THE DURABILITY OF FLY ASH CONCRETE IN MARINE AND SOFTWATER ENVIRONMENTS.

A thesis presented as full requirement
for the degree of Master of Science in
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Town, Department of Civil Engineering.

By
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DECLARATION

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

signature removed

Signed by candidate

J.R. MACKECHNIE

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ABSTRACT

Concrete is attacked by aggressive agents in the marine and softwater environments which reduce the durability of concrete. To help lessen the effect of this aggressive attack, fly ash concrete has been recommended for use in these environments. The lower permeability, increased chemical resistance and higher long-term strength of fly ash concrete are expected to improve the concrete durability.

In this research the effect of fly ash was investigated with regard, initially to general concrete properties such as bleeding, early set, workability, mortar excess and compressive strength. Lethabo field 2 fly ash and Western Cape materials were used for this work. Having developed a wide range of concrete mixes, further investigation was done into specific concrete properties such as the effect of different curing regimes, water absorption, permeability and freeze-thaw resistance. These properties are considered to have an influence on concrete durability.

Comparisons were made between the concrete properties of Lethabo field 2, Lethabo classified and Matla classified fly ash concrete. The three types of concrete were tested for compressive strength, sorptivity (rate of water absorption) and density.

At the same time, fly ash and OPC concrete samples were exposed to the marine and softwater environment for up to 10 months. Marine exposure was done in the submerged, tidal and spray zones in Table Bay. Softwater exposure was done at Constantia Nek and Steenbras Water Treatment Plants. The performance of concrete in the various exposure conditions was measured by compressive strength, sorptivity and density tests.

Fly ash improved many of the properties of concrete, with fly ash concrete having better workability, higher long-term strength, reduced bleeding, lower sorptivity and reduced permeability than similar OPC concrete. Some of the properties of concrete were however worsened by using fly ash. Fly ash concrete had longer setting times, reduced resistance to freezing and thawing and was more adversely affected by dry curing than similar OPC concrete.

Lethabo field 2 fly ash concrete had higher compressive strength and lower sorptivity than either Lethabo classified or Matla classified fly ash concrete. The long-term performance of Lethabo classified and Matla classified fly ash concrete was better than that of Lethabo field 2 fly ash concrete, with regard to compressive strength development and sorptivity reduction.

Fly ash concrete performed well in both the marine and softwater environments. After 10 months of exposure in either marine or softwater conditions, fly ash concrete had higher compressive strength and lower sorptivity than similar OPC concrete. The good performance of fly ash concrete in the marine and softwater environment confirmed the ability of fly ash to improve many of the important durability properties of concrete.

From this medium-term durability investigation it was found that Lethabo field 2 fly ash improved the performance of concrete in marine and softwater environments while fly ash, in general, improved many of the durability properties of concrete.

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GLOSSARY

OPC -	Ordinary Portland Cement.
OPC concrete -	Ordinary concrete made with no fly ash.
Fly ash concrete -	Concrete made with OPC and fly ash.
Cementitious content -	The sum of the OPC and fly ash in the concrete mix.
Percentage fly ash -	The percentage of the total cementitious content that the fly ash makes up.
C/W ratio -	Total cementitious content to water ratio.
Grade of concrete -	Mean Compressive strength of concrete after 28 days of wet curing.
Similar concrete -	Concrete of similar grade.

CHAPTER 1: INTRODUCTION

Pulverized fuel ash (pfa) is the non-combustible residue of the finely ground coal used to fire thermal power stations. Also referred to as fly ash, it has been used as a cement extender in concrete for over fifty years. In South Africa fly ash was initially not considered suitable for concrete production due to the poor quality of fly ash from the early power stations. With the advent of modern power stations higher quality fly ash has been produced and is being used increasingly in concrete production in South Africa. The better quality fly ash from these modern power stations is due to more efficient combustion and the use of a single coal source.

The inclusion of fly ash in concrete improves many of the fresh and hardened properties of concrete. Some of the improvements of the fresh concrete properties include better workability, less segregation and bleeding, lower water demand and lower heat of hydration. Most notable of the hardened concrete properties which are improved, are lower permeability, increased chemical resistance and better long-term strength development. Many of these beneficial features of fly ash concrete are desirable for durable concrete but more research is needed to confirm the potential of a particular fly ash to produce concrete of good durability.

Concrete has generally been considered to be a durable material due to its strength and chemical inertness. Recently this assumption has been questioned due to the rapid deterioration of many modern concrete structures. Numerous research projects are in progress on various aspects of concrete durability such as carbonation, alkali-aggregate reaction and exposure to aggressive environments. Little is known however about the long-term performance of fly ash concrete in aggressive environments such as marine and softwater exposure.

Concrete deteriorates in the marine environment due to chemical attack by sea salts on the hardened cement paste and due to physical factors such as wave action, wetting and drying and freezing and thawing in colder climates. Fly ash should improve the durability of concrete in the marine environment because of the better chemical resistance, lower permeability and higher ultimate strengths associated with fly ash concrete. These advantages of fly ash concrete should also help resist the aggressive attack of softwater on concrete in a similar manner.

Work done for this research was confined to practical concrete mixes used in the Western Cape using local materials. Due to the short time of 18 months available no real long-term testing of concrete was possible. Instead a medium-term comparative study was done using OPC and fly ash concrete exposed to either the marine or softwater environments. This work was done in conjunction with research into other concrete durability properties.

Initially a wide range of concrete mixes were developed using Lethabo field 2 fly ash and Western Cape materials. Lethabo field 2 fly ash was used as it was expected that it would be similar to Lethabo classified fly ash which was not available at the beginning of this research. These concrete mixes varied in percentage fly ash, design strength and sand to stone ratio and were used to measure the effect of fly ash on several fresh and hardened concrete properties. This work was also done to gain some expertise in the design, mixing and compaction of fly ash concrete.

Using the results of concrete made during the initial work, further concrete was produced and tested for specific concrete durability properties such as permeability, sorptivity, freeze-thaw resistance and water absorption. The effect of wet, fog and dry curing on fly ash and OPC concrete was also investigated. At the same time concrete samples were exposed to the marine or softwater environment for periods up to 10 months. The performance of concrete exposed to either softwater or sea water was determined by compressive strength, sorptivity and density tests.

Finally a limited investigation was done on fly ash concrete produced with Lethabo classified ash, which became available in 1989, and Matla classified fly ash. The two classified fly ash concretes were tested for compresive strength, sorptivity and density for comparison with Lethabo field 2 fly ash concrete. From these results the relative quality of the three fly ashes could be determined with regard to their concrete properties.

CHAPTER 2: MATERIALS.

2.1. INTRODUCTION:

All research for this thesis was done on concrete with varying proportions of sand, stone, water, OPC and fly ash. Except for the fly ash, all other ingredients were kept the same throughout. No additives or admixtures were used due to the limited time available.

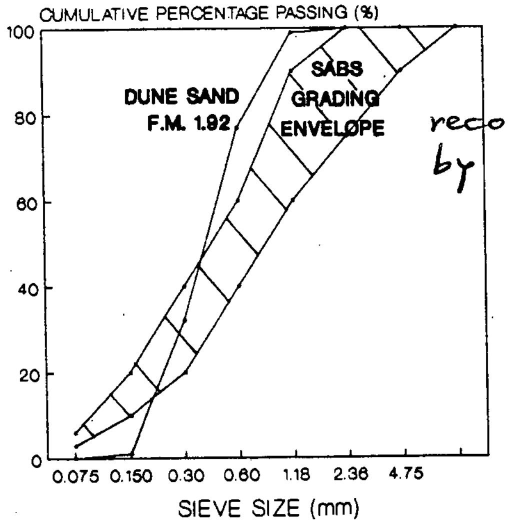
Materials chosen were those commonly used in the Western Cape. Cape Flats Dune sand was used as the fine aggregate, Malmesbury shale as the coarse aggregate and De Hoek OPC as the cement. Lethabo field 2 fly ash was used for most of the research, though some comparative work was done using Matla classified and Lethabo classified fly ash.

Each ingredient in concrete has an important role to play in both the fresh and hardened concrete. The chemical and physical nature of each material will impart distinctive characteristics to the concrete.

2.2. FINE AGGREGATE.

Cape Flats Dune sand is a wind blown sediment characterised by well rounded grains. It is a ~~coarse~~ dune sand with little fine material below 150 μm. The sorting power of the wind causes material of similar particle shape, relative density and mineral composition to collect together.

The grading of Cape Flats Dune sand is very poor and the particle size distribution falls outside the recommended limits laid down by SABS 1083 (1). The grading of sand has a minor effect on water demand, but has a major influence on properties like bleeding, workability and cohesiveness. Fig. 1 shows the typical grading curve for Cape Flats Dune sand against that recommended by SABS 1083.



recommended by PCI.

Fig. 2.1 : Typical grading curve for Cape Flats dune sand

The fineness modulus (FM) of Cape Flats sand varies according to its source. It generally has a FM in the range of 1,7 to 2,1 and may therefore be considered as a "fine" sand. The well rounded particles are responsible for the relatively low water demand of the sand which is usually between 180 and 210 l/m^3. The relative density of the sand is 2,63.

2.3. COARSE AGGREGATE.

Malmesbury shale is a hornfels that developed by thermal metamorphism from argillaceous rocks. It is a fine grained "glassy" rock consisting of quartz, feldspar, mica and iron oxides. It does not crush to a good cubical particle shape and consequently the shape is usually elongated and flaky. This poor shape results in harsh mixes when used with a poorly graded sand such as Cape Flats Dune sand.

Hornfels is often found to be alkali reactive and when used with alkali rich cement, may show signs of alkali aggregate reaction under certain environmental conditions. This is found to be particularly prevalent in marine environments.

13mm Malmesbury shale was used and a typical grading is shown below. This is seen to fall well within the recommended limits laid down by SABS 1083.

	PERCENTAGE PASSING THROUGH SIEVE	
SIEVE SIZE (mm)	Malmesbury Shale	Recommended Limits
19.0	100.0	100
13.2	97.8	85-100
9.5	28.6	0-55
6.7	2.7	0-25
4.75	0.6	0-10

2.4. CEMENT.

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 in cement may vary from one factory to the next, and even at one particular factory the cement will vary from day to day. The variations arise due to changes in the raw materials, production methods and production levels.

Cement used for this thesis was De Hoek OPC. The cement was ordered from one production batch and stored in air-tight drums. It was hoped that the cement would not deteriorate signifantly over the period of a year that it was used. The chemical composition of the cement and the usual proportions for South African cements are shown below:

	De Hoek (%)	Usual SA Cement(%)
CaO	64,0	63 - 68
SiO_2	21,5	19 - 24
Al_2O_3	3,9	4 - 7
Fe_2O_3	3,9	1 - 4
MgO	1,1	0,5 - 3,5
Na_2O	0,22	0,2 - 0,8
K_2O	0,53	0,2 - 0,8
SO_3	2,5	-
LOI	2,3	-

Relevant properties of the cement are listed below:

Alkali content - 0,57
Specific surface area (Modified Blaine) - 2970 cm^2/g
Relative Density - 3,15
Initial set - 3hr 19 min.
Final set - 4hr 15 min.

2.5. FLY ASH.

Fly ash is the residue of the combustion of finely ground coal used to generate electricity in thermal power stations. The coal dust, which is smaller than 75 µm, is injected into a furnace where the temperature is around 1500°C. 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 pozzolanic material, which means it possesses hydraulic cementing properties when mixed with water in the presence of $Ca(OH)_2$. This pozzolanic activity results in many benefits for hardened concrete. Some of the fresh concrete properties are also improved by the use of fly ash.

At present fly ash is commercially produced at the Matla power station. The fly ash is sorted in an air classifier to produce a uniform product. In the near future classified fly ash will be produced at Lethabo power station.

2.5.1. Chemical and Mineral Composition.

The three main constituents of fly ash are SiO_2, Al_2O_3 and Fe_2O_3 which together make up more than 70% of the whole mass of any South African fly ash. The composition of fly ash is largely dependent on the type of coal used. The carbon content, which is assumed to be roughly equal to the loss of ignition, will depend largely on the efficiency of the power station. Modern power stations have far more efficient operations than before and consequently the loss of ignition of the fly ash produced is low.

Fly ash is mostly composed of non-crystalline glassy phases. The reactivity of the fly ash depends on the nature and proportion of the glassy phase present (2). The reactivity of this glassy phase within fly ash may also be affected by the characteristics of the Portland cement used with it.

The chemical analyses of the three fly ashes used for this thesis are shown below:

Compound	Lethabo Field 2	Lethabo Classified	Matla Classified
SiO_2	50.93	53.20	47.30
Al_2O_3	35.97	32.40	28.60
Fe_2O_3	3.91	3.90	4.30
TiO_3	1.80	1.95	-
SO_3	-	0.17	0.77
MnO	0.05	-	-
MgO	1.36	1.20	2.90
CaO	4.66	4.98	9.40
Na_2O	0.32	0.30	0.40
K_2O	0.53	0.55	1.08
P_2O_5	0.66	0.60	-
LOI	0.40	0.23	0.90

2.5.2. Physical Properties

The shape, fineness, particle size distribution and composition of fly ash particles influence the properties of fresh and hardened concrete. Generally fly ash particles are spherically shaped, being either solid or hollow (3). The particles range in size from less than one µm to greater than one mm. The majority of fly ash particles should pass through the 45 µm sieve if it is to be used as a pozzolan in concrete.

The fineness of fly ash is usually measured by the percentage material retained on the 45 μm sieve. This fineness has a direct influence on many important factors such as the pozzolanic activity. The "quality" of fly ash is commonly determined by measuring its fineness. The fineness should not be used in isolation to determine the "quality" of fly ash as other factors, especially the presence of ultra-fine particles, may change the characteristics of a fly ash.

Relevant physical properties of the three fly ashes used are given below :

	Lethabo Field 2	Lethabo Class.	Matla Class.
Specific surface Blaine (cm^2/g)	-	-	4200
Fineness (% retained on 45 μm sieve)	7.7	6.4	9.6

2.5.3 Lethabo Field 2 Fly Ash

Lethabo field 2 fly ash comes from the second electrostatic precipitator field at Lethabo power station. It was selected for this research because it was hoped that it would closely resemble Lethabo classified fly ash when that became available. The fineness of the fly ash would indicate a high quality fly ash and the above average presence of ultra-fine particles should further improve the fly ash quality. Three tonnes of Lethabo field 2 fly ash were obtained in March 1988 and stored in air-tight drums.

2.5.4 Lethabo Classified Fly Ash

Lethabo classified fly ash is not yet commercially available but small quantities have been air classified for experimental work. It is hoped that Lethabo classified fly ash will become available by 1990 and eventually the Lethabo power station will provide all the fly ash used in the Cape. One tonne of Lethabo classified fly ash was obtained in February 1989 and stored in air-tight drums.

2.5.5 Matla Classified Fly Ash

Air classified fly ash from Matla power station has been available for several years. The classification ensures a uniform product which has been found to vary even less than cement in quality. Matla classified fly ash has been used with confidence by the construction industry and its effect on concrete has been researched thoroughly. The work done with Matla classified fly ash was limited just to comparing it with the fly ash produced at Lethabo. 50 kg of Matla classified fly ash was obtained from Ready Mixed Concrete in May 1989.

2.6 REFERENCES

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2. DHIR, R.K. Pulverised Fuel Ash. CEMENT REPLACEMENT MATERIALS. Ed. R.N. Swamy. Concrete Technology and Design, Vol. 3, Surrey University Press, 1986
3. AMERICAN CONCRETE INSTITUTE. Use of Fly Ash in Concrete. Detroit. ACI Materials Journal. September-October 1987, pp 381-409

CHAPTER 3. CONCRETE MIXES

3.1 INTRODUCTION

There are many ways of designing fly ash concrete mixes and the chosen method will depend on what purpose the concrete is used for. When comparing fly ash concretes either the total cementitious material is kept constant or the cement water ratio is held constant or equal compressive strengths are used to make comparisons. Similarly the other materials may be held constant or allowed to vary for different mixes.

This research was a comparative study of fly ash concrete and OPC concrete using local materials and typical mixes. In keeping with these practical considerations all concrete mixes were designed primarily for a chosen 28 day compressive strength. Each concrete mix was thus designed to give a certain grade of concrete and a slump of 50 mm, for a chosen percentage fly ash and a chosen sand to stone ratio.

3.2 CONCRETE MIX DESIGN METHOD

The design of OPC concrete was done according to the PCI method as detailed by Fulton (1). In this method the water requirement of the mix is determined first by trial mixes although an estimate can be made from the aggregate properties. A cement water ratio is chosen according to the required compressive strength at 28 days, the stone content obtained from tables and the sand content calculated from the assumed volume of 1 m^3. This method has been used extensively in South Africa for many years and is probably the most well known method to concrete technologists.

