured creep decreases with an increase in the size of the specimen, but when the specimen thickness exceeds about 900mm, the size effect becomes negligible (Ref.12.).

8.5. THE CREEP OF PUMP MIXES CONTAINING FLY ASH.

Pumpable concrete must be proportioned in such a way that enough lubrication is provided to produce a permanent lubricating surface in the pipe.

These mixes were designed to have slumps of over 100mm. To determine whether the mix was pumpable or not, a slump cone was inverted and placed on the floor. It was filled with concrete and compacted in three layers. When the cone was full, it was lifted up so that the concrete could flow out of the bottom opening. If the concrete mix did indeed flow out smoothly, then it was classified as a pumpable mix. The pump concrete mix proportions are listed in Appendix D.

CURED UNTIL LOADED AT:	7 days	28 days	
DESIGN STRENGTH:	50 MPa	50 MPa	30 MPa
0 % FLY ASH	*	*	*
30 % FLY ASH	*	*	*

Table.8.5. Range of pump mixes used

In order to get the range of concrete mixes listed in Table 8.5. to have this pump characteristic, the aggregate content in each mix was decreased by about 100kg per mix and the water content was increased by about 20 liters and hence the cementitious material was also increased by about 40 kg. (See Appendix D)

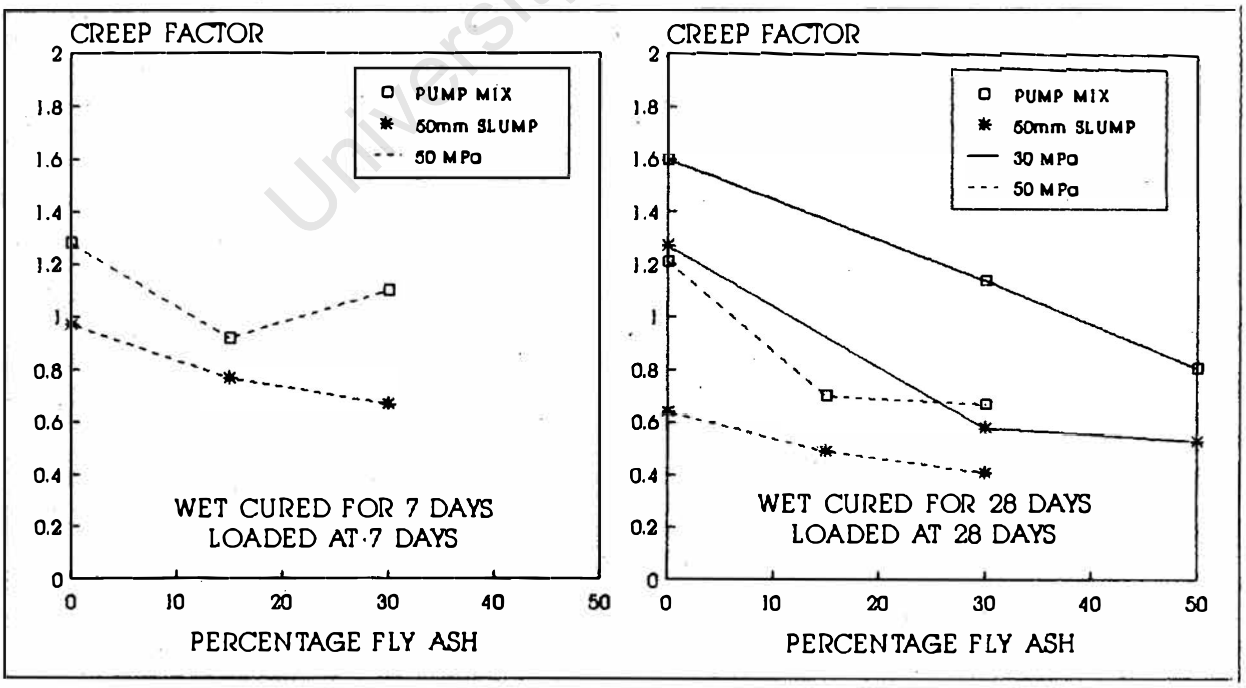

Fig.8.9. Creep factors of pump mixes compared to normal mixes, both of which have been wet cured until loaded for the range of mixes specified.

One would thus expect higher creep values for the pump mixes. The was a lesser "dilution" of the paste by the aggregate present and also an increase in the paste and water ~~moisture~~ content. This was indeed the case and can be observed in Fig.8.9. above. The development of the creep factors with time of the pump mixes is plotted in Appendix F.

The results show that the pump mixes have higher creep factors than the non-pumpable mixes with slumps of 50mm for all the curing and loading cases. Further the decrease in creep factor for increasing percentages of fly ash is confirmed for pump mixes as well. Finally one can also observe that for higher strengths, lower creep factors were obtained.

8.6. CONCLUSIONS

From the results and graphs above the following can be concluded:

- concretes containing classified Lethabo fly ash have lower creep factors than OPC concretes, although no clear trends were apparent for increasing percentages of fly ash;

- the creep factor of concrete specimens, loaded to the same stress/strength ratio, decreases with increasing compressive strengths, irrespective of age at loading, curing or percentage fly ash present;

- the usual increase in the stone content of fly ash mixes does not increase the total volume of aggregates present in a mix and hence the role of aggregates in the reduction of the creep factor is minimal for fly ash mixes;

- the water ~~moisture~~ contents of fly ash mixes are lower than the OPC mixes, which is relevant in the reduced creep factors of fly ash mixes;

- the increased duration of wet curing results in a downward trend of the creep factor;

- for all ranges of curing and strengths, specimens loaded at 90 days exhibited lower creep values than the specimens loaded at 7 days.

- the difference in size of the 105mm diameter cylinder and the 150mm diameter cylinder on the creep factor of the concrete was found to be negligible;

- the pump mixes had higher creep factors than the normal mixes with a slump of 50mm for all the strength, curing and loading cases considered.

- the pump mixes also exhibited decreasing creep factors for increasing percentages of fly ash present in the concrete mixes.

It should be noted that the above results and conclusions were derived from a limited number and range of mixes and the figures quoted should not be taken as applying generally to any fly ash.

8.7. REFERENCES

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9
THERMAL MOVEMENT

9.1. INTRODUCTION

When concrete is exposed to a change in temperature it expands when heated and contracts when cooled. Concrete has a positive coefficient of thermal expansion, which can be defined as the change in linear dimensions per unit length divided by the temperature change. Thermal expansion and contraction of concrete varies with factors such as aggregate type, richness of mix, C/W ratio, temperature range, concrete age and relative humidity of the air (Ref.1.).

This property of concrete could provide a problem in structures which are exposed to large temperature fluctuations. The effect of fly ash in the concrete mix on the coefficient of thermal movement was investigated in this thesis.

9.2. METHOD OF TESTING

The test method selected to establish the coefficient of thermal movement of the range of concrete mixes was ASTM C 157 (Ref.2.).

The test required the casting of prisms (280 X 50 X 50mm), with a brass anvil at each end for the accurate measurement of length. Six prisms (three mortar and three concrete) were cast for each mix investigated. The prisms were cured in the moulds for 24 hours in a fog room with a relative humidity of 90%, then demoulded.