The design of fly ash concrete mixes was done according to the method outlined by Ash Resources (2). The method is similar to the PCI method with a few modifications which are described below.

1. The cement water ratios are slightly higher than those for OPC concrete to allow for the lower cementing efficiency of fly ash.
2. Water demands are lower because of the better workability of fly ash concrete.
3. Stone contents are increased for fly ash concrete due to the better workability.

The design charts used to determine the cement water ratio for a given grade of concrete were devised by Ash Resources. The values are relevant for Transvaal materials and Matla classified fly ash. During the preliminary work using Lethabo field 2 fly ash it became clear however that the design charts gave much higher compressive strengths than were predicted. In an attempt to get the actual compressive strength closer to the predicted design strength at 28 days, a new set of design charts was produced from the results of the preliminary work. This is discussed further in Chapter 4. Fig. 3.1 shows the revised design chart for Lethabo field 2 fly ash.

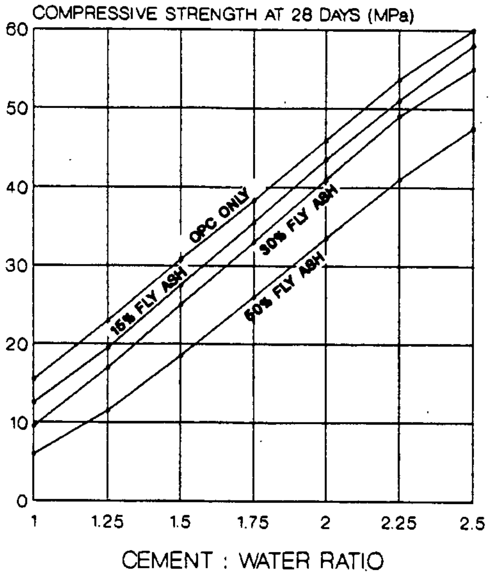

Fig. 3.1: Revised design chart for Lethabo field 2 fly ash

3.3 MIXING PROCEDURE

Dry material for each concrete mix was weighed to an accuracy of ~~less~~ better than 0.7 %. Mixing of concrete was done in either a 50 litre capacity pan mixer or a 100 litre capacity drum mixer. A standard mixing time of two minutes was used and a measured amount of water was added until the concrete reached 50 mm slump. Once the concrete was found to be at the correct slump of 50 ± 15 mm the concrete was accepted.

For the concrete to be accepted the actual water demand had to be within 10 l/m^3 of that estimated for the design mix. Thus if more than this amount of water was withheld or added to the concrete mix to obtain a 50 mm slump the concrete was discarded. When the concrete was accepted the amount of water withheld or added was noted and the final concrete mix proportions calculated.

Once the concrete was found to be within acceptable limits it was placed in the required concrete moulds and compacted. Compaction was done mechanically on a vibrating table until the concrete appeared to be fully compacted. The time taken for compaction varied from mix to mix and also varied with the eventual slump of the mixes. Generally the 100 mm cubes took about 30 seconds to compact while the bigger beams and cylinders took up to 60 seconds to compact. The whole process of mixing, placing and compacting the concrete was usually completed in less than 30 minutes.

3.4 RANGE OF MIXES DEVELOPED

Material for all mixes was kept the same as described in Chapter 2. Fly ash used in the concrete was Lethabo field 2 fly ash throughout unless stated otherwise.

3.4.1 Preliminary Work

For the initial investigation of Lethabo field 2 fly ash concrete three sand to stone ratios were used, for either over-, medium- or under-sanded concrete mixes. This preliminary work on bleeding, early set, strength development, workability and mix economics is described in detail in Chapter 4. The cement water ratios for the 18 concrete mixes for each sand to stone ratio are shown below.

Grade of Concrete (MPa)		10	20	30	40	50	
	0%	0.90	1.17	1.51	1.84	2.25	cement water ratios
	15%		1.23	1.59	1.92	2.35	
% fly ash	30%	1.02	1.36	1.74	2.12	-	
	50%	1.09	1.70	2.26	-	-	
	70%	1.75	2.25	-	-	-	

OPC mixes stone content : Over-sanded mix series - 950 kg/m^3
Medium-sanded mix series - 1050 kg/m^3
Under-sanded mix series - 1220 kg/m^3

3.4.2 Durability Work

The medium and under-sanded concrete mix series were repeated for an investigation of durability properties. The same cement water ratios and stone contents were used but the water requirement was found to vary slightly due to the variability of the sand. The following aspects were investigated :

1. Wet versus dry curing.
2. Wet versus cyclical wet and dry curing.
3. Freeze - thaw resistance.
4. Water absorption of concrete.

This work is described in detail in Chapter 5.

3.4.3 Exposure Samples

For these and all subsequent concrete mixes the adjusted cement water ratios, determined from the preliminary work, were used. The stone content was also fixed at 1050 kg/m^3 for OPC concrete mixes so that all the concrete was medium-sanded. Twelve concrete mixes were each used to produce samples for softwater and marine exposure. The cement water ratios for these mixes are shown below.

Grade of Concrete (MPa)		30	40	50
	0%	1.48	1.80	2.13
	15%	1.58	1.88	2.20
% fly ash	30%	1.65	1.95	2.25
	50%	1.88	2.22	2.65

3.4.4 Wet versus Fog versus Dry Curing

The concrete used in this investigation into curing regimes was similar to that used for the exposure samples. The stone content was kept the same and the cement water ratios were identical. The water requirements of the mixes are shown below.

Grade of Concrete (MPa)		30	40	50
	0%	211	208	201
	15%	196	194	188
% fly ash	30%	180	178	174
	50%	164	159	156

3.4.5 Lethabo Classified Fly Ash Concrete Mixes

Identical mix proportions to those used for the exposure work were adopted. The only difference was that the Lethabo classified fly ash gave smaller reductions in water requirement than those found for Lethabo field 2 fly ash. The water requirements of the mixes are shown below.

Grade of Concrete (MPa)		30	40	50
	0%	211	206	203
	15%	196	195	190
% fly ash	30%	181	179	176
	50%	167	162	160

3.4.6 Matla Classified Fly Ash Concrete Mixes

Again the same 12 concrete mixes were used with identical cement water ratios and stone contents as those used in the exposure work. The reductions in water requirement found using Matla classified fly ash was less than both Lethabo field 2 and Lethabo classified fly ash. The water requirements of the mixes are shown below.

Grade of Concrete (MPa)		30	40	50
	0%	211	206	203
	15%	197	195	192
% fly ash	30%	183	183	180
	50%	173	170	168

3.5 REFERENCES

1. FULTON'S CONCRETE TECHNOLOGY. 6th rev edition. Midrand, Portland Cement Institute, 1986
2. ASH RESOURCES. The design of pfa concrete mixes. Randburg, Technical Information Bulletin No. 5, 1985

CHAPTER 4: PRELIMINARY WORK.

4.1. INTRODUCTION:

Before research was started on the various aspects associated with concrete durability, some initial work was done on more general concrete properties. This preliminary work was done on three different concrete mix series each with 18 individual concrete mixes. The three concrete mix series were: over-sanded; medium-sanded and under-sanded, as described in detail in Chapter 3. The materials used for this work were the same as those used later for the durability work, as described in detail in Chapter 2.

Properties considered in this preliminary work were: compressive strength, workability, bleeding, early set and mix economics. All tests were performed on concrete produced from one batch which was mixed in a 50 litre pan mixer.

4.2. TEST METHODS.

4.2.1. Compressive Strength

Three 100 mm cubes were cast for each compressive strength test and were tested in accordance with SABS 863 (1). Concrete was tested at intervals of 7, 28 and 90 days, after being cured in water at 25°C. This is a standard test for concrete and is usually used to determine the quality of concrete. The use of fly ash in concrete generally causes some reduction in the 28 day compressive strength. Therefore the cement water ratio has to be increased with increasing percentage of fly ash as specified by Fulton (2).

4.2.2. Bleeding.

Bleeding of concrete was determined by the pipette method (ASTM C232) for which concrete was cast in 280 mm diameter rigid steel cylinders, and the bleed water drawn off at intervals until bleeding stopped (3). It was decided to take the measurements at 15 minute intervals throughout the period of bleeding. The bleed cylinders were kept at a constant temperature of 23°C and were covered to prevent excessive evaporation. The initial mix temperature varied according to the ambient temperature of the laboratory which was between 12 and 20°C.

4.2.3. Early Set.

Early set of concrete was determined by penetration resistance in accordance with ASTM C403 (4). In this test the penetration resistance of the concrete mortar, obtained by sieving out the stone from the freshly mixed concrete, was measured by forcing standard needles into the mortar at a set rate. Early set was defined as the time taken for the concrete to reach a penetration resistance of 3,5 MPa. All testing was carried out in a controlled environment at a constant temperature of 23°C. The cube moulds containing the mortar were covered to reduce moisture loss and the accumulated bleed water was removed just before the first penetration test. As with the bleed tests the origin mix temperature was uncontrolled but stabilised to 23° C within a few hours.

4.2.4. Workability.

Workability was determined by using the slump and Vebe test (5). The concrete mixes were designed so that slumps were in the range of 50 mm with a tolerance of 15 mm. Water was added or left out of each mix to ensure an adequate amount of slump and mixes where the water requirement differed from the design requirement by more than 5 l/m^3 were repeated. Once the slump was done the Vebe consistency test was carried out and the Vebe time recorded.

4.3. RESULTS AND DISCUSSION

4.3.1. Compressive Strength.

The actual compressive strength results at 28 days for Lethabo field 2 fly ash concrete were either similar or slightly higher than the values predicted from the design curves for Matla fly ash and Transvaal materials (6). This can be seen in fig. 4.1a and 4.1b which show this trend to be more pronounced for higher percentages of fly ash and higher strengths.

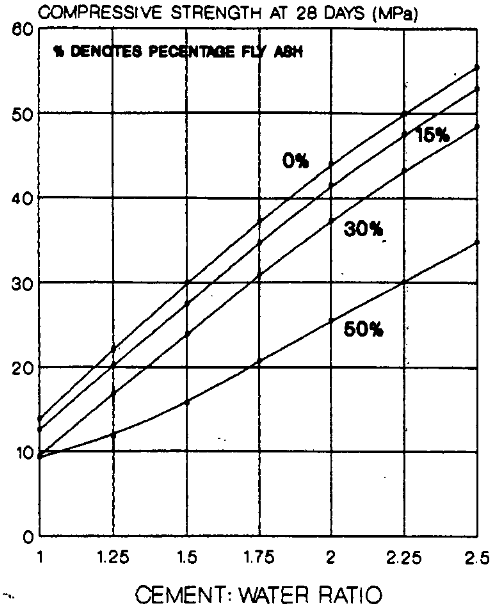

Fig 4.1a: Ash Resources Design Chart - Matla fly ash

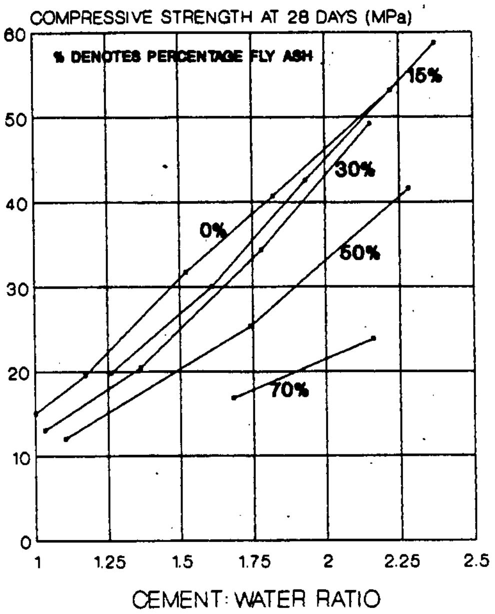

Fig 4.1b: Actual 28 day Compressive Strength - Lethabo Field 2 fly ash

This gain in strength, above that predicted, was mostly due to the high quality of Lethabo Field 2 fly ash and to a lesser extent due to the local cement used. Fig. 4.2 shows how the discrepancy between the predicted and the actual 28 day compressive strength widened with increasing percentage fly ash. It was found that when testing 50 % fly ash concrete, the actual strengths were as much as 10 MPa higher than the predicted values. The OPC concrete was found to have similar 28 day compressive strength to that predicted for the Transvaal materials. This would indicate that the local cement did not have a significant effect on the observed differences.

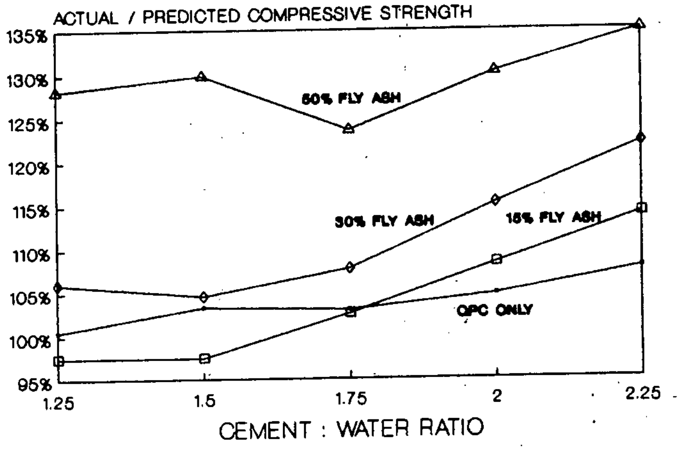

Fig. 4.2: Compressive Strength Ratios - Actual / Predicted

When considering the early strength results ie concrete tested at 7 days, it was clear that fly ash concrete develops strength at a lower rate than OPC concrete. Fig. 4.3a compares the 7 day strength to that achieved at 28 days for the different types of concrete. OPC concrete, which had more rapid strength development, achieved almost 80% of its 28 day strength after 7 days. A high percentage fly ash concrete of over 50% fly ash achieved only about 50% of its 28 day strength after 7 days. Fig. 4.3b shows the long term strength development as measured by the ratio of the 90 day strength to the 28 day strength. As expected, the fly ash concrete was found to have better long-term strength development due to the slow pozzolanic reaction of the fly ash.

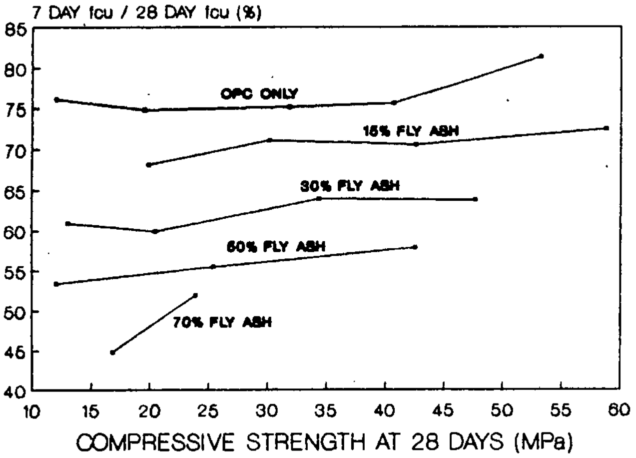

Fig. 4.3a: Early Strength Development - At 7 days

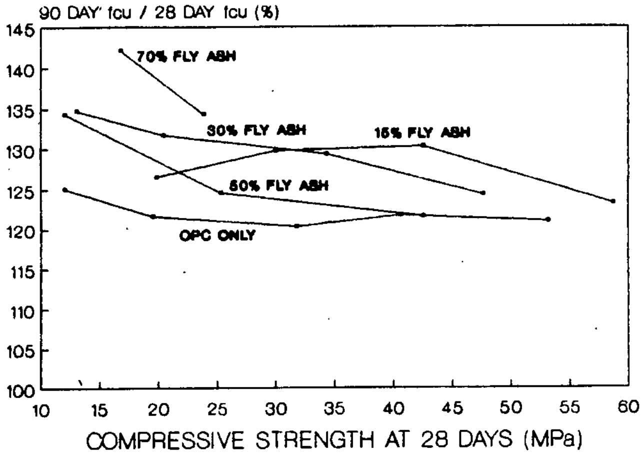

Fig. 4.3b: Long Term Strength Development - At 90 days

Considering the early strength development, it was clear that fly ash concrete hydrates slower and so gains strength more slowly than a similar OPC concrete. There was also a clear trend of more rapid strength development with increasing strength for all types of concrete. As regards the long term strength development, general trends were not as obvious. Fly ash concrete was found to have higher long term strength than OPC concrete but the results were found to be scattered within a narrow range. With up to 50% fly ash there was no more than 10% increase in long term strength over that gained by similar OPC concrete. It was found that the low strength concrete had better long term strength development for all types of concrete.

The fineness of Lethabo Field 2 fly ash and the presence of ultra fine particles is the most likely reason for the unexpected long-term strength performance of the fly ash concrete. The ultra fine particles are known to accelerate the hydration of cement and hydrate more rapidly themselves thereby increasing the rate of strength development (7). This would explain the higher than expected 28 day strengths which have been discussed earlier. This rapid early strength development must have caused the slower than usual long-term strength development. The fly ash concrete was found to behave more like an OPC concrete with fairly rapid early strength development which slowed down quickly after 28 days. The effect of fly ash on strength development is discussed further in Chapter 5.

Generally the compressive strength results were above average due to the high quality of the fly ash. There was a definite penalty in using fly ash in the form of higher cement water ratios but this was not nearly as severe as predicted. If the total cementitious content of each mix was compared against the resulting 28 day strength, it would be seen that there is no penalty at all. This was due to the large reduction in water requirement experienced by the fly ash mixes. The total cementitious content of a typical mix series are shown below. Fig. 4.4 shows the total cementitious content of each concrete plotted against its 28 day compressive strength.

GRADE	PERCENTAGE FLY ASH					
	0%	15%	30%	50%	70%	
10 MPa	192		191	190	250	total cementitious material (kg/m^3)
20 MPa	239	236	241	272	316	
30 MPa	296	288	296	338		
40 MPa	348	338	347			
50 MPa	416	405				

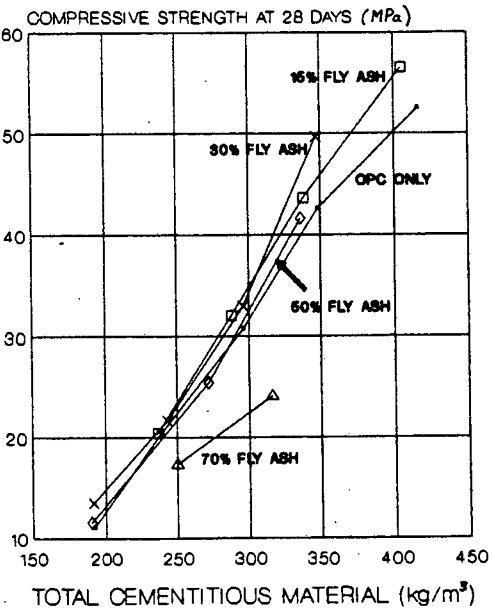

Fig. 4.4: Total Cementitious Content vs. Compressive Strength - Tested at 28 days

4.3.2 Bleeding.

Bleeding results from the inability of the solid constituents of a concrete mix to hold all the mix water as they settle downwards after compaction. Moderate amounts of bleeding are not detrimental to concrete and may even have several benefits. However excessive bleeding may cause problems such as weak surface layers, vertical bleed channels, water lenses under coarse aggregate and reinforcement and accumulation of bleed water on the concrete surface. Bleeding depends on the mix materials, particularly the amount and quality of the fines in the mix. The use of a poorly graded fine aggregate such as Cape Flats sand is likely to introduce major bleeding problems. It was hoped to counteract the likely excessive bleeding of the concrete by using fly ash.

The addition of fly ash to concrete was found to reduce the total volume of bleeding, called the bleed capacity. The bleed rate was also found to be reduced substantially. This reduction in the bleed rate meant that even though the time of bleeding increased with increasing fly ash, the bleed capacity was reduced. Fig. 4.5a to 4.5e show the average results of the bleeding tests for the three sand to stone ratios for concrete grades 10 MPa to 50 MPa. For all grades of concrete there is a clear trend of reduced bleeding with increasing percentages of fly ash. Also apparent is the reduction in bleeding for increasing strength for any particular type of concrete.

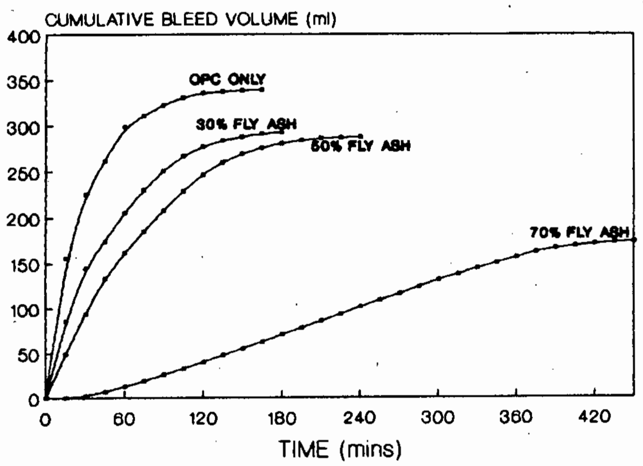

Fig. 4.5a: Bleeding vs. Time - Grade 10 MPa

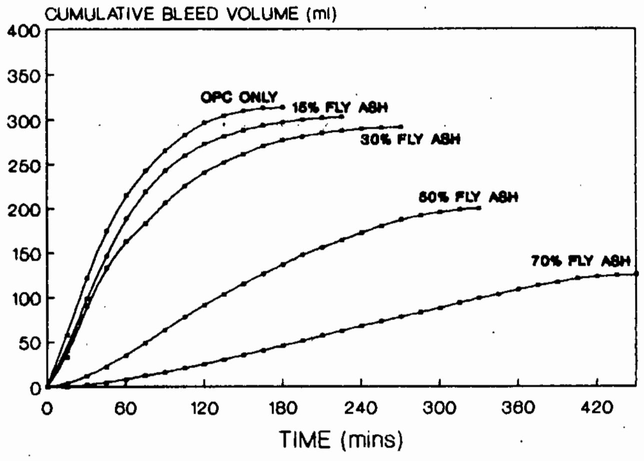

Fig. 4.5b: Bleeding vs. Time - Grade 20 MPa

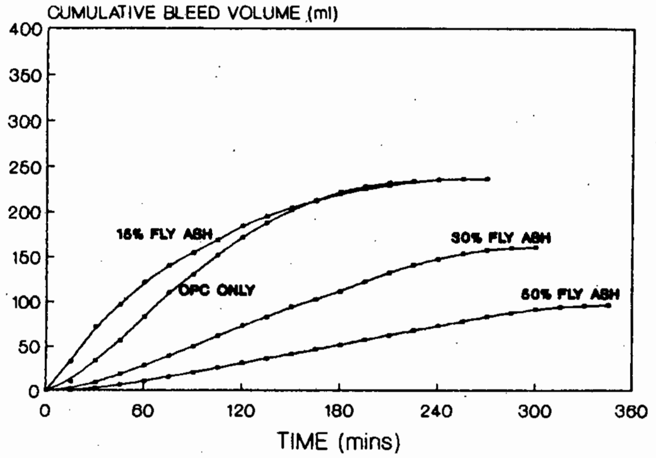

Fig. 4.5c: Bleeding vs. Time - Grade 30 MPa

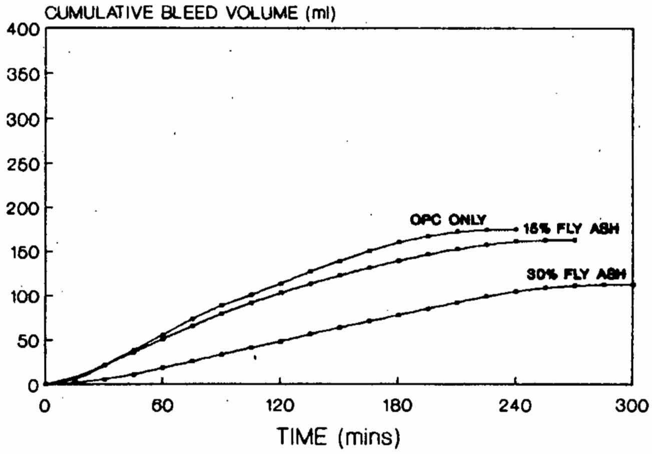

Fig. 4.5d: Bleeding vs. Time - Grade 40 MPa

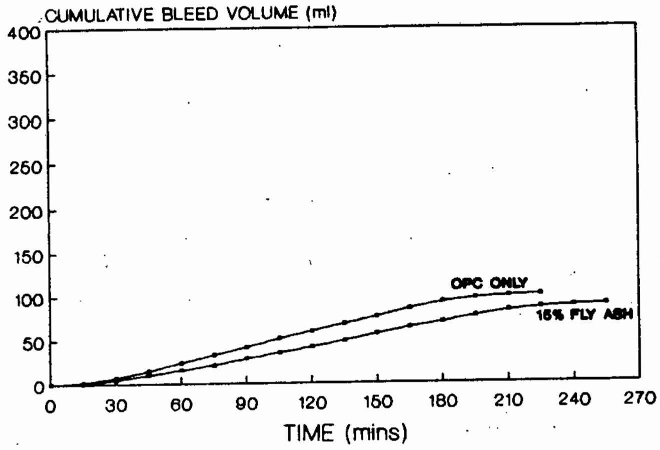

Fig. 4.5e: Bleeding vs. Time - Grade 50 MPa

The addition of fine material such as fly ash would be expected to reduce the bleeding of concrete. This is because the fines block up the bleed channels and reduce the flow of mix water upwards as the heavier solid constituents of the concrete settle downwards. An increase in the cement content, which would occur with a stronger concrete, would also reduce the bleeding in a similar way. The fly ash particles are also lighter than cement and tend to bouy up the cement particles as they settle downwards. Research on other fly ash has generally found that though the bleed rate is reduced, the bleed capacity is similar to an equivalent OPC concrete because of the longer bleed duration (8). Concrete will carry on bleeding until it has set sufficiently to arrest the downward settlement of the solid constituents. Fly ash causes the setting of concrete to be delayed and this in turn produces longer bleed durations of fly ash concrete. If the bleed duration of a fly ash concrete is increased substantially the bleed capacity may be high even though the bleed rate is fairly low.

The substantial reduction observed in both the bleed rate and capacity was due to the fineness of the Lethabo field 2 fly ash. The fine particles of fly ash are assumed to have filled many of the voids around the cement and aggregate, and so reduced the displacement of the mix water. The high quality fly ash did not seem to increase the setting characteristics of the fly ash concrete excessively since the fly ash concrete bleed durations were not as long as expected.

When comparing the bleed rate and the bleed capacity against the relevant 28 day compressive strength, the effect of fly ash addition is not as obvious. This is because of the additional strength gain of the fly ash concrete above that predicted for any particular grade. Thus a grade 30 MPa OPC concrete may have had an actual strength of 30 MPa while a 50% fly ash concrete may have had an actual strength of 38 MPa. Fig. 4.6a and 4.6b show that even when compared against actual compressive strength, both the bleed rate and the bleed capacity were reduced for increasing percentages of fly ash.

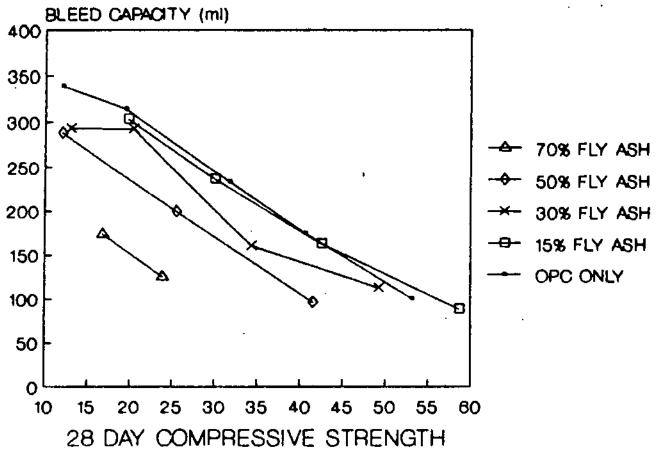

Fig. 4.6a: Bleed Capacity vs. 28 day Compressive Strength

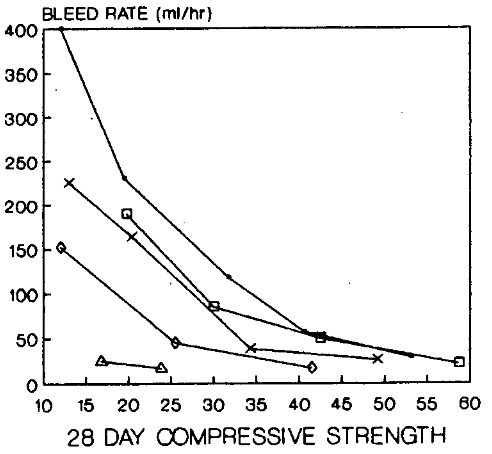

Fig. 4.6b: Bleed Rate vs. 28 day Compressive Strength

4.3.3 Early Set

The determination of the setting characteristics of concrete is important when considering factors such as delays during placing, intervals between lifts, finishing of the concrete surface and stripping of formwork. A slow setting concrete may prove to be expensive if it delays the turnaround time of equipment on site. Fly ash has generally been found to delay the setting of concrete as the fly ash remains relatively inert during the setting process.

Lethabo field 2 fly ash was found to retard the setting of concrete as shown in Fig. 4.7a - 4.7e. Each graph represents the average result of the three concrete mix series. For all grades of concrete there is a clear trend of slower setting with increasing percentages of fly ash. The amount of retardation was roughly proportional to the percentage fly ash in the concrete.

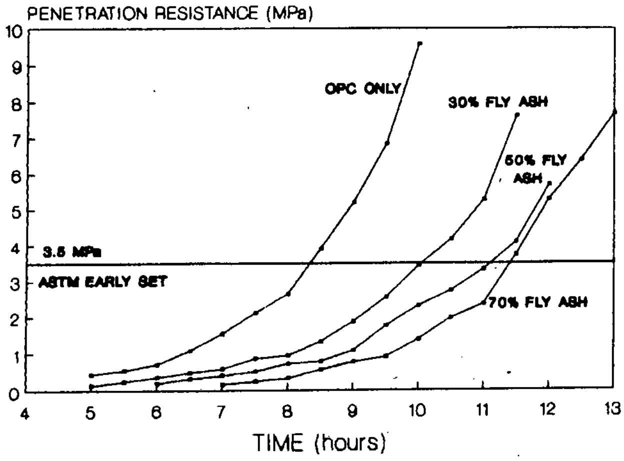

Fig. 4.7a: Penetration Resistance vs. Time - Grade 10 MPa

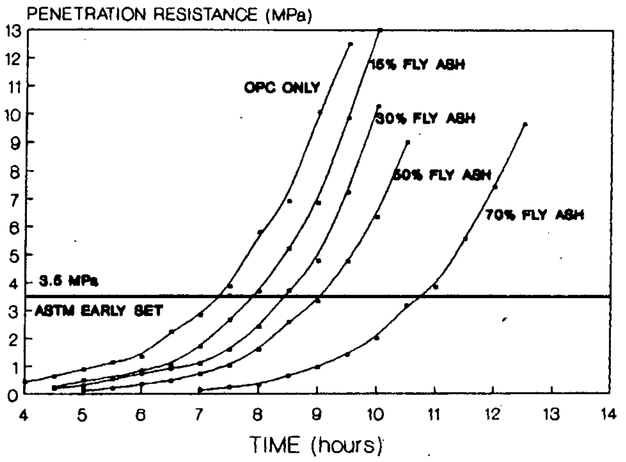

Fig. 4.7b: Penetration Resistance vs. Time - Grade 20 MPa

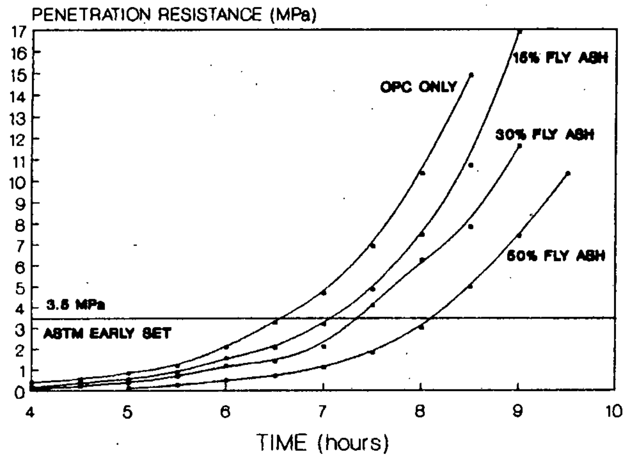

Fig. 4.7c: Penetration Resistance vs. Time - Grade 30 MPa

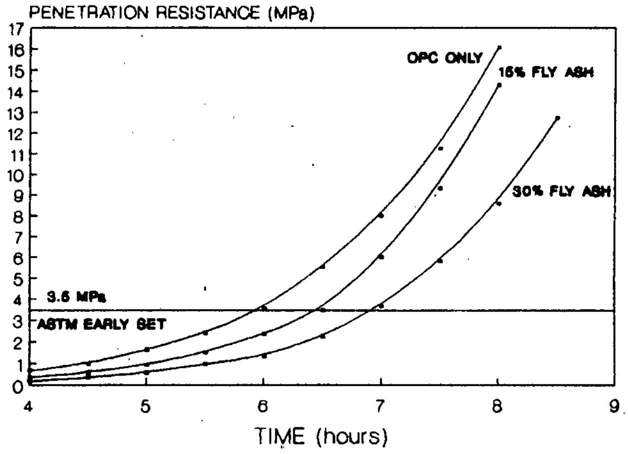

Fig. 4.7d: Penetration Resistance vs. Time - Grade 40 MPa

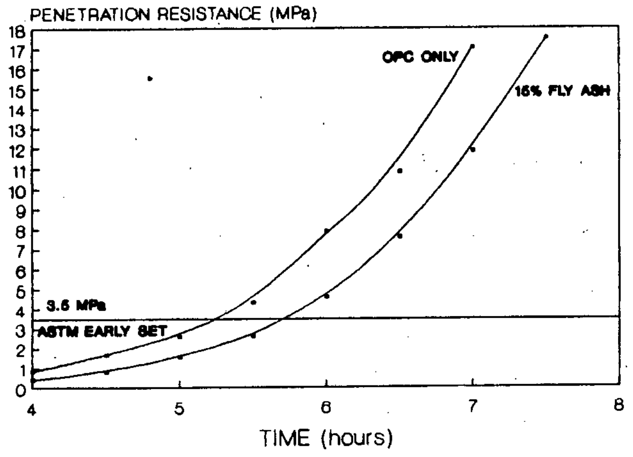

Fig. 4.7e: Penetration Resistance vs. Time - Grade 50 MPa

The delays in the early ~~set times~~ setting caused by the fly ash were found to be relatively small. For with up to 30% fly ash concrete there was at most only 90 minutes delay in setting. Fig. 4.8 shows the early set time plotted against the 28 day compressive strength. As expected both the OPC and fly ash concrete were found to have shorter setting times with higher strengths.