The prisms were cured in water at a temperature of 23° C +- 1° C for 28 days. After the specified curing, the prisms were surface dried in the constant humidity room at 23° C +- 1° C and 50% relative humidity for 24 hours, before establishing the original length by measuring the prisms with a 300 mm micrometer screw gauge.

The prisms were then placed in the fridge set at a constant temperature of 0° C +- 1° C for 24 hours. The prisms were individually removed from the fridge and measured immediately with the micrometer and the result recorded. The prisms were then transferred to an oven set at 30° C +- 1° C and a relative humidity of less than 25%. The prisms were individually removed from the oven after 24 hours and measured immediately with the micrometer and the result recorded.

For practical reasons, it was not possible to raise the temperature in the constant humidity room and the oven had to be used instead. Hence it was not possible to keep the humidity constant.

The same prisms were then placed back in the refrigerator and cooled to 0° C +- 1° C and the change in length measured after 24 hours. Then the prisms were allowed to warm up in the humidity room to 23° C for a further 24 hours and the change in length measured and recorded.

For each change in temperature the thermal strain was calculated by dividing the change in length by the original length. The average of the results for each concrete and mortar type was taken. For each case, the coefficient of thermal movement was obtained by dividing the thermal strain by the change in temperature. To obtain the coefficient of thermal movement for the mortar and concrete of each mix, the average of the values obtained for the four temperature changes is taken.

For a given mix, the magnitude of thermal expansion or contraction at temperatures from freezing to 65° C is the same for each unit temperature change, so the coefficient of thermal expansion is a constant figure (Ref.3).

9.3. RANGE OF MIXES USED

FLY ASH	c)28 DAYS WET CURED
0%	X #
30%	X #

x) Grade 50 MPa design strength
#) Grade 30 MPa design strength

Table.9.1. Range of mixes used for thermal movement testing

Due to the increased stone content with increasing percentages of fly ash (see Fig.4.1.) it was decided to do thermal movement tests on both mortar and concrete prisms.

9.4. DISCUSSION OF RESULTS

The coefficient of thermal expansion of concrete depends on the composition of the mix, on its state of hydration and its moisture content at the time of the temperature change.

The results show that different coefficients of thermal movement were obtained when the prisms were heated than when they were cooled. It can also be seen that the mortar prisms displayed larger variations than the concrete prisms (see Fig.9.1.). This could be attributed to the fact that drying shrinkage took place when the prisms were placed in the oven at a relative humidity of less than 25%. It was previously established in Chapter 7 that concrete (containing stone) shrinks less than mortar when dried.

The influence of the moisture condition applies to the paste component and is due to the fact that the thermal coefficient is made up of two parts, the true kinetic thermal coefficient and a swelling pressure. The swelling pressure arises from a decrease in the capillary tension of water held by the paste with an increase in temperature (Ref.4.). The reduction of water by drying would result in less swelling pressure and therefore less expansion when heated.

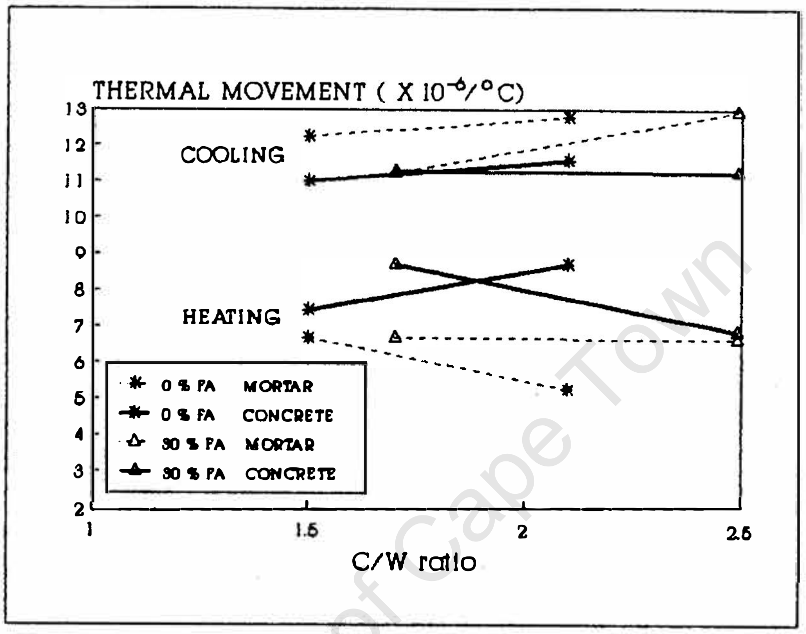

Fig.9.1. Coefficients of thermal movement for cooling and heating of specimens vs the C/W ratio.

The influence of the mix proportions on the coefficient of thermal movement arises from the fact that the three main constituents of concrete, the cement paste, the fine and coarse aggregate, all have dissimilar thermal coefficients. The coefficient of concrete is a resultant of the three values.

The aggregate comprises from 80% to 85% by volume of the concrete, so its thermal properties greatly influence the behaviour of the concrete. Thermal expansion can vary widely among aggregates because of the differences in the mineralogical content (Ref.3, Ref.5). The coefficient of linear expansion for concretes containing Malmesbury hornfels from the Cape Peninsula is approximately 10.9 X 10^{-6} /°C (Ref.6).

Cement paste occupies only about 15% to 20% of the concrete volume. Cement paste has a coefficient of thermal expansion that is a function of moisture content and this effects the concrete expansion. When incorporated in a concrete the influences of different cement coefficient is therefore small and the use of different cements has only a minor effect on the thermal expansion of the concrete (Ref.6). This would appear to be also the case when fly ash is added to the cementitious material.

When studying Fig.9.1., there does not seem to be any obvious trend due to the use of fly ash. The small increase in the volume of stone in the fly ash mixes (see Fig.3.4.) does not appear to have any effect on the concrete prisms. The reduction in the water content of the fly ash mixes (see Fig.3.3.) also does not result in any obvious trend when comparing the coefficients of thermal movement.

Little has been reported on the thermal movement of fly ash concrete and the available results are of a random nature with regard to the effect of the inclusion of fly ash. There appears to be some tendency for fly ash to exhibit a slightly lower value than the corresponding OPC concrete, but any difference is negligible for practical purposes (Ref.7).

9.5. CONCLUSIONS

From the results, graphs and references above the following can be concluded:

- the classified Lethabo fly ash present in the concrete mix does not have a noticeable effect on the thermal movement of both the mortar and the concrete prisms;

- the test prisms did not give the same coefficient of thermal movement when heated as they did when cooled. This could be attributed to the drying out of the prisms;

- the mortar prisms were affected to a greater extent by this "drying out effect" than the concrete prisms, when exposed to heating.

It should be noted that the above results and conclusions were derived from a limited number and range of mixes and the figures quoted should not be taken as applying generally.

9.6. REFERENCES

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10
CONCLUSIONS

When drawing conclusions from the work done in this thesis , it must be noted that the observations were made from a limited range and number of mixes and results. Also a proper analysis of the long-term characteristics of the deformation properties was not possible due to time constraints.

In order to attain the same 28 day compressive strengths as the Ordinary Portland Cement (OPC) concrete mixes, higher cementitious material to water ratios are required for concrete mixes with classified Lethabo fly ash. The actual volume of cementitious material per mix is not greatly increased for increasing C/W ratios to obtain a given strength, as the presence of the classified Lethabo fly ash substantially reduces the water requirement of the concrete mixes.

It was found that due to the stickiness of the fly ash mixes, the slump test does not give a good indication of the workability of the mix for high percentages of fly ash present. This may have resulted in unnecessarily wet mixes in order to obtain the required slump. This may have influenced the results of deformation properties of the fly ash concretes. A more reliable form of establishing the workability and consistency of the fly ash mixes needs to be established.

The extent of the effect of fly ash in the concrete mix is dependent on the basis of comparison viz. C/W ratio or strength. For a given strength, fly ash concretes exhibit lower mortar excesses, reduced bleed volumes and rates and longer setting times. For a given C/W ratio the fly ash concrete also reduces bleed volumes and rates and has a longer setting time, but does not show any difference in the mortar excess. The author proposes that for future research on the fresh properties, the C/W ratio be used as the basis for comparison as the fresh properties are not directly dependent on the strength of the concrete.

The compressive strength development over long periods for concrete with classified Lethabo fly ash is higher than for OPC concrete. The compressive strength at early ages (7 days) of the fly ash concrete is lower than the OPC concrete for the same 28 day design strength, whereas the compressive strength at 90 days of the fly ash concrete is higher than the OPC concrete. The compressive strength development is higher for fly ash concrete with the increase of the percentage of classified Lethabo fly ash present in the cementitious material when cured in water for 28 days at 23° C. These are important factors when considering loading a concrete structure or specimen with fly ash present in the cementitious material.

Although the stone content was increased for increasing percentages of fly ash, the total volume of aggregates remained fairly constant for a given strength of concrete. So the effect of the aggregates on the deformation properties was virtually the same for all the percentages of fly ash included in the cementitious material. Any variation in the deformation properties for fly ash mixes are thus due to the matrix configuration of the paste.

Much of the literature available on the topic of deformation properties of concrete has conflicting conclusions. Although, in some cases the fly ash concretes deformed less than OPC concretes, no specific trend with increasing percentages of fly ash was noticeable in this research. The general trend of the deformation characteristics of the concrete mixes with various percentages of classified Lethabo fly ash present was that they did not differ greatly from the concrete mixes with Ordinary Portland Cement.

In most cases the 15% fly ash mixes caused a "kink" in the graphs plotted in this thesis and disturbed any possible downward trend that may have existed. On the other hand this may be a trend in itself, with the graphs peaking at 15% resulting in less deformation than at 30%. The deformations decrease steadily from 30% fly ash to 50% fly ash. This trend could illustrate optima at 15% and 50% fly ash and requires further investigation.

In this research, the Young's modulus of elasticity was not found to be affected by the percentage of fly ash and the elastic property of the fly ash concrete was similar to that of the OPC concrete for the same strength. However, higher static moduli of elasticity were obtained when the stone content was increased for increasing percentages of fly ash. The stone offered more rigidity to the concrete. However, when the dynamic modulus of elasticity was related to the stone content, no apparent trend could be observed for increasing percentages of fly ash. The total volume of aggregates present did not vary much and hence was not a relevant parameter in this investigation.

The small increase in the stone content for increasing percentages of fly ash, did not affect the drying shrinkage of the concrete prisms tested. For each type of concrete mix , it was established that an increase in C/W ratio resulted in higher drying shrinkage and that lower overall shrinkage values were obtained with longer wet curing. The reduction in the water requirement of the fly ash mixes did not noticeably contribute to the decrease in the drying shrinkage. It may be safely assumed that drying shrinkage for concrete with classified Lethabo fly ash is essentially the same as for OPC concrete.

Similarly, the classified Lethabo fly ash does not have a noticeable effect on the thermal movement of the concrete when compared to that of the OPC concrete. The effect of fly ash on the plastic shrinkage of freshly cast concrete still needs to be investigated as the literature is not consistent in the results obtained. More specifically, research is presently in progress at the University of Cape Town on the plastic shrinkage of concretes with classified Lethabo fly ash.

It has been established in this thesis that concretes containing classified Lethabo fly ash have lower creep factors than the OPC concretes, although no clear trends were apparent for higher percentages of fly ash. It was observed that for increasing strengths of concrete, the creep factor decreased. This is relevant to fly ash concrete as it has a higher long term strength development and one would expect a lower creep factor for fly ash concretes in the very long term. Due to time constraints this could not be investigated but is worth investigating with respect to structures that will be exposed to loads for many years.

The moisture contents of the fly ash mixes were lower than the OPC mixes. This property may be relevant in the reduction of the creep factor of the fly ash mixes. The pump mixes had higher moisture contents than the normal mixes with 50mm slumps.

The volume of the aggregates was not a variable in this thesis, except when designing the pump mixes where the volume of aggregate was decreased. The mixes designed for pumpability had higher creep factors than the mixes designed for slumps of 50mm for all strengths, curing and age at loading, due to the above two factors.

There was a downward trend of creep factor for increasing durations of wet curing as well as for concretes loaded at higher ages. These factor allowed the concrete to hydrate more and hence have improved compressive strengths. The creep of concretes with classified Lethabo fly ash loaded at early ages still needs to be addressed.

The size of the test sample for all the investigations, may have had some influence on the results recorded due to the high surface to volume ratio. The effect of the difference in size of the 105mm diameter cylinder and the 150mm diameter cylinder on the creep factor of the concrete was found to be negligible. A larger size difference is necessary for further investigation.

In conclusion then, the presence of classified Lethabo fly ash in concrete (made with local Western Cape materials) does not noticeably affect the deformation properties of the concrete for equivalent compressive strengths. Where some effect was noticed, the fly ash concretes displayed slightly lower deformations.

11
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APPENDICES

APPENDIX A
Mixes used in this thesis designed for a 50mm slump.

APPENDIX B
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APPENDIX C
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APPENDIX D
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APPENDIX E
Creep factor vs the age under load for the range of normal concrete mixes tested, for various wet curing durations and ages at loading.

APPENDIX F
Creep factor vs the age under load for the range of pump mixes tested, for various wet curing durations and ages at loading.

APPENDIX A

Mixes used in this thesis designed for a 50mm slump

PERCENTAGE FLY ASH PRESENT	MIX MATERIALS	TARGET STRENGTH AT 28 DAYS		
		10 MPa	30 MPa	50 MPa
0 %	C/W Ratio	.90	1.50	2.10
	Cement (OPC)	198 kg	309 kg	420 kg
	Fly ash	0 kg	0 kg	0 kg
	Stone	1050 kg	1050 kg	1050 kg
	Sand	856 kg	800 kg	723 kg
	Water	220 kg	206 kg	200 kg
15 %	C/W Ratio			2.37
	Cement (OPC)			369 kg
	Fly ash			65 kg
	Stone			1083 kg
	Sand			705 kg
	Water			183 kg
30 %	C/W Ratio	1.00	1.70	2.53
	Cement (OPC)	139 kg	214 kg	321 kg
	Fly ash	59 kg	92 kg	138 kg
	Stone	1102 kg	1102 kg	1102 kg
	Sand	846 kg	794 kg	653 kg
	Water	198 kg	180 kg	180 kg
50 %	C/W Ratio	1.10	2.20	3.20
	Cement (OPC)	102 kg	179 kg	284 kg
	Fly ash	102 kg	170 kg	284 kg
	Stone	1127 kg	1127 kg	1127 kg
	Sand	835 kg	766 kg	508 kg
	Water	186 kg	162 kg	175 kg
70 %	C/W Ratio	1.45	2.70	3.50
	Cement (OPC)	72 kg	122 kg	189 kg
	Fly ash	168 kg	284 kg	441 kg
	Stone	1151 kg	1151 kg	1151 kg
	Sand	831 kg	687 kg	388 kg
	Water	160 kg	159 kg	180 kg

APPENDIX B

Development of a plastic shrinkage test apparatus.