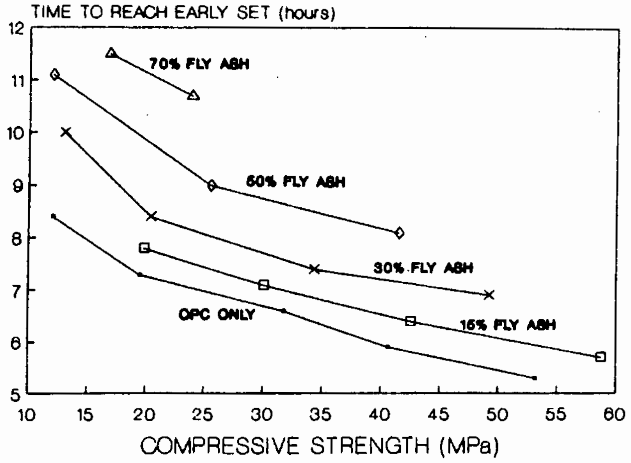

Fig. 4.8: Early Set Time vs. Compressive Strength at 28 days

Doulgeris reported that 30% fly ash concrete had early set delays of 6 hours or more when tested at 23°C (8). More recent work by Ash Resources on Grootvlei and Matla fly ash concrete found significant delays in setting times (9). Using a grade 30 MPa concrete they found that 15% fly ash concrete delayed the early set time by between 30 and 60 minutes. 30% fly ash concrete had delays of between 120 and 180 minutes.

Using Lethabo Field 2 fly ash the maximum delay for a 15% fly ash concrete was 40 minutes while that for a 30% fly ash mix was 100 minutes. No doubt the high quality of Lethabo field 2 fly ash contributed to these results.

4.3.4 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. Workability involves many factors and there are numerous tests which attempt to measure it.

The slump test does not measure the workability of concrete directly but is useful in detecting variations in the uniformity of a mix. It is a simple test to perform and can be used with some confidence for comparative purposes if done properly. The slump test was found to give reliable results for most types of concrete, but for the high percentage fly ash concrete mixes, the stickiness of the mix may have influenced the final slump. As the slump cone was lifted, the concrete adhered to the cone and some shearing action must have taken place. This occurred even though the slump cone was dampened before the test was performed.

Having designed all concrete mixes for 50 mm slump, it is difficult to make comparisons of slumps for the varying percentages of fly ash. However, if the water requirement to reach these slumps is considered, it is clear that fly ash increases the slump dramatically. The average reduction in water requirement with increasing percentages of fly ash for Lethabo field 2 and Matla classified fly ash is as follows:

Percentage fly ash	Water Reduction (l/m^3) Lethabo Field 2	Water Reduction (l/m^3) Matla Classified
10 - 15%	10 - 15	10
15 - 30%	15 - 25	15 - 20
30 - 50%	25 - 40	20 - 25

The reasons for the higher than expected water reduction of Lethabo field 2 fly ash were the high quality of the fly ash and the poor quality of the aggregate used. Cape Flats dune sand which is poorly graded and Malmesbury shale with its angular shape will produce fairly harsh concrete mixes. When using such poor material it is expected that fly ash would help to lubricate the mix considerably.

The Vebe workability test measures the effort involved in changing the shape of fresh concrete by remoulding it on a vibrating table. The amount of effort is measured as the time taken to be fully remoulded. As a constant slump of 50 mm was used throughout, the Vebe times fell within a very narrow range, and no trend was noted. The repeatability of the test is also questionable in this range, with a large amount of scatter.

4.3.5. Mix Economics.

A basic cost comparison was done on the various concrete mixes used. Only the material costs were considered in this analysis, and no attempt was made to calculate costs such as mixing, handling and placing. The material costs were those valid in June 1988. The price of Lethabo field 2 fly ash was assumed to be equal to the then current price of Matla fly ash.

Cape Flats sand	R 13,76 /m^3
13mm Malmesbury shale	R 36,03 /m^3
De Hoek OPC	R 7,85 /50 kg pocket
Lethabo field 2 fly ash	R 6,46 /50 kg pocket
Water	R 0,50 /m^3

The material cost was compared against the 28 day compressive strength. OPC concrete was found to be more expensive than similar fly ash concrete with up to 50% fly ash. The cost saving of using fly ash concrete was more apparent at strengths above 30 MPa. At lower strengths there was little difference in material costs between OPC and fly ash concrete. 70% fly ash concrete was found to be more expensive than OPC concrete but this type of concrete should really be compared at a later age when most of its strength has been achieved.

Fig. 4.9a-c shows the material cost of the OPC and fly ash concrete for the under-, medium- and over-sanded concrete. The material cost is plotted against the 28 day compressive strength. It was thought that since the sand was almost three times cheaper than the stone the over-sanded concrete would be cheaper than the under-sanded concrete. This was not found because of the optimum packing between sand and stone in concrete, which had a large influence on the volume of concrete.

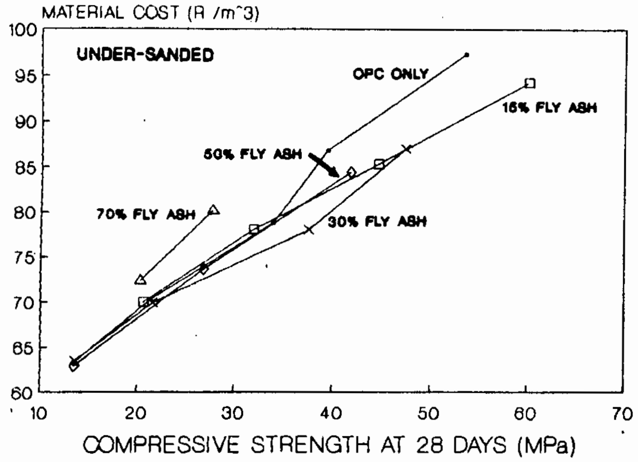

Fig. 4.9a: Material Cost vs. Compressive Strength - Under-sanded Concrete

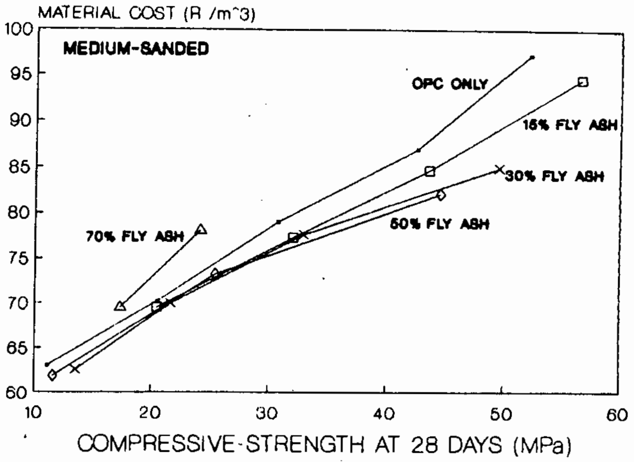

Fig. 4.9b: Material Cost vs. Compressive Strength - Medium-sanded Concrete

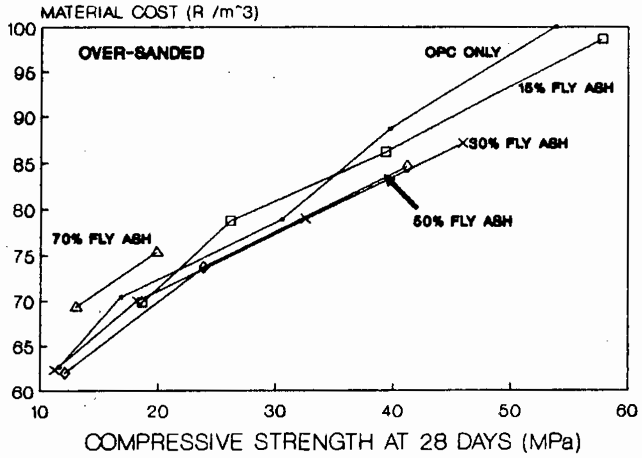

Fig. 4.9c: Material cost vs. compressive strength - Over-sanded Concrete

The main reason for the lower material cost of the fly ash concrete was the reduced cementitious content of the fly ash concrete. The extremely high quality of Lethabo field 2 fly ash concrete not only produced substantial reductions in the water requirements of the concrete, but also resulted in higher than expected compressive strengths at 28 days. The reduced water requirement of the fly ash concrete mixes meant that even though the cement water ratio of the fly ash concrete was higher than similar OPC concrete, the resulting total cementitious material of the fly ash concrete was lower than that of the OPC concrete.

4.4. CONCLUSIONS.

This preliminary work provided a great deal of information about the quality of the materials used. The following points summarise the findings of the research:

1. The actual 28 day compressive strength results for fly ash concrete were higher than the predicted values due to the high quality of Lethabo field 2 fly ash.
2. Long term strength development of Lethabo field 2 fly ash concrete was lower than expected while the short term strength development was higher than expected, both due to the fineness of the fly ash.

3. Both the bleed rate and the bleed capacity of fly ash concrete were lower than that for OPC concrete.
4. Lethabo field 2 fly ash extended the setting times of fly ash concretes. The delay in setting however was found to be much less than the delay experience with Matla classified fly ash.
5. Workability was improved by adding Lethabo field 2 fly ash to concrete.
6. Water requirements of fly ash mixes were substantially lower than those for OPC mixes.
7. The material cost of the fly ash concrete with up to 50% fly ash was lower than that of the OPC concrete.

From the above points it is clear that using a high quality fly ash, such as Lethabo field 2 fly ash, will have many benefits. Most of the physical properties considered in this investigation were enhanced by using fly ash. Properties such as early set characteristics of fly ash concrete were adversely affected but not by as much as expected. Perhaps the only negative point was that the long term strength, as measured at 90 days, was lower than expected.

4.5 REFERENCES

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CHAPTER 5: CONCRETE DURABILITY

5.1 INTRODUCTION

A durable material is defined as one which is capable of lasting or remaining useful for a period. The durability of concrete has become much more important recently with the rapid deterioration of many modern concrete structures. Concrete may be considered durable if it can withstand the conditions it was designed for over its design life.

Concrete durability depends on several factors which vary in importance according to the conditions to which the concrete is exposed. Some of the more important factors are compressive strength, permeability, flexural strength, chemical resistance and abrasion resistance. Given the numerous physical and chemical properties that can have an influence on durability, it is difficult to get an objective measure of the likely durability of concrete. No factor or requirement can be applied universally to all types of concrete nor to different applications and types of exposure. At the moment the only controls on durability are the guidelines and standards laid down in the various codes of practice. These guidelines generally give minimum 28 day compressive strengths and cover to reinforcement.

A lot of research has been done recently on fly ash concrete properties both locally and overseas. A brief review of the existing literature on major durability aspects is given below.

5.2 LITERATURE SURVEY

5.2.1 Compressive Strength

Traditionally the compressive strength of concrete has been used as a measure of the quality of concrete. Normally a 28 day compressive strength was specified as the only consideration, although a minimum cement content has also been introduced. The poor durability performance of many concrete structures that had satisfied the basic strength criteria, necessitated introducing these minimum cement contents.

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. Kelham, for instance, showed how the compressive strengths of concrete, cured in either air or underwater were similar but their rate of water absorption were noticeably different (1). If concrete is well protected from the environment and required mainly to withstand compressive forces, then one can rely on the compressive strength as an indication of the likely durability. If this is not the case then other factors must be considered which are relevant to the conditions of exposure.

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 slower rate of strength development but carries on gaining strength longer than OPC concrete (2). This difference in the rates of strength development can be used to advantage in mass concrete where long term strength is required. Where early strength is required however, the slower rate of strength gain of fly ash concrete may be a disadvantage.

Even though compressive strength does not measure durability directly it is an easy test to perform, is widely known and gives good comparative information. Most research on the performance of concrete will include standard compressive strength results of the concrete tested. Compressive strength is often used as a benchmark to which other properties of concrete are compared.

5.2.2 Permeability

The durability of concrete near an exposed surface is often more influenced by the rate at which harmful agents can penetrate into the concrete than by any other property. Many ways have been devised to measure what can loosely be called the permeability of concrete. Strictly the permeability of concrete is the flow caused by a pressure differential across the concrete sample. Recently the term "permeability" has come to encompass other fluid flow mechanisms such as water absorption and capillary flow. These various "permeability" tests are often difficult to compare and may only be relevant to certain conditions. The tests however are useful for comparative studies and for use in standard specifications.

One of the reasons for the proliferation of "permeability" tests is the varied nature of exposure of the concrete and the function that the concrete has to perform. In a water retaining structure the relative degree of through-flow in the structure is of importance. To simulate, this a steady flow must be measured under an applied head across a concrete sample. This is the basis of the output permeability method such as that devised by the CSIR (3). With a reinforced concrete structure in an aggressive environment, the rate of infitration of harmful agents into the cover concrete is of importance. Here a test measuring the depth of penetration of water at the required head would indicate how vulnerable the concrete was to attack. This is the basis of the DIN 1048 permeability test (4). Alternatively, if the concrete was unsaturated, the predominant mechanism might be capillary action in which case a water absorption method would be used. This is the basis of the sorptivity test which measures the rate of penetration of water as described by Ho and Lewis (5). Clearly the "permeability" method chosen must have some relevance to the type of exposure most likely to occur to the concrete on site.

It is a general observation that the stronger a concrete is, the denser it will be and therefore the more impermeable (6). Similarly the inclusion of high quality pozzolanic material such as fly ash in concrete has been shown to improve the impermeability of concrete (7). Therefore fly ash concrete would be expected to be more durable than similar OPC concrete in certain environments where the concrete permeability is a major durability factor.

5.2.3 Chemical Resistance

The chemical resistance of concrete to attack by harmful substances is of particular importance in aggressive environments. Common forms of attack include sulphate, sea water, soft water and acid attack. Apart from using denser concrete, specialised cements and additives can be used to resist to some extent the harmful effect of these forms of attack on the hydration products of the cement.

Fly ash concrete has been found to resist sulphate and sea water attack due to the better impermeability of the concrete and because the fly ash combines with the free $Ca(OH)_2$ produced by the cement hydrating (8). It is thought that this additional reaction helps block up the pores of the concrete and so lessen the effect of aggressive attack. Similarly in soft water and slightly acidic water the fly ash removes the free $Ca(OH)_2$ from the cement hydration and so stops it being leached out of the concrete as soluble $Ca(OH)_2$ (9). Even though fly ash concrete has been shown to be more chemically resistant than similar OPC concrete, it is still vulnerable to severe exposure such as strong acid solutions.