1. Investigations at the University of Natal into the restrained plastic shrinkage of concrete made use of a test rig constructed as illustrated in Fig.B.1. (Ref.a).

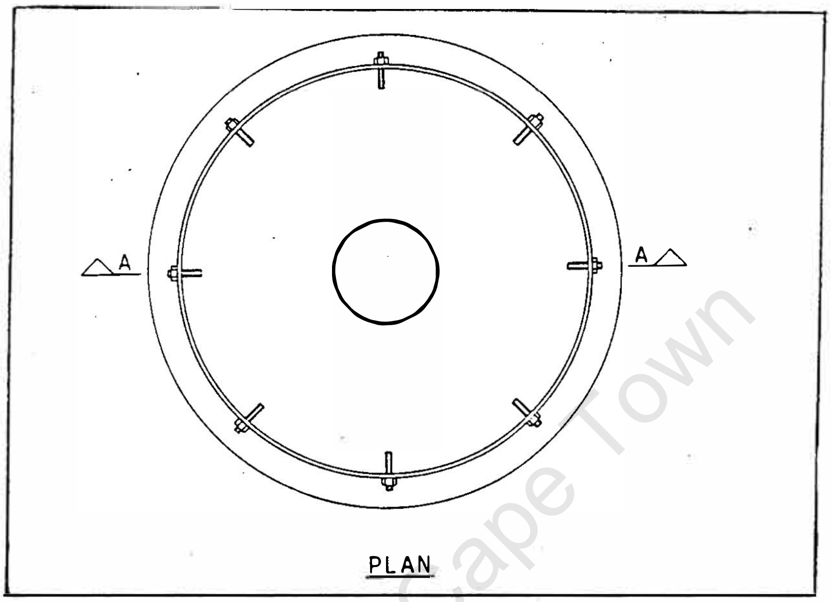

Fig.B.1. Plastic shrinkage testing rig used at Natal University (Ref.a.)

Samples of a concrete mix were cast into the above test rig onto polythene sheeting over shutterboard under direct sunlight. A fan was directed over each sample to aid evaporation and help instigate plastic shrinkage cracking. Each specimen was observed at hourly intervals after casting to check for cracking.

The crack numbers and sizes were compared for various mixes. In some cases it was possible that the crack pattern was distributed to give very fine and shallow cracks, not visible to the eye even when aided with a magnifying glass.

2. For this reason, an attempt has been made at the University of Cape Town to measure the plastic shrinkage by measuring the actual movement of unrestrained concrete.

A batch of concrete was mixed and then sieved to remove the stone from the mix. The remaining mortar was placed in a mould (100mm long X 30mm wide X 10mm deep) and vibrated gently to get rid of the air bubbles. The mould was then floated in a bath of mercury. The bottom plate was gently removed and then the side supports of the mold were lifted up, leaving the prism of mortar floating on the mercury.

The prism was floated on mercury with the aim of providing an unrestrained test sample that was free to move without being held by friction. Two targets were placed near the ends of the sample and the distance between them was read with the aid of a travelling microscope, read at regular intervals and the shrinkage calculated.

Fig.B.2. Travelling microscope and a specimen floating in a bath of mercury.

The test apparatus was kept in a fume cupboard with an extractor fan. The fan provided a steady flow of air over the sample and also removed any poisonous mercury fumes. It was not possible to control the temperature and the humidity of the air in the fume cupboard. Plastic shrinkage is very sensitive to these two parameters as they determine the rate of drying and the volume of water removed from the surface.

It can be seven for results obtained in Fig.B.3. that it is possible to measure the amount of plastic shrinkage undergone by the concrete with the test method described above. It can also be seen that the temperature and relative humidity do affect the magnitude of shrinkage (Fig.B.4.).

It became apparent that good repeatability was not possible under these conditions. With the fluctuations of the temperature and humidity, the results were not consistent. Whether this inconsistency can only be attributed to the atmospheric conditions in the fume cupboard or the lack of repeatability of the test method itself can be debated. However, good repeatability were observed by the results of the tests done under similar conditions.

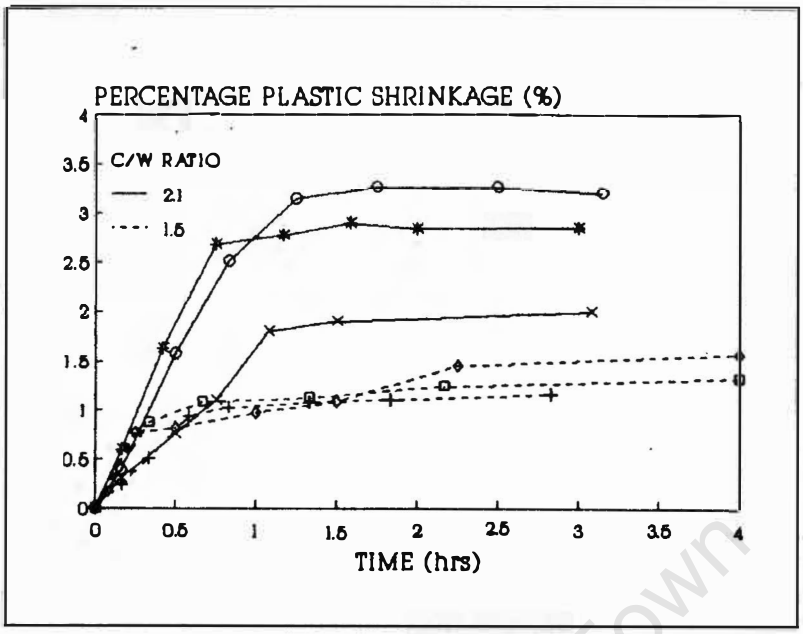

Fig.B.3. Plastic shrinkage results for high and low C/W ratios for OPC mixes

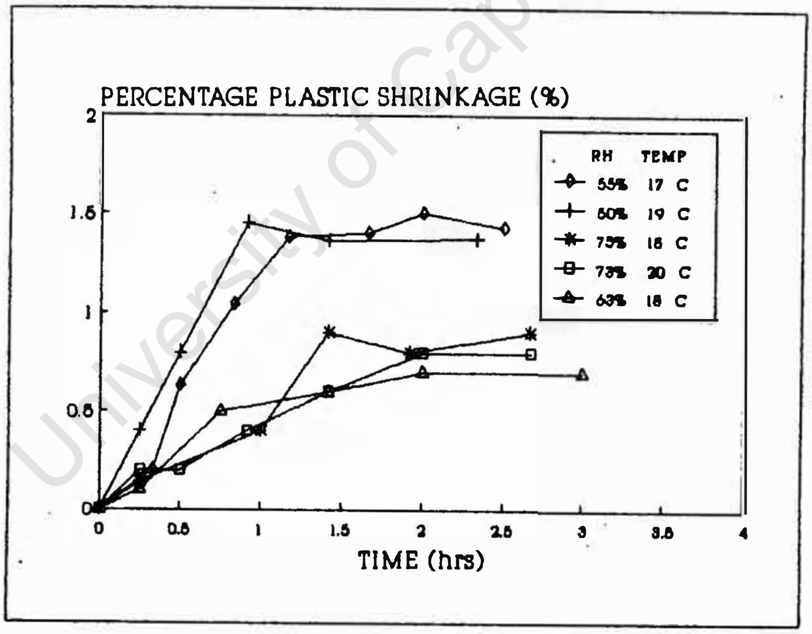

Fig.B.4. Plastic shrinkage results for OPC concrete with C/W ratio of 1.5 to illustrate the effects of uncontrolled temperature and humidity on the mortar sample.