5.2.4 Physical Resistance

The physical resistance of concrete is mostly influenced by its strength and pore structure. Concrete may have to resist frost action, physical abrasion, impact loading, repeated wetting and drying, erosion, cavitation, thermal fluctuations and shrinkage. Several methods have been devised using these properties to determine the physical resistance of concrete. Examples of these types of tests are the freeze-thaw test, drying shrinkage test and wire brush abrasion test.

Some researchers have found that fly ash concrete is less resistant to repeated cycles of freezing and thawing than similar OPC concrete (10). However most research seems to indicate that fly ash concrete has comparable resistance with similar OPC concrete to freeze-thaw action (11). The resistance of fly ash concrete to surface abrasion has also been found to be similar to that for OPC concrete. The shrinkage properties of fly ash concrete have been found not to be significantly different to OPC concrete for equal volumes of paste (12). The overall physical resistance of a concrete will obviously depend on which of the forms of physical attack are taking place in the field.

5.3 TEST METHODS AND PROCEDURES

5.3.1 Compressive Strength

Three types of fly ash were considered in this study of compressive strength of fly ash concrete. Lethabo field 2, Lethabo classified and Matla classified fly ash were used with the other materials remaining the same. Twelve concrete mixes were produced for each type of fly ash using three grades of concrete. The mixes were identical from one type of fly ash to the next except for the variation in water requirements caused by the particular fly ash. The actual concrete mixes used and their water requirements are discussed in more detail in Chapter 3.

All the 100 mm concrete cubes were wet cured in a curing tank at 20°C before being crushed at either 7, 28 or 90 days. Compressive strength testing of concrete was done in accordance with SABS 863 (13). Early strength development was determined at 7 days, the concrete grade was determined at 28 days and the long term strength development was determined at 90 days. It was intended that any differences in compressive strength between similar types of concrete would be due only to the type of fly ash used.

5.3.2 Freeze-Thaw Resistance

Although damage to concrete from freeze-thaw action is not a real problem in South Africa the test is useful for comparative work on the physical resistance of concrete. A medium-sanded concrete was used with 18 concrete mixes decribed in more detail in Chapter 3. 100 mm concrete cubes were used for this test which was done in accordance with ASTM C 666-84 (14). The concrete was initially cured underwater for 28 days before being exposed to repeated cycles of freezing and thawing. Freezing was done for 6 hours at -15°C in a cold room followed by 6 hours of thawing in a water curing tank at 20°C. The concrete samples were subjected to 100 freeze-thaw cycles before being tested for compressive strength at 90 days. The concrete cubes were kept in the frozen state during any interruption in the freze-thaw cycles and after 100 cycles until the concrete reached an age of 90 days. The deterioration of the concrete samples due to the freeze-thaw action was determined by the change in compressive strength between 28 and 90 days.

5.3.3 Water Absorption

Using a medium- and under-sanded concrete mix series standard water absorption tests were done on 150 mm concrete cubes (15). The concrete cubes were initially wet cured in a curing tank before being tested. After 28 or 90 days of wet curing the concrete cubes were oven dried at 105°C for 48 hours and then submerged in water at 20°C for 24 hours. The gain in weight due to the water absorption was measured and this value, expressed as a percentage was the water absorption.

Van Dijk reported that fly ash reduced the water absorption of concrete as measured using this test (16). The test really measures the surface absorption of the concrete as the time for both drying and wetting is not long enough for complete drying or for full absorption of the concrete cube. The test is useful for making comparisons between different types of concrete. The sorptivity test, which is discussed next, may be seen as a refinement of the basic water absorption test.

5.3.4 Sorptivity

Water sorptivity is defined as the movement of water through a porous material due to capillary action. The concept of sorptivity may be applied to concrete because capillary action is often the predominant mechanism causing water movement in concrete. Particularly in above ground concrete structures, water absorption of concrete is of more importance than concrete permeability measured using an applied hydrostatic head.

Ho and Lewis determined the sorptivity of concrete by splitting six prism samples of concrete of dimensions 400 x 170 x 60 mm and measuring the depth of water penetration (17). The concrete samples were subjected to continuous water spraying after initially being air-dried from their saturated conditions for 21 days at 23°C and 50% R.H. The depth of water penetration was visually noted by splitting specimens at periods of 1/2, 2, 4, 8, 16 and 24 hours. The depth of water penetration into the concrete was found to be proportional to the square root of time. The concrete sorptivity was then determined by calculating the slope of the graph obtained ie. the rate of penetration of water into the concrete with time. A typical graph obtained by this method is shown in Fig. 5.1 below.

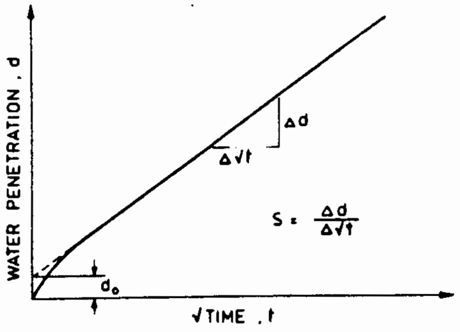


Fig. 5.1: Depth of Water Penetration vs. Square Root of Time - Typical Result

This method was found to give consistent results which could be applied to concrete on site. Knowing the sorptivity of concrete, the number of rain hours required to saturate the concrete to a given depth could be determined. It was decided not to use this test due to the following shortcomings:

1. Six specimens are required to obtain a single test result.
2 The test only measures the depth of penetration of water over the first 24 hours. For a dense concrete the total depth of penetration in this period may be quite small so that the accuracy of the test may be poor.
3. The test does not measure the effective porosity of the concrete and the time to reach full saturation is also unknown.

Kelham proposed a water absorption test to measure the sorptivity of concrete (1). In this method the mass of water absorbed by an unsaturated concrete sample was measured at various time intervals until fully saturated. By plotting the resulting weight gain due to the water absorption against the square root of time, the sorptivity, effective porosity and time to reach full saturation could be determined.

The samples used for Kelham's water absorption test were 150 mm diameter by 50 mm deep which had been oven dried at 105°C for 1 week. This is a particularly harsh drying environment and it was accepted that some damage could be caused to the concrete pore structure. The sides of the samples were sealed with bitumen and water-proof tape and the top of the sample was covered with a perspex lid containing a 2 mm air gap. This air gap was joined to the atmosphere by a capillary tube to allow any air displaced by the absorbed water to escape. The sample was then suspended in water with the bottom concrete surface in contact with water while the top surface was exposed to the atmosphere so that water was free to be absorbed by capillary action. The weight of water absorbed by the concrete was then measured at intervals until the concrete reached full saturation. The apparatus used by Kelham is shown in Fig. 5.2 below.

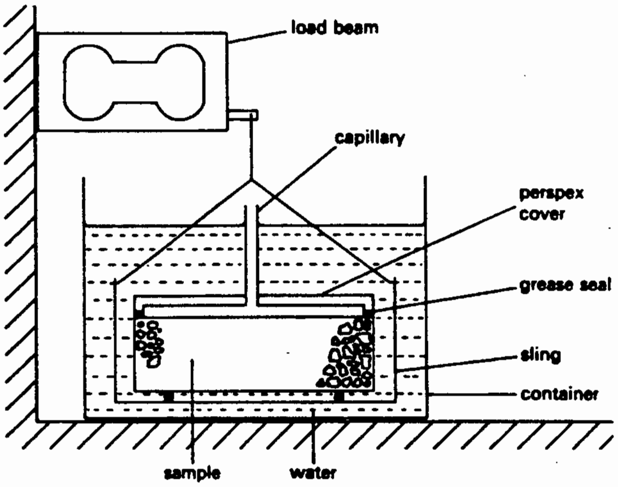


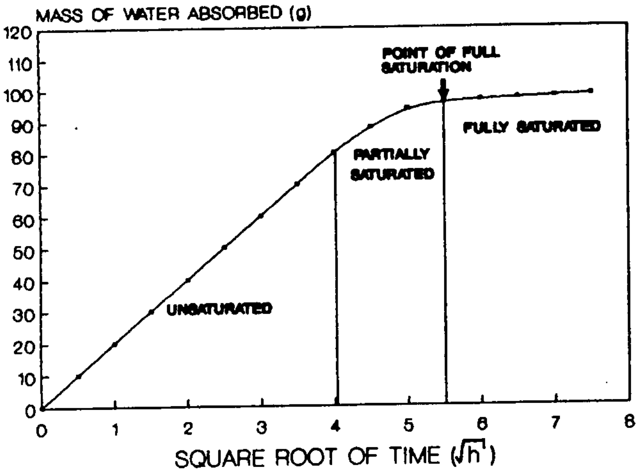
Fig. 5.2: Kelham Water Absorption Apparatus

The sorptivity of the concrete was determined from both the slope of the graph, which is the rate of water absorption with time, and the full saturation value, which is the effective porosity of the concrete. The weight change caused by water absorption was measured continuously and logged automatically. This weight change was actually the change in bouyancy of the concrete as the absorbed water displaced the air in the pores.

It was decided to use the sorptivity method described by Kelham with the following modifications :

1. The thickness of the concrete disc was reduced to 40 mm so that 6 usable discs could be cut from a single 300 mm deep cylinder.
2. The sides of discs were sealed with wax because the bitumen and water-proof tape method was too time consuming and expensive for the number of tests to be done.
3. Samples were submerged in a large curing tank and weight readings measured manually with a digital scale. In this way up to 30 samples could be tested simultaneously.

The concrete sorptivity was found from the average of six discs cut from the same cylinder. The initial weight of the sample suspended in water had to be determined by extrapolating the results back to zero. This was because after submersion in water the samples took up to one minute to settle down. Fig. 5.3 shows a typical graph obtained showing the various stages of water absorption.



Effective Porosity,

$$P = \frac{\text{Mass of water absorbed}}{\text{Volume of sample}} \times 100$$

Sorptivity,

$$S = \frac{\text{Slope } (\Delta \text{Mass} / \Delta\sqrt{\text{Time}})}{\text{Area} \times \text{Porosity} \times \text{Water Density}}$$

Fig 5.3: Water Absorption vs. Square Root of Time - Typical Result

The sorptivity measured by this method was that for unsaturated concrete. It is unlikely that any concrete structure in the field will be totally unsaturated so concrete sorptivities measured insitu will generally be lower than those measured experimentally. Hall, in a recent review of water sorptivity, reported that the degree of saturation of concrete will affect the sorptivity of concrete (18). Although the sorptivity measured by this method could not be applied directly to concrete insitu it produced consistent results for comparative work.

5.3.5 Depth of Penetration

A rudimentary exercise was done using applied hydrostatic heads on unsaturated concrete samples. The test was a simplification of the input permeability test prescribed by DIN 1048. 150 mm concrete cubes were wet cured before being tested at 28 or 90 days. The concrete cubes were then oven dried at 105°C for 48 hours before being subjected to an applied head.

Initially a hydrostatic head of 5m was applied for a period of 1 hour after which the concrete cubes were split and the maximum depth of water penetration was measured. It was soon realised that the capillary forces were probably far higher than the applied head of water because of the concrete was tested in the unsaturated state. It was estimated that the capillary suction of the unsaturated concrete was equivalent to a 15m head of water.

To determine how significant the the capillary action was in causing water movement the second series of concrete cubes were subjected to a reduced head of 150 mm while the duration of the test was increased to 6 hours. The depth of penetration of water was again determined by splitting the samples at the end of the test.

5.3.6 Permeability

Work was carried out in conjunction with Ash Resources in Johannesburg using the input permeability method in accordance with DIN 1048. The concrete used for this work was similar to that used at UCT for research into other permeability properties of concrete. The material used was identical to that used at UCT having been transported to Johannesburg specifically for this research. In this test three prism samples of dimensions 200 x 200 x 120 mm were tested for depth of water penetration after being wet cured for 28 days. The specimens were removed from their moulds after 24 hours and one of the side surfaces was roughened to remove the water resistant surface layer. This roughened surface was subjected to water at increasing pressure of 100, 500 and 700 kPa over a period of 5 days after being wet cured. Unlike the sorptivity test, this test is done on saturated concrete.

The depth of water penetration was determined at the end of 5 days of applied hydrostatic head by splitting the sample and measuring the maximum depth of water penetration. The position of the water front could be seen clearly as water under pressure in the pores seeped to the split surface immediately after the sample was split.

For this research an OPC concrete and a 30% fly ash concrete of grade 30 MPa were compared. The type of fly ash used was Lethabo classified fly ash. The OPC and fly ash concrete mixes were cast concurrently and were repeated a week later for confirmation. Testing of the OPC and fly ash concrete samples was done together in the six test rigs after 28 days wet curing.

5.4 RESULTS AND DISCUSSION

5.4.1 Compressive Strength

The 28 day compressive strength was used to indicate the cementing efficiency of the fly ash. Of the three types of fly ash used in this research Lethabo field 2 fly ash was found to be the best with regards to cementing efficiency. This can be observed by comparing the 28 day compressive strengths of the three types of fly ash concrete. Fig. 5.4a-c shows the 28 day compressive strengths plotted against the cement water ratio for Lethabo field 2, Lethabo classified and Matla classified fly ash concrete.

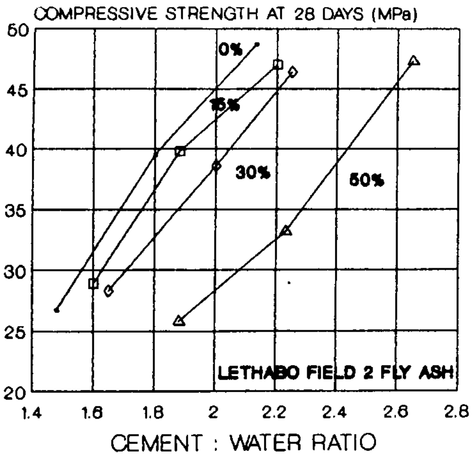


Fig. 5.4a: Compressive Strength vs. Cement Water Ratio - Lethabo field 2 fly ash

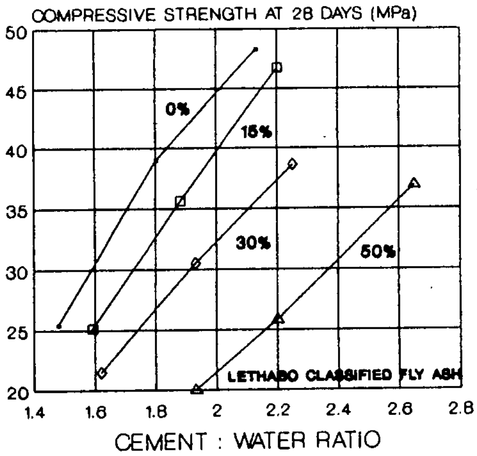


Fig. 5.4b: Compressive Strength vs. Cement Water Ratio - Lethabo classified fly ash

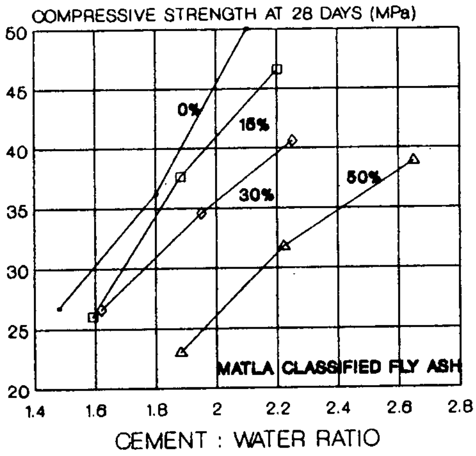


Fig 5.4c: Compressive Strength vs. Cement Water Ratio - Matla classified fly ash

From the graphs it can be seen that Lethabo field 2 fly ash concrete produced the highest 28 day strengths for any given cement water ratio followed by Matla classified fly ash concrete while Lethabo classified fly ash concrete produced the lowest strengths. The high strengths of Lethabo field 2 fly ash concrete were expected because of the fineness of the fly ash and the above average presence of ultra-fine particles. What was surprising was the low compressive strength results of Lethabo classified fly ash concrete. It was expected that the results for Lethabo classified fly ash concrete would be comparable to those for Lethabo field 2 fly ash concrete as the two fly ashes had similar fineness values. The only explanation for this anomaly was that Lethabo classified fly ash lacked the ultra-fine particles found in Lethabo field 2 fly ash.

The 28 day compressive strength results of Matla classified fly ash concrete were found to be similar to those predicted by Ash Resources (19). Matla classified fly ash concrete had a higher fineness value of 9.6 compared to that for Lethabo classified or Lethabo field 2 fly ash (6.4 and 7.7 respectively). Therefore the compressive strengths for Matla classified fly ash concrete were not expected to be as high as the strengths for either of the Lethabo fly ash concretes. The Matla classified fly ash concrete compressive strength results were higher than those for Lethabo classified fly ash concrete. This shows how the the fineness value as measured by the percentage fly ash passing the 45 μm sieve may be misleading as a measure of the quality of fly ash.

The same trend observed above was apparent when comparing the 7 day compressive strength results for the three types of fly ash concrete. Lethabo field 2 fly ash concrete produced higher compressive strength results than either Lethabo classified or Matla classified fly ash concrete. This can be seen by comparing the actual 7 day compressive strengths for the three types of fly ash concrete. Fig 5.5a-c shows the 7 day compressive strength results for Lethabo field 2, Lethabo classified and Matla classified fly ash concrete.

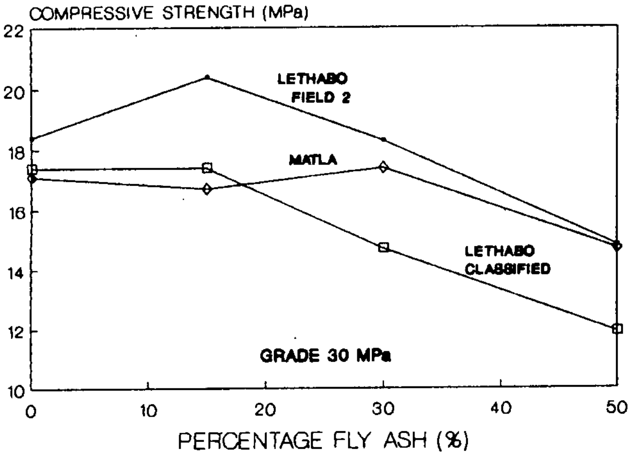


Fig. 5.5a: Compressive Strength at 7 days - Grade 30 MPa

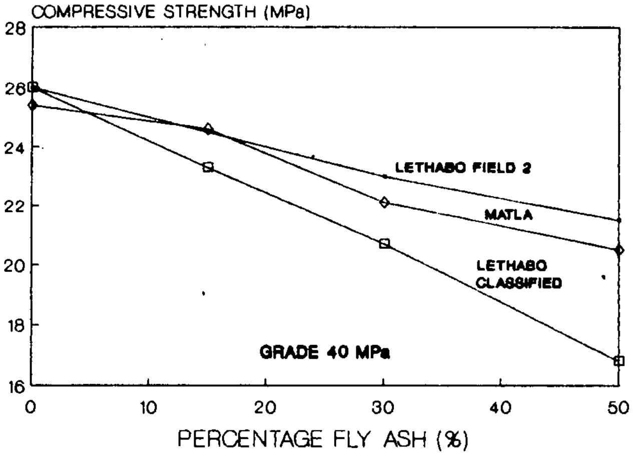


Fig. 5.5b: Compressive Strength at 7 days - Grade 40 MPa

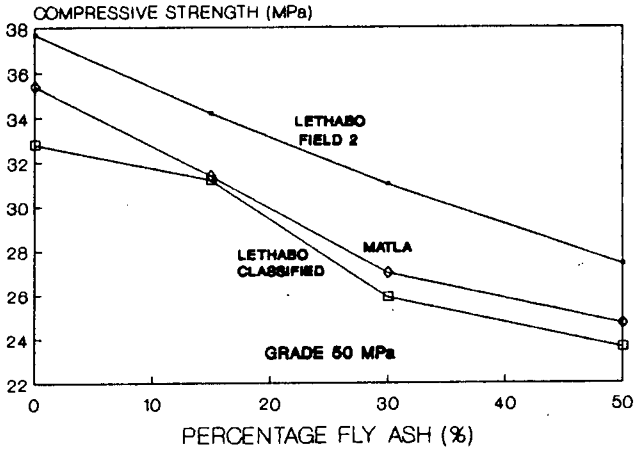


Fig. 5.5c: Compressive Strength at 7 days - Grade 50 MPa

If the strength development of the three fly ash concretes are compared it is clear that Lethabo field 2 fly ash concrete gained strength more rapidly than the other two fly ash concretes. This rapid early strength development of Lethabo field 2 fly ash concrete was followed by much slower long-term strength development. This can be seen in Fig. 5.6a-d where the compressive strength of the three fly ash concretes are plotted against time for the grade 50 MPa concrete.

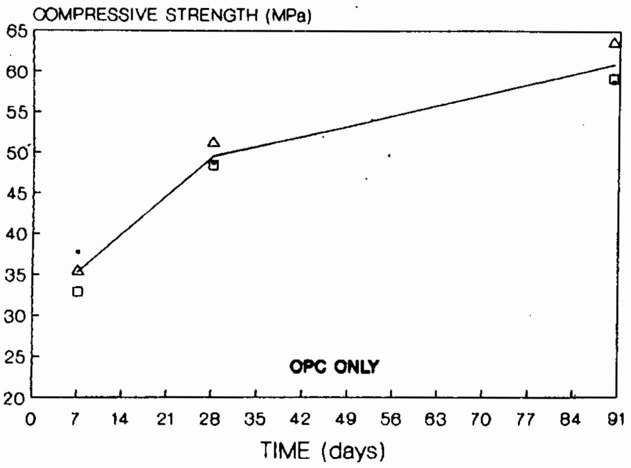


Fig. 5.6a: Compressive Strength Development - 0% Fly Ash

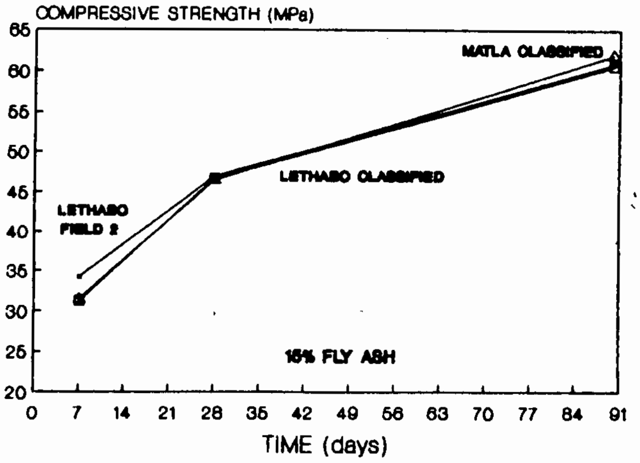


Fig. 5.6b: Compressive Strength Development - 15% Fly Ash

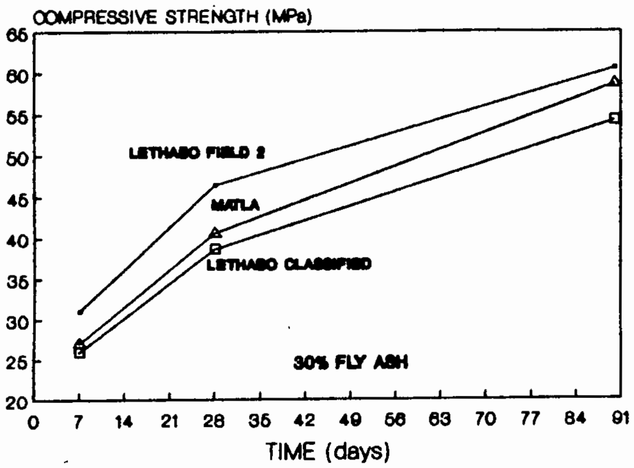


Fig. 5.6c: Compressive Strength Development - 30% Fly Ash

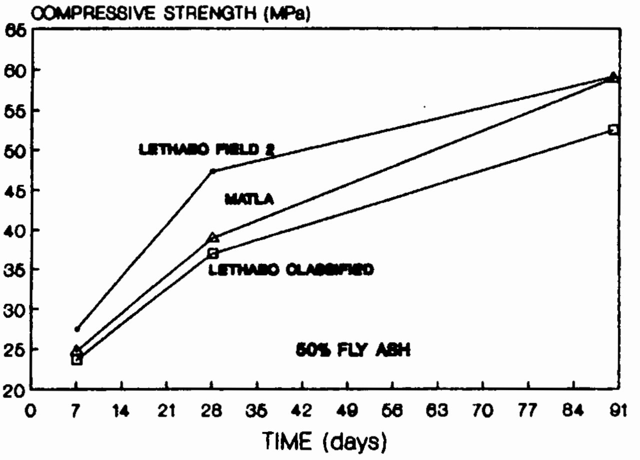


Fig. 5.6d: Compressive Strength Development - 50% Fly Ash

The graph for the OPC only concrete shows the amount of variation in the compressive strength results as the three different concrete mixes had virtually identical mix constituents but were mixed at different times as controls for the various types of fly ash concrete. The long-term strength development of Lethabo classified and Matla classified fly ash concrete were found to be higher than that for Lethabo field 2 fly ash concrete. This effect was found to be more pronounced at higher percentages of fly ash. Matla classified fly ash concrete with 50% fly ash was found to have equal 90 day compressive strength to that for Lethabo field 2 fly ash concrete. This occurred even though the compressive strength of Matla classified fly ash concrete was substantially lower than similar Lethabo field 2 fly ash concrete at 28 days.

The slower long-term strength development of Lethabo field 2 fly ash concrete can be seen more clearly by comparing the compressive strength at 90 days over that at 28 days for the three types of fly ash concrete. This compressive strength ratio measures the long-term strength development after 28 days. The better long-term strength development of the Lethabo classified and Matla classified fly ash concrete would be best used in mass concrete structures where the long term strength is important and the concrete is not affected by poor curing. Lethabo field 2 fly ash concrete would be best suited to reinforced concrete structures where early strength is required and where poor curing is possible. Fig. 5.7a-c shows the compressive strength ratio as measured by the compressive strength at 90 days to that at 28 days for Lethabo field 2, Lethabo classified and Matla classified fly ash concrete for concrete of grades 30, 40 and 50 MPa.

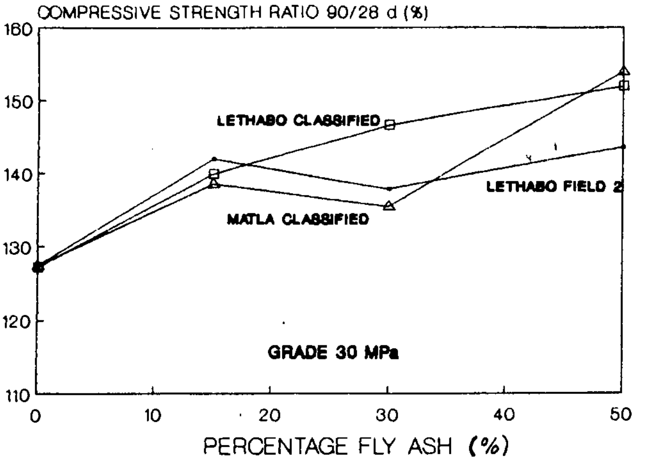


Fig. 5.7a: Long-term Compressive Strength Ratio - Grade 30 MPa

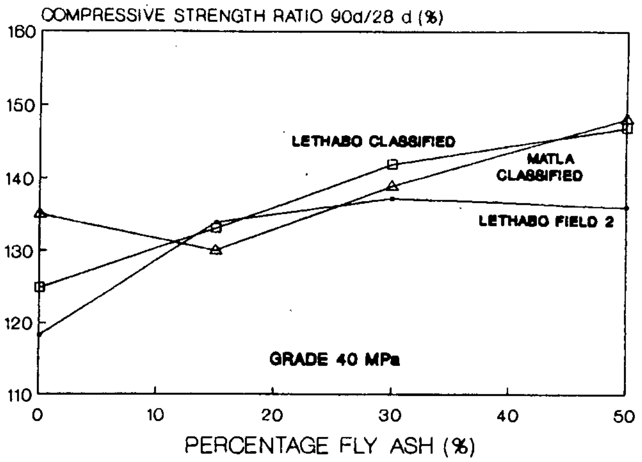


Fig. 5.7b: Long-term Compressive Strength Ratio - Grade 40 MPa

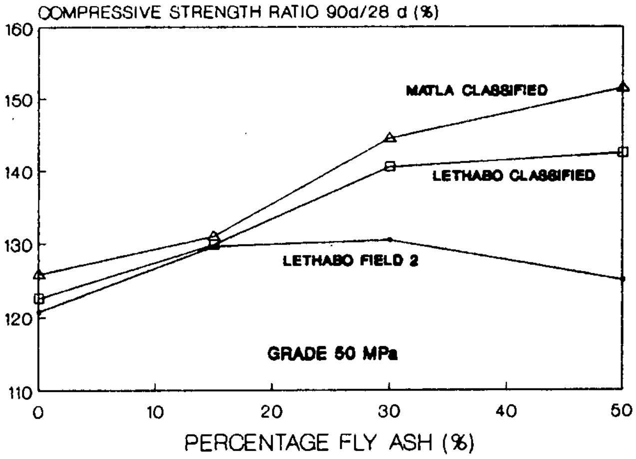


Fig. 5.7c: Long-term Compressive Strength Ratio - Grade 50 MPa

The grade 30 MPa OPC concrete shown in Fig. 5.7a had almost exactly the same long-term compressive strength development as would be expected from virtually identical concretes. The scatter of results for the grade 50 MPa OPC concrete was fairly typical of the cube test while that found for the grade 40 MPa OPC concrete was exceptionally high.

The compressive strength results were expected to be reliable because of the nature of the test. Results showed that the degree of control used in mixing, compacting, curing and crushing of the cubes was very good. Generally the coefficient of variation of the three cube results was less than 5% A statistical exercise was done with 20 cubes of the same concrete crushed at 28 days. The resulting coefficient of variation of the cube compressive strength result was 3.8% which fairly low, even for laboratory mixed concrete.

5.4.2 Freeze-thaw Resistance

Concrete used for this work ranged in strength from grade 10 MPa to grade 50 MPa and so it was not surprising that the amount of deterioration experienced by the concrete varied considerably. Low strength concrete was far more adversely affected by freezing and thawing than was the high strength concrete. All the grade 10 MPa concrete cubes showed significant damage after 100 cycles of freezing and thawing with large pieces of concrete spalling off the cubes.

The extent of the freeze-thaw action on the concrete was determined from the compressive strength ratio at 90 days, by measuring the compressive strength of concrete after 100 cycles of freezing and thawing to the compressive strength of the same concrete which was wet cured. This compressive strength ratio varied from 60% for some grade 10 MPa concrete to 95% for the higher strength concrete. Fig. 5.8 shows the compressive strength ratios for the 18 types of concrete plotted against their original 28 day compressive strengths.

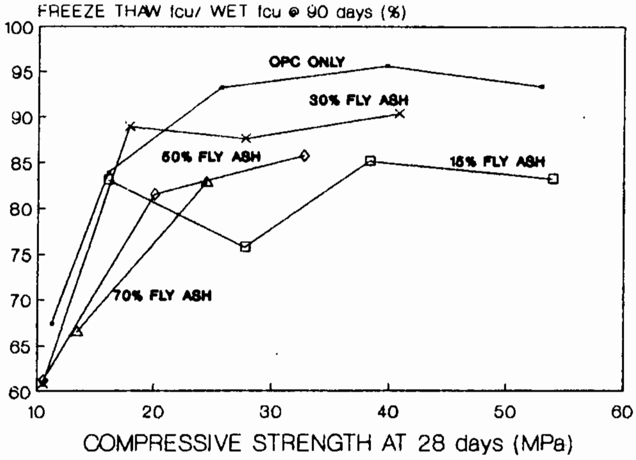


Fig. 5.8: Compressive Strength Ratio vs. Compressive Strength - 100 cycles of freezing and thawing

OPC concrete appeared to be less severely affected by the freeze-thaw cycling than similar fly ash concrete. The results show quite a lot of scatter and no definite trend can be seen for increasing percentages of fly ash in concrete. The OPC concrete appeared to be better able to resist the damage from the freeze-thaw cycles particularly at compressive strengths above 30 MPa.

Fly ash concrete was expected to perform at least as well as OPC concrete with regard to freeze-thaw durability. This was expected because of the lower permeability and better long-term strength development of fly ash concrete compared to that for OPC concrete. The only explanation for the poor performance of fly ash concrete to freeze-thaw action was that the finer pore structure of fly ash concrete was less able to resist the expansive forces caused by the water freezing.

Some of the damage to the concrete cubes must have been caused by handling the specimens from the cold room to the curing tank. This occurred due to water freezing under the cubes which were placed on plastic matting in the cold room. The cubes had to be pulled off the matting when they were removed from the cold room. It was assumed that this damage was equally distributed over all types of concrete as all the specimens were tested at the same time.