The temperature room, in which most the testing in this thesis was carried out, would provide constant atmospheric conditions, but some concern was expressed as to the safety of using mercury in a closed environment.

Continuation of this test method seemed fruitless and the investigation was terminated.

3. The problem has since been set as an undergraduation thesis topic under the authors guidance. The method which is currently being developed by this student also attempts to make the sample unrestrained by suspending the sample with thin wires as illustrated in Fig.B.5. The movement of the sample is determined by measuring the distance between the outermost strands with the aid of a theodolite at specific time intervals.

   It is possible to carry out the test under controlled conditions in the temperature room as there are no toxic fumes. This method is currently giving good repeatability. At the time when this thesis was submitted, no tests had yet been done on fly ash mixes.

Fig.B.5. Specimen suspended by thin wires.

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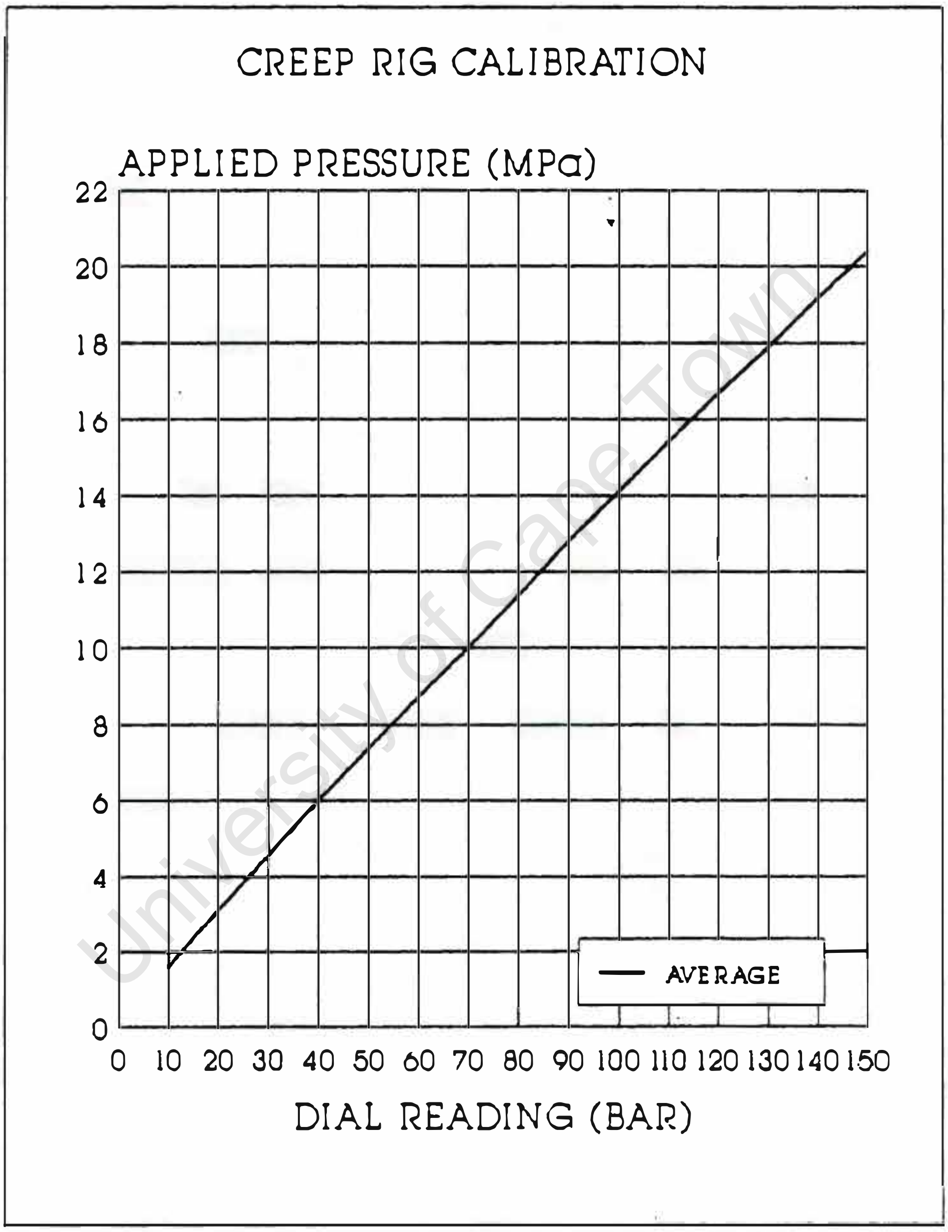
APPENDIX C

Creep rig calibration curve.



APPENDIX D

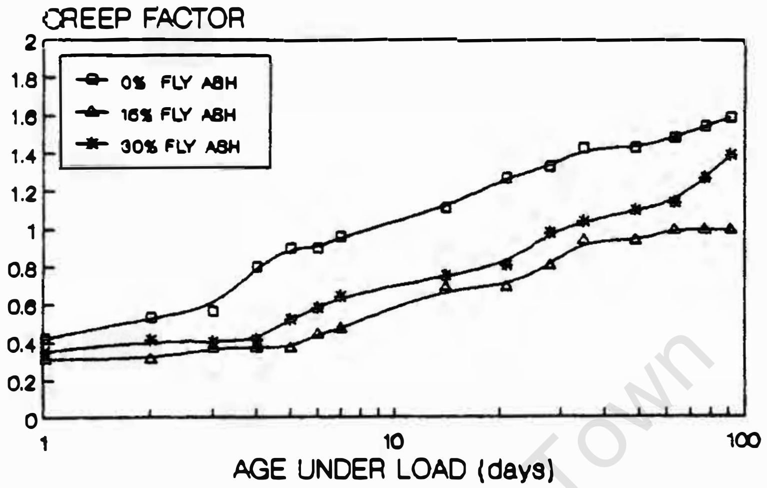
Mix proportions for pump mixes

PERCENTAGE FLY ASH PRESENT	MIX MATERIALS	TARGET STRENGTH AT 28 DAYS		
		10 MPa	30 MPa	50 MPa
0 %	C/W Ratio		1.50	2.10
	Cement (OPC)		339 kg	462 kg
	Fly ash		0 kg	0 kg
	Stone		885 kg	885 kg
	Sand		884 kg	797 kg
	Water		226 kg	220 kg
15 %	C/W Ratio			2.37
	Cement (OPC)			394 kg
	Fly ash			70 kg
	Stone			913 kg
	Sand			785 kg
	Water			206 kg
30 %	C/W Ratio		1.70	2.53
	Cement (OPC)		238 kg	357 kg
	Fly ash		102 kg	153 kg
	Stone		929 kg	929 kg
	Sand		880 kg	729 kg
	Water		200 kg	200 kg
50 %	C/W Ratio		2.20	
	Cement (OPC)		194 kg	
	Fly ash		194 kg	
	Stone		950 kg	
	Sand		832 kg	
	Water		185 kg	
70 %	C/W Ratio			
	Cement (OPC)			
	Fly ash			
	Stone			
	Sand			
	Water			

APPENDIX E

Creep factor vs the age under load for the range of normal mixes tested, for various wet curing durations and ages at loading.

DESIGN STRENGTH :50 MPa
WET CURED : 0 days
LOADING AGE : 7 days



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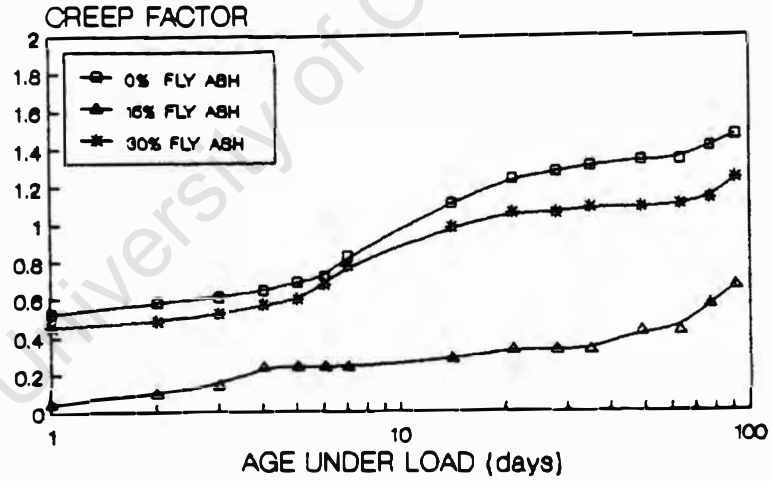
WET CURED : 0 days
LOADING AGE : 28 days



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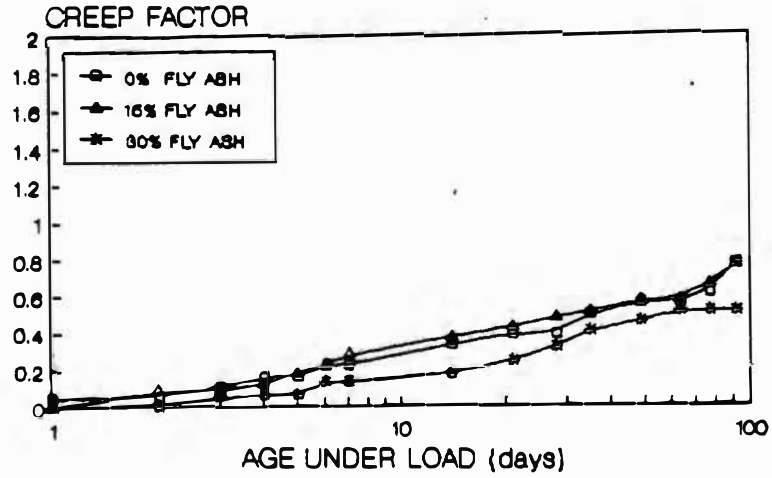
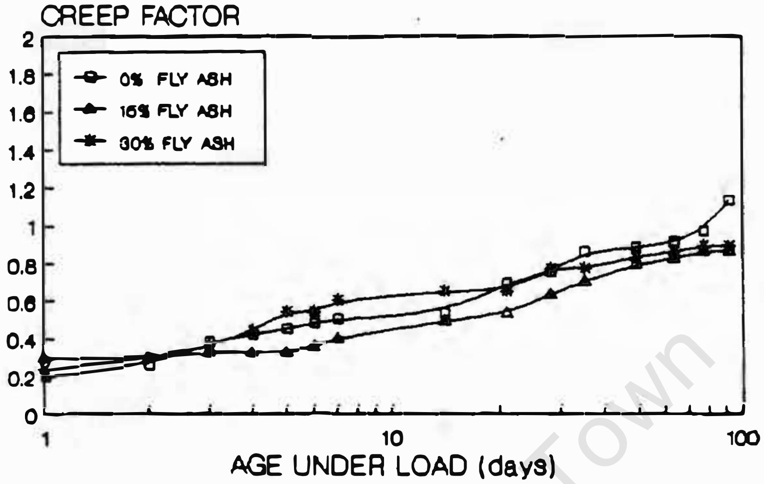
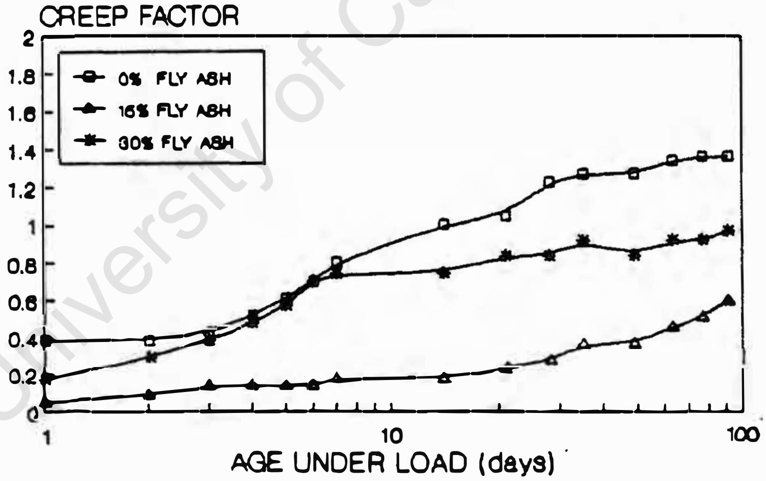
WET CURED : 0 days
LOADING AGE : 90 days



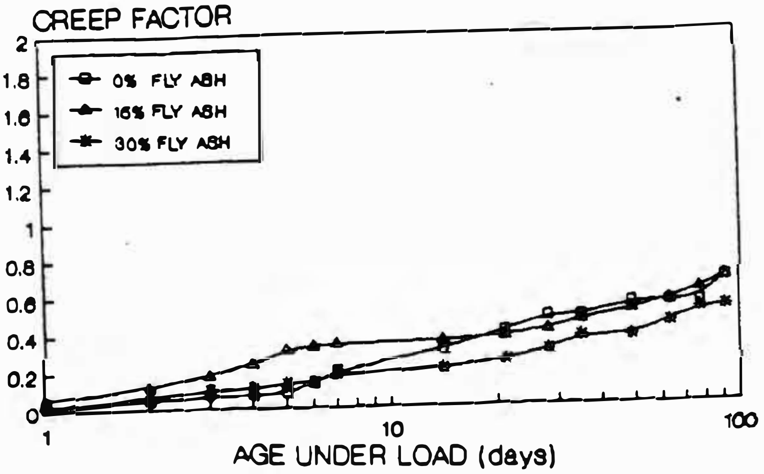
DESIGN STRENGTH : 50 MPa
WET CURED : 7 days
LOADING AGE : 7 days