5.4.3 Water Absorption

The water absorption of concrete was found to decrease with increasing compressive strength of concrete and with increasing percentage fly ash in concrete. This was found for both the medium- and under-sanded concrete at 28 and 90 days. Fig. 5.9a-d shows the water absorption of concrete for both medium- and under-sanded concrete when tested at 28 and 90 days.

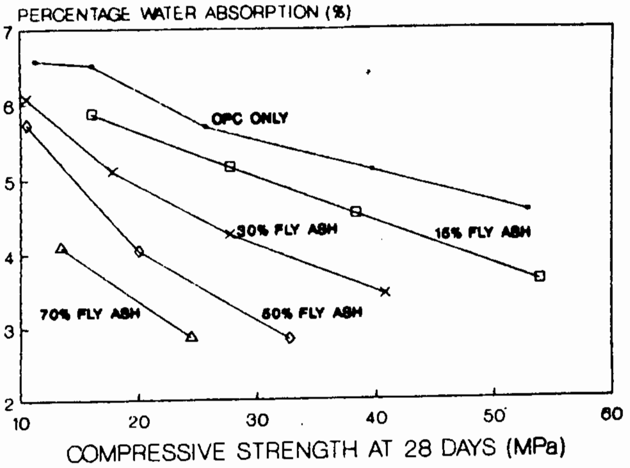


Fig. 5.9a: Water Absorption vs. Compressive Strength - Medium-sanded at 28 days

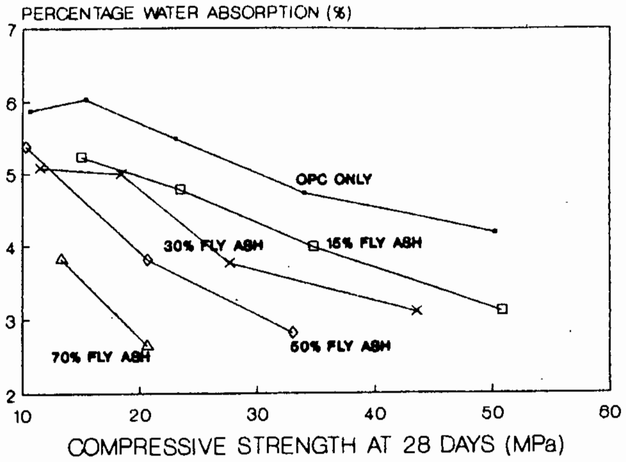


Fig. 5.9b: Water Absorption vs. Compressive Strength - Under-sanded at 28 days

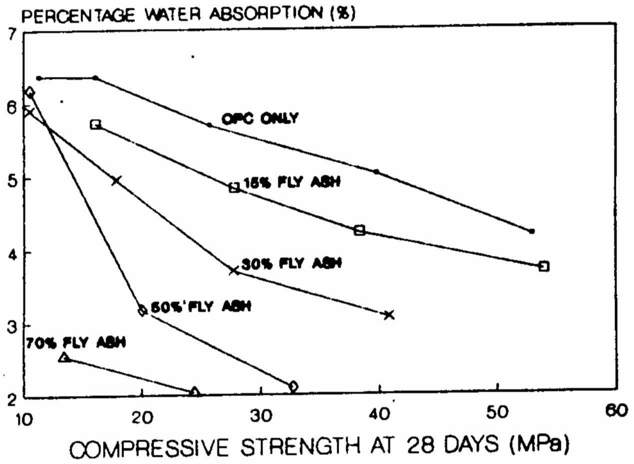


Fig. 5.9c: Water Absorption vs. Compressive Strength - Medium-sanded at 90 days

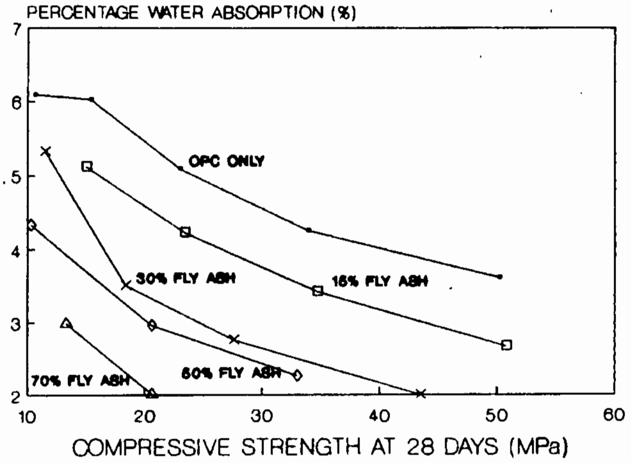


Fig. 5.9d: Water Absorption vs. Compressive Strength -Under-sanded at 90 days

The results from this test were surprisingly consistent especially considering that only one test specimen was used for each result. The inclusion of fly ash had a major effect in reducing the water absorption of concrete. A 50% fly ash concrete had roughly half the water absorption of an OPC concrete. The effect of increasing compressive strength was not nearly as dramatic in reducing the water absorption of concrete.

The decrease in water absorption between 28 and 90 days was related to the gain in compressive strength of the concrete. OPC concrete was found to have little decrease in water absorption between 28 and 90 days. During the same period OPC concrete had little further compressive strength development and this would indicate that the pore structure of the concrete remained almost unchanged. Fly ash concrete, particularly high percentage fly ash concrete, showed substantial reduction in water absorption between 28 and 90 days. The compressive strength development during the same period was higher than that for OPC concrete which indicates continued hydration of concrete and the resultant narrowing of the pore structure. This explains the lower water absorption of fly ash concrete at 90 days. Fig. 5.10a and b show the water absorption development as measured between 28 and 90 days for the medium- and under-sanded concrete.

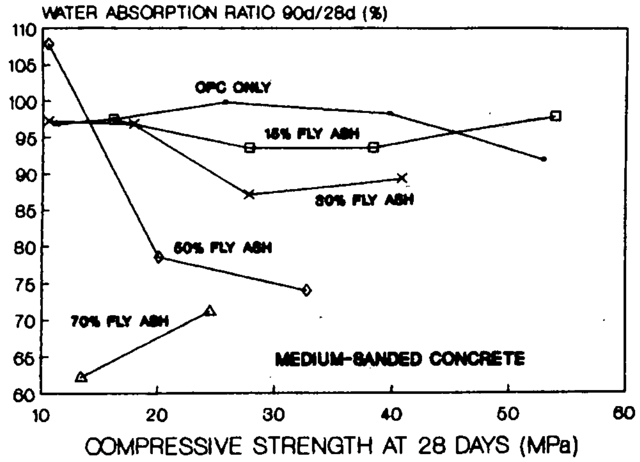


Fig. 5.10a: Water Absorption Development
- **Medium-sanded concrete**

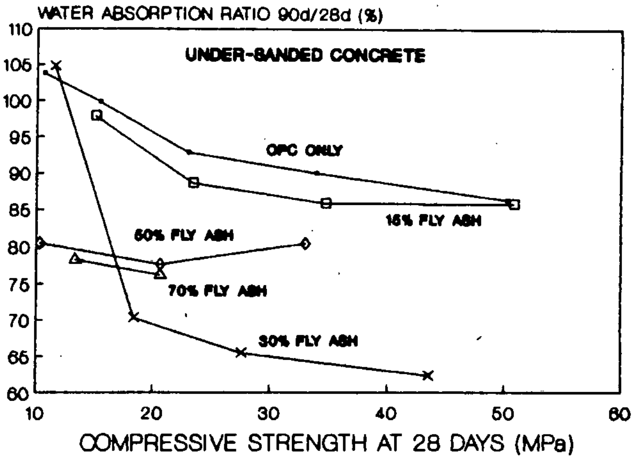


Fig. 5.10b: Water Absorption Development
- Under-sanded concrete

5.4.4 Sorptivity

The effect of increasing compressive strength of concrete was found to reduce the rate of water absorption of OPC concrete. This can be seen in Fig. 5.11 where the mass of water absorbed is plotted against the square root of time for grades 30, 40 and 50 MPa concrete tested at 28 days. Each curve represents the average of 6 results which have been corrected to the average thickness of 40 mm. From these curves the sorptivity, effective porosity and time to reach full saturation can be determined. The point of full saturation was determined as being that point at which the water absorption curve reached the flatter plateau.

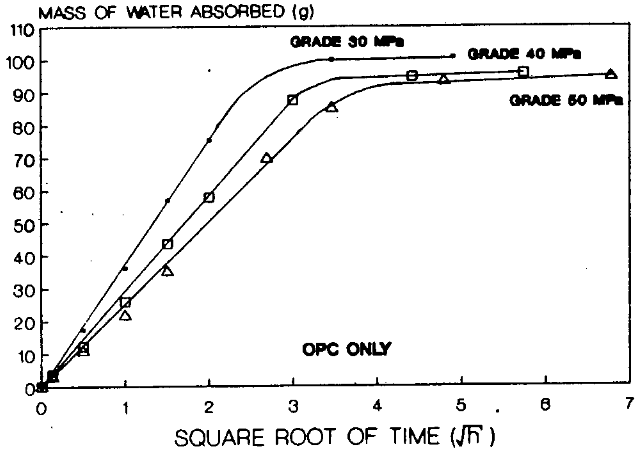


Fig. 5.11: Mass of Water Absorbed vs. Square Root of Time
- OPC Only Concrete Tested at 28 days

Grade of Concrete (MPa)	Actual 28 day Comp. Strength (MPa)	Sorptivity ($mm/\sqrt{h}$)	Effective Porosity (%)	Time to Reach Saturation (h)
30	26.7	15.07	14.10	9.8
40	36.2	12.39	13.25	12.7
50	51.2	10.65	13.04	16.6

The sorptivity and effective porosity of OPC concrete were both found to decrease with increasing compressive strength. This was expected as stronger concrete has a denser structure with narrower capillaries and lower porosity. This would have contributed towards the lower rate of water absorption and the lower total amount of water absorbed by the stronger concrete. If the sorptivity and porosity values are compared against the 28 day compressive strengths for the OPC concrete these trends are confirmed. Fig. 5.12a shows the graph of sorptivity tested at 28 days plotted against the 28 day compressive strength for all the OPC concrete tested. Fig. 5.12b shows the similar graph of effective porosity plotted against 28 day compressive strength for OPC concrete.

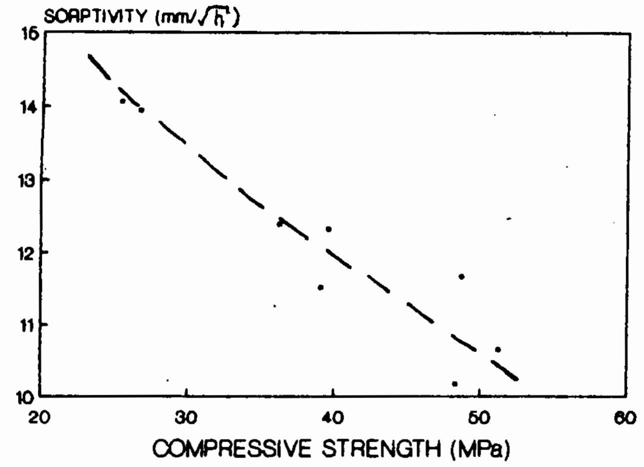


Fig. 5.12a: Sorptivity vs. Compressive Strength - Tested at 28 days

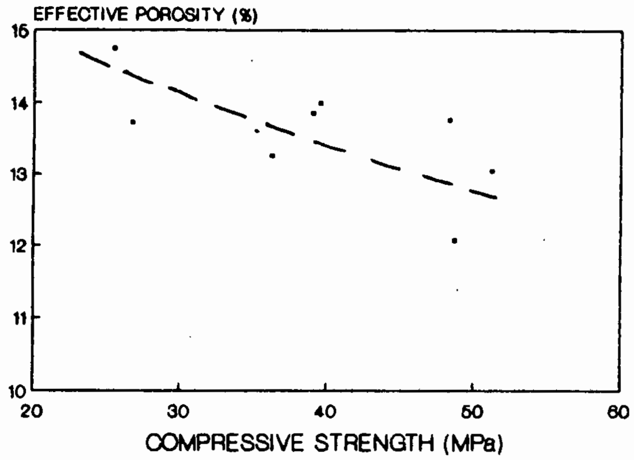


Fig. 5.12b: Effective Porosity vs. Compressive Strength - Tested at 28 days

The sorptivity of concrete was also found to be influenced by the percentage fly ash in the concrete, particularly after 28 days when the pozzolanic reaction was well underway. The decrease in sorptivity caused by the addition of fly ash was found to be proportional to the percentage fly ash in the concrete. Fig. 5.13a and b show the average water absorption curves for OPC and Lethabo field 2 fly ash concrete of grade 30 and 50 MPa tested at 28 days. It was found that the effective porosity of concrete also decreased with increasing percentages of fly ash.

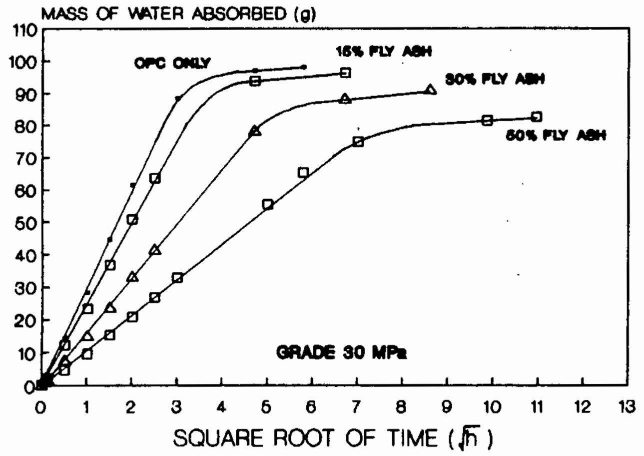


Fig. 5.13a: Mass of Water Absorbed vs. Square Root of Time - Grade 30 MPa at 28 days

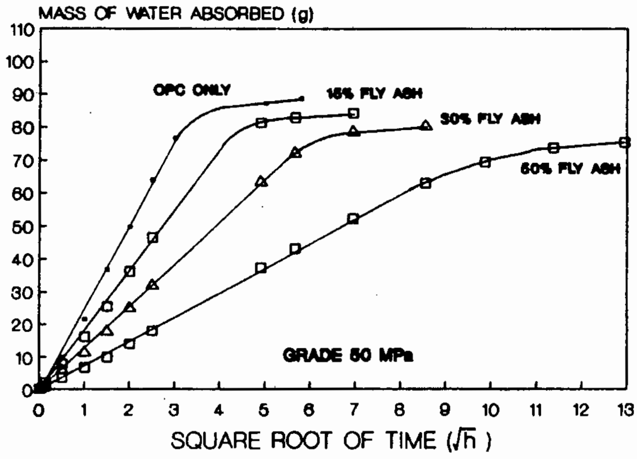


Fig. 5.13b: Mass of Water Absorbed vs. Square Root of Time - Grade 50 MPa at 28 days

When the sorptivities of the three types of fly ash concrete were compared it was clear that Lethabo field 2 fly ash concrete had much lower sorptivities than either Lethabo classified or Matla classified fly ash concrete when tested at 7 or 28 days. This was due to the high quality of Lethabo field 2 fly ash which helped block the pores initially and contributed to the rapid early strength development which closed up the pore structure. In comparison the sorptivities of Lethabo classsified and Matla classified fly ash concrete measured at 7 days were often higher than similar OPC concrete. This indicates that the fly ash had not started to react significantly and had not begun to close up the pore structure. Fig 5.14a-c shows the sorptivity development of Lethabo field 2, Lethabo classified and Matla classified fly ash concrete of grade 30 MPa as measured at 7, 28 and 90 days.