DESIGN STRENGTH : 50 MPa
WET CURED : 7 days
LOADING AGE : 28 days



DESIGN STRENGTH : 50 MPa
WET CURED : 7 days
LOADING AGE : 90 days



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WET CURED : 0 days
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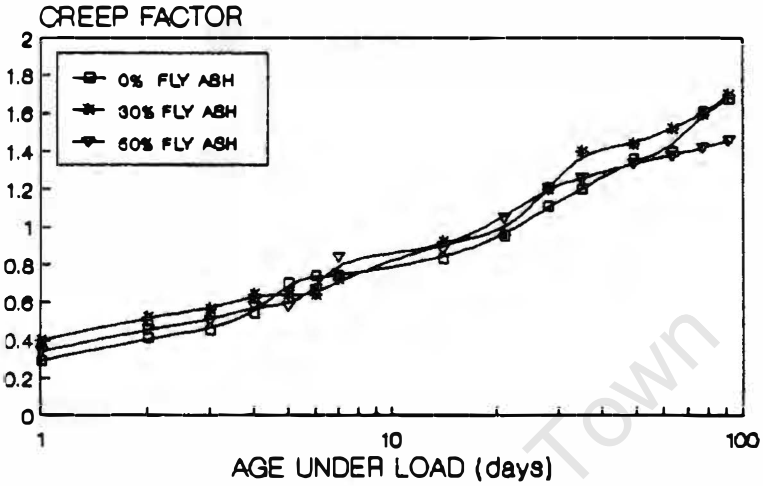

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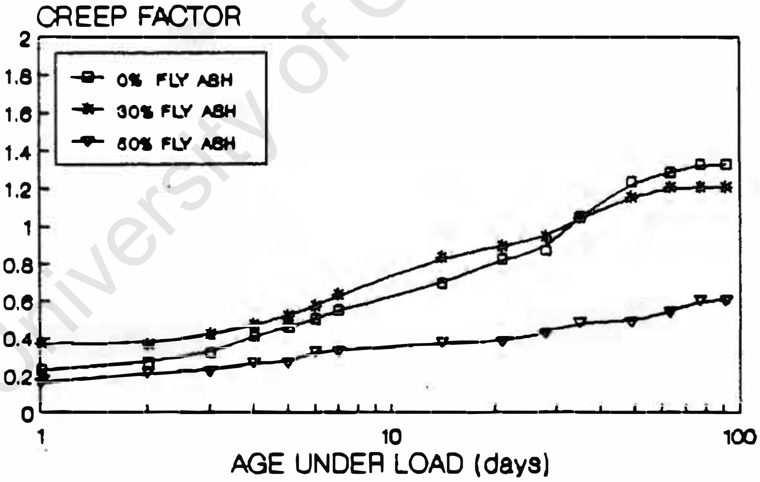
WET CURED : 0 days
LOADING AGE : 28 days



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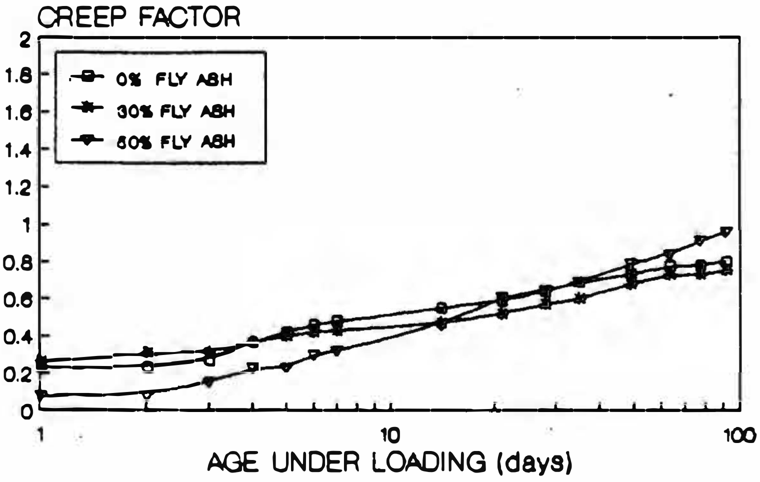

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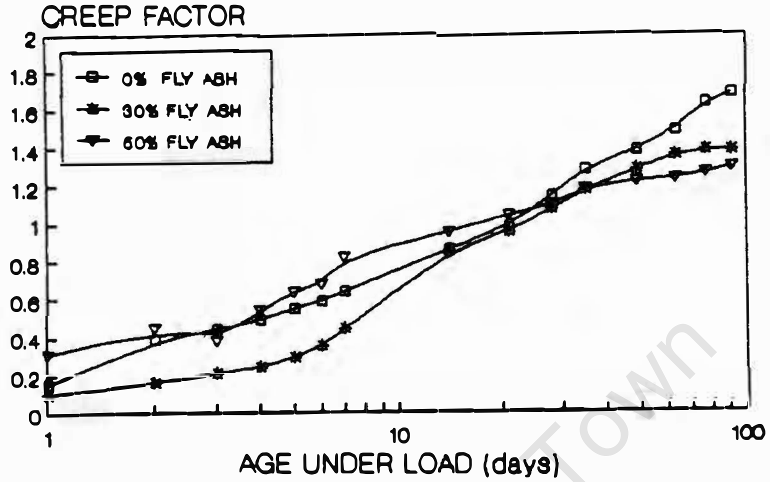

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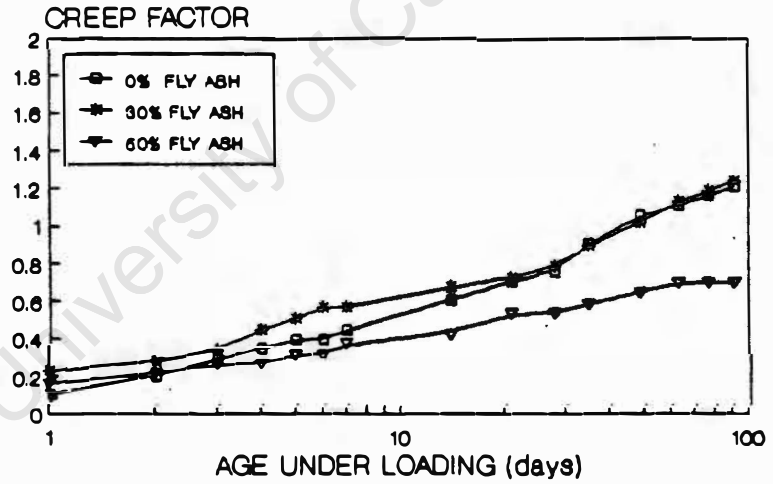

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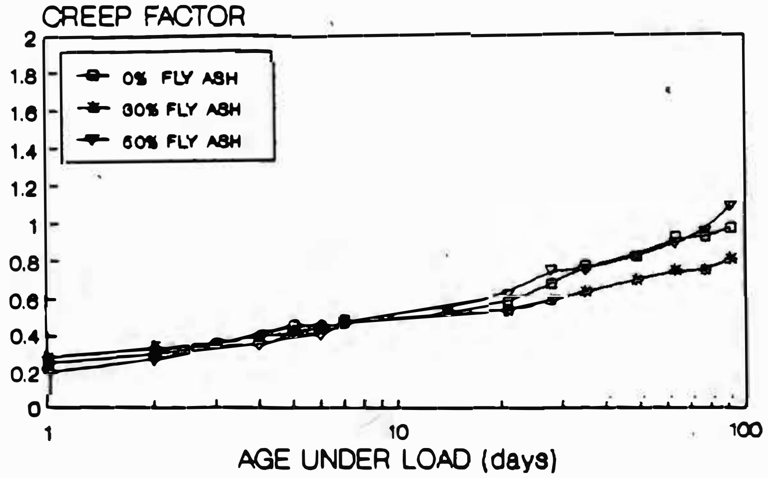

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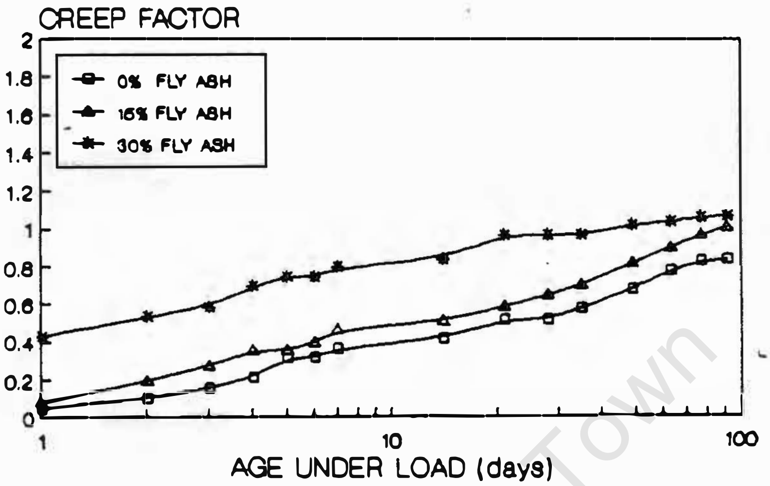

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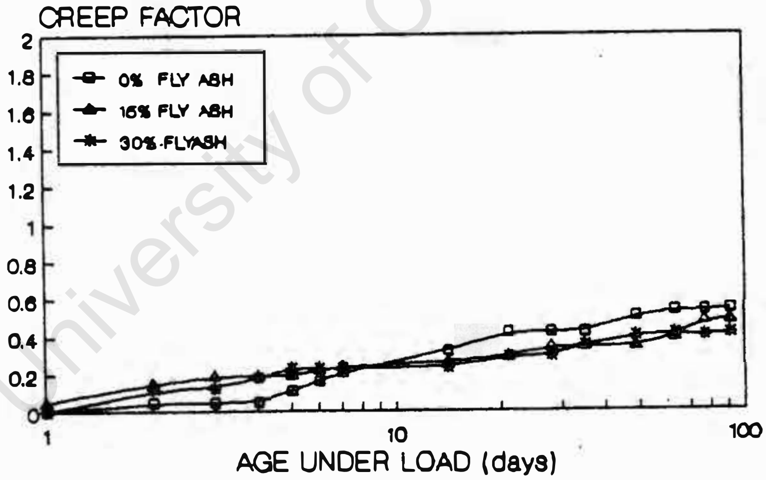
WET CURED : 28 days
LOADING AGE : 28 days



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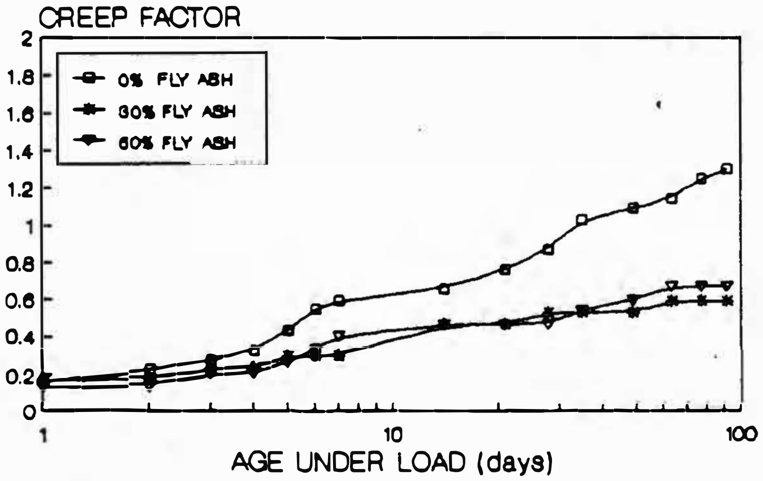
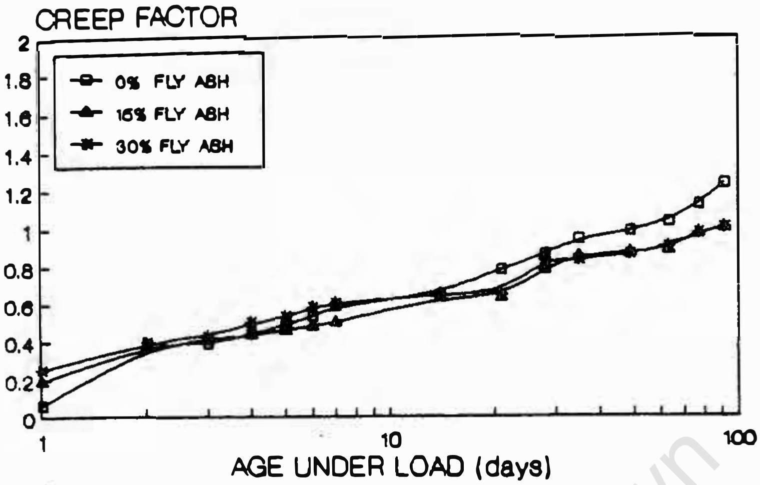


APPENDIX F

Creep factor vs the age under load for the range of pump mixes tested, for various wet curing durations and ages at loading.

DESIGN STRENGTH : 50 MPa
WET CURED : 7 days
LOADING AGE : 7 days



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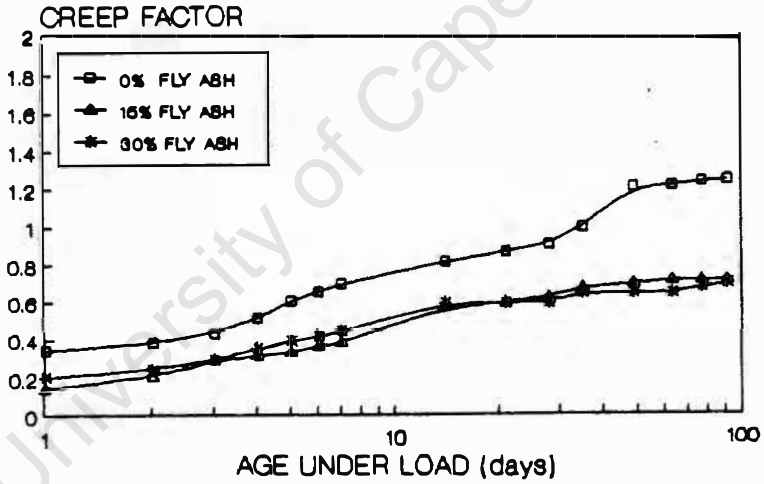
LOADING AGE : 28 days



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WET CURED : 28 days
LOADING AGE : 28 days