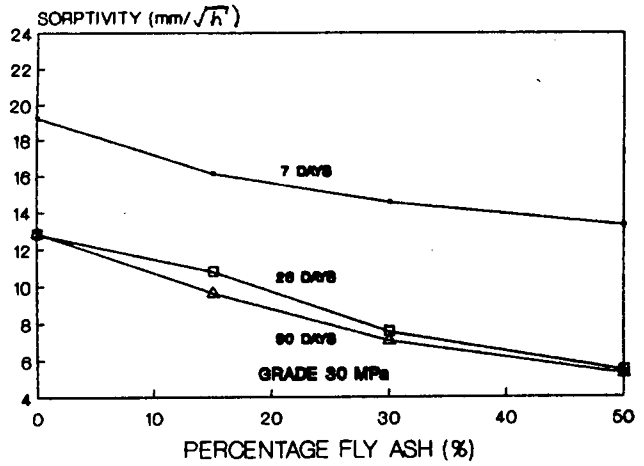


Fig. 5.14a: Sorptivity Development
Lethabo Field 2 Fly Ash

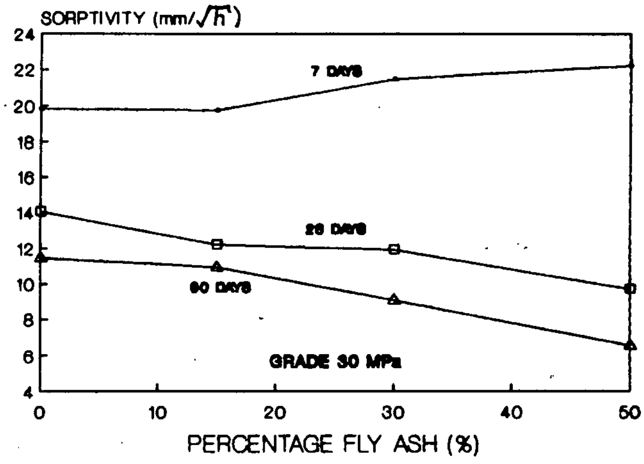


Fig. 5.14b: Sorptivity Development
Lethabo Classified Fly Ash

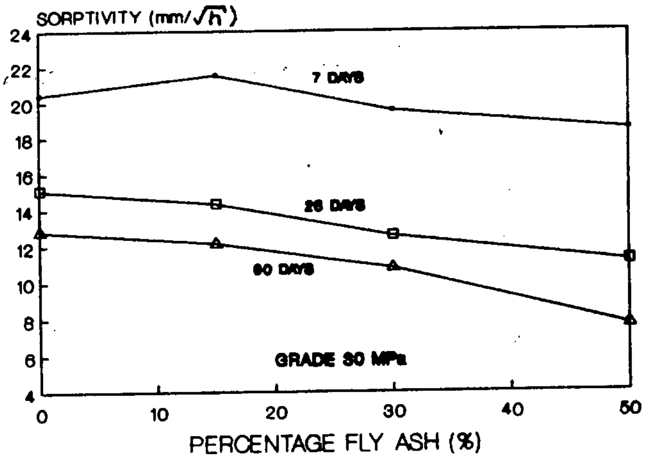


Fig. 5.14c: Sorptivity Development
Matla Classified Fly Ash

Lethabo field 2 fly ash concrete was found to have little reduction in sorptivity after 28 days indicating that the pore structure remained largely unchanged during this period with little further narrowing of the capillaries. This was found even with the high percentage fly ash concrete where substantial long-term pozzolanic activity was expected. This finding, as with the poor long-term compressive strength performance of Lethabo field 2 fly ash concrete, must have been caused by the above average presence of ultra-fines in the fly ash which caused rapid early strength development. Both the Lethabo classified and Matla classified fly ash concrete had further reductions in sorptivity between 28 and 90 days which ranged from between 15 to 30%. Even with the better long-term sorptivity development of Lethabo classified and Matla classified fly ash concrete, the sorptivities of Lethabo field 2 fly ash concrete were still lower at 90 days.

Fly ash was found to reduce the sorptivity of all types and grades of concrete when tested at 28 days or more. It was found that a 50% fly ash concrete if well cured will eventually have a sorptivity value of less than half that of a similar OPC concrete. This reduction in sorptivity must produce more durable concrete particularly when the concrete is exposed to an aggressive environment.

The sorptivity test was done by taking the average of the results of six 40 mm discs cut from one 300 mm long concrete cylinder. It was found that there was a slight variation in sorptivity according to where the disc was cut from in the cylinder. Generally the bottom disc had the lowest sorptivity value while the top disc had the highest sorptivity value. The reasons for this variation are as follows :-

1. The heavier cement particles tended to settle downwards during vibration of the concrete.
2. Bleeding caused water to rise towards the top of the concrete and produced bleed channels near the surface.
3. The concrete was vibrated on a table vibrator which compacted the concrete at the bottom of the mould better than that further up the cylinder.

Fig. 5.15 shows the variation of sorptivity of concrete down the cylinder for OPC and fly ash concrete. The results shown are the average of 27 sorptivity tests tested at either 7, 28 or 90 days. There was no particular trend for increasing percentages of fly ash in the concrete.

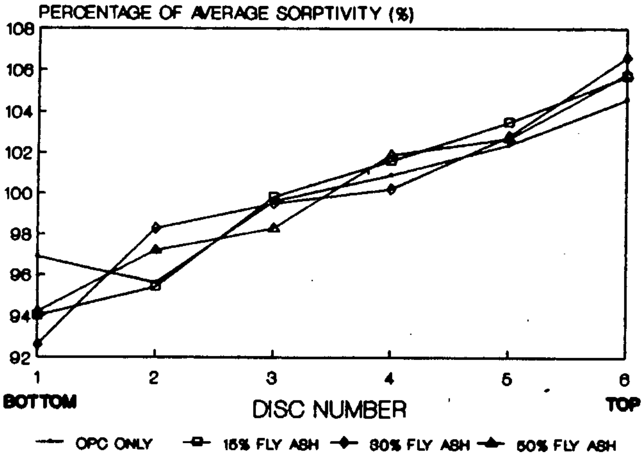


Fig. 5.15: Variation of Sorptivity Down Cylinder

5.4.5 Depth of Penetration

The medium-sanded concrete exposed to 5m water head for 1 hour had decreasing depths of penetration for increasing compressive strength of concrete. No trend was observed in comparing the depths of penetration of fly ash concrete to those of OPC concrete because of the variability of the results. The wide scatter of results was probably caused by the short time period of 1 hour and the rudimentary apparatus used to pressurise the concrete.

The under-sanded concrete exposed to a head of 150 mm of water produced far more reliable results where the trend of decreased depth of penetration with increased compressive strength of concrete was again observed. OPC concrete was found to have higher depths of penetration than similar fly ash concrete. All types of concrete were found to have higher depths of penetration than those obtained using the 5m head of water. This shows how significant capillary action is with regard to water movement in unsaturated concrete. Fig. 5.16a and b shows the depth of penetration for the medium- and under-sanded concrete tested at 28 days under a head of either 5m or 150mm.

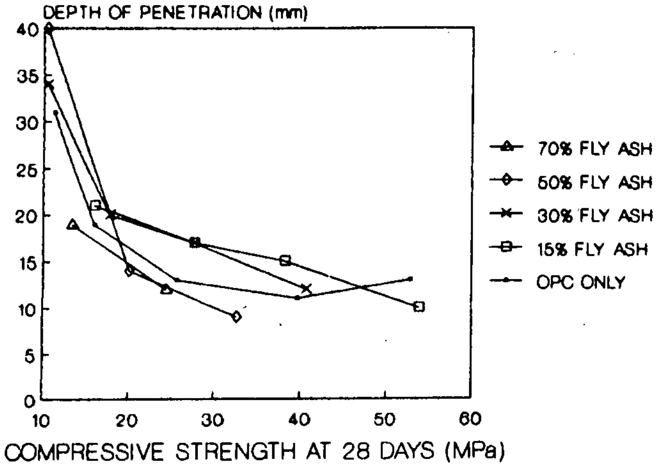


Fig. 5.16a: Depth of Penetration vs. Compressive Strength - Medium-sanded concrete

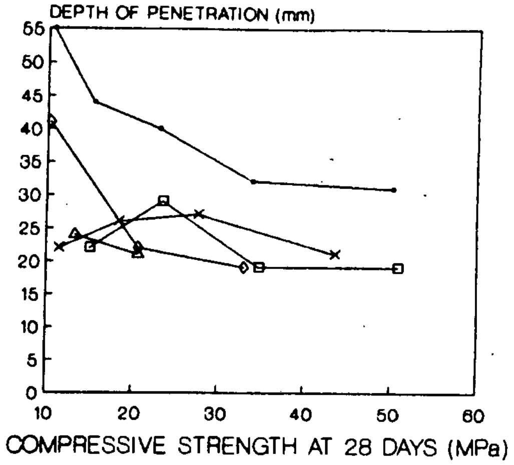


Fig. 5.16b: Depth of Penetration vs. Compressive Strength - Under-sanded concrete

The depth of penetration measured with the 150 mm head of water was not the maximum possible depth of water penetration but merely the position of the water front after 6 hours. The test may be compared to the sorptivity test used by Ho and Lewis where the depth measured at 6 hours would merely be one reading on the water absorption graph.

5.4.6 Permeability

Results of the permeability tests done by Ash Resources in Johannesburg in accordance with DIN 1048 showed that Lethabo classified fly ash concrete was more impermeable than similar OPC concrete. The results of this work are shown below together with the results for similar concrete made at UCT for investigation into the sorptivity of concrete

A. Ash Resources -Input Permeability Results

Mix	Cement/Water Ratio	28 day fcu (MPa)	Depth of(mm) Penetration	Average. D.o.P.(mm)	D.o.P. Ratio
OPC	1.50	24.0	72	68.0	1.32
OPC	1.50	24.0	64		
30% F.A.	1.76	25.5	50	51.5	
30% F.A.	1.76	22.0	53		

B. U.C.T. - Sorptivity Results

Mix	Cement/Water Ratio	28 day fcu (MPa)	Sorptivity $(mm/\sqrt{h})$	Sorptivity Ratio
OPC	1.48	25.4	14.06	1.28
30% F.A.	1.76	23.4	10.98	

Fig. 5.17a and b show OPC and fly ash concrete specimens which have been split after 5 days of applied hydrostatic head. The depth of water penetration of the OPC concrete specimens is clearly greater than that of the fly ash concrete.

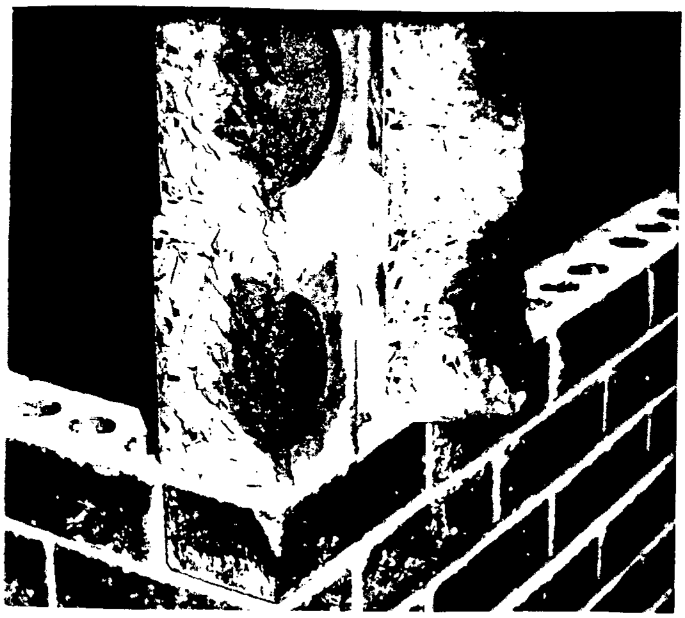


Fig. 5.17a: Split Concrete Sample - OPC Concrete

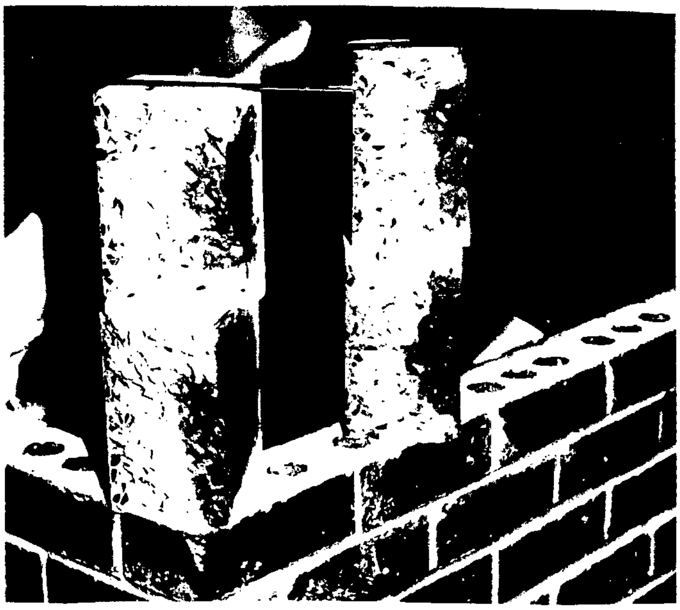


Fig. 5.17b: Split Concrete Sample - 30% Fly Ash Cocrete

Both the input permeability method and the sorptivity method indicated that the 30% Lethabo classified fly ash concrete was more impermeable than similar OPC concrete at 28 days. The depth of penetration ratio comparing OPC concrete to fly ash concrete was quite similar to that of the sorptivity ratio comparing OPC to fly ash concrete. Many more tests would be needed however to establish if a relationship exists between the two test methods.

The average coefficient of variation for the three results measured for each test using the input permeability method was 12.7% In comparison the average coefficient of variation of the sorptivity test using six samples per test was only 8.3% The type of concrete used for this work was reasonably permeable, giving measurable results and therefore fairly good accuracy. Depths of penetration below 30 mm are likely to produce too much variability for comparison with similar concrete.

5.5 CONCLUSIONS

The following conclusions can be made from the experimental results.

1. Fly ash concrete was found to have slower early strength development than similar OPC concrete but had better long-term strength development.
2. Lethabo field 2 fly ash concrete was found to produce higher compressive strength at 7 and 28 days than did either Lethabo classified or Matla classified fly ash concrete.
3. The long-term strength development of Lethabo classified and Matla classified fly ash concrete was significantly higher than that for Lethabo field 2 fly ash concrete.
4. Freeze-thaw resistance of concrete was proportional to compressive strength.
5. Fly ash concrete was more adversely affected by freeze-thaw action than was similar OPC concrete.
6. Fly ash concrete was found to have lower percentages of water absorption than similar OPC concrete.
7. The sorptivity and effective porosity of concrete was dependent on the compressive strength of concrete, decreasing with increasing compresssive strength.

8. The sorptivity of Lethabo field 2 fly ash concrete was lower than that of Lethabo classified and Matla classified fly ash concrete when tested at 7 or 28 days.
9. The long-term sorptivity reductions experienced by Lethabo classified and Matla classified fly ash concrete were far greater than those for Lethabo field 2 fly ash concrete.
10. The addition of fly ash to concrete was found to reduce the sorptivities of all mature concretes.
11. The depth of penetration of water into concrete decreased with increasing compressive strength.
12. The permeability of Lethabo classified fly ash concrete was lower than that for similar OPC concrete.

The lower permeability of fly ash concrete together with the better long-term strength development, compared to that of OPC concrete, will enhance the durability of fly ash concrete. Fly ash concrete should prove to be more durable than similar OPC concrete particularly in aggressive environments.

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CHAPTER 6. CURING REGIMES

6.1 INTRODUCTION

Good curing of concrete is important for most types of concrete work and few will argue that this is even more necessary for fly ash concrete. This is due to the slower cementing action of fly ash as compared with cement. The slower hydration of fly ash concretes means that longer curing may be required to ensure good durability.

The importance of good curing might not seem to be an issue in large mass concrete structures commonly found in marine and fresh water environments. Here only the surface concrete is likely to be adversely affected by poor curing and the rest of the concrete is largely unaffected. This surface concrete is important however in resisting the aggressive attack of the environment. In reinforced concrete structures the concrete cover protecting the steel reinforcement plays a vital role in maintaining a durable concrete member. Even in mass concrete structures a poorly cured surface layer of concrete may eventually have implications on the structure as a whole.

Work has been done at some length both locally and overseas into the possible effects of different curing regimes on fly ash concretes. These projects are useful as comparative surveys but caution should be used in trying to extract any definitive results. Generally it is best to make comparisons between fly ash concrete and similar ordinary portland cement concrete.

6.2 LITERATURE SURVEY

The effect of curing on OPC concrete has been investigated thoroughly in the past. Neville showed how the length of wet curing influenced many factors such as compressive strength and permeability (1). Generally it was found that the longer concrete was cured the better the durability prospects. The effect of curing on fly ash concrete has also been investigated recently by several different researchers, with slightly conflicting conclusions.

Gopalan and Haque found that the compressive strength of fly ash concrete was more dependant on proper curing than was plain concrete (2). They studied the effect of fog and dry curing on the compressive strength of 200 mm long by 100 mm diameter cylinders. It may be argued that this is a particularly harsh regime as no concrete element in the field would have such a large surface area to volume ratio. On the other hand the surface concrete of a slender reinforced concrete column may be exposed to drying of nearly this order. Even if the drying is considered to be too excessive to be realistic, the research is still useful as a lower bound condition to establish any apparent trends.

Research done by C.S.I.R. showed that fly ash concrete needs to be carefully cured to ensure satisfactory concrete properties (3). This work has lead to recommendations for longer curing periods of fly ash concrete than those used for OPC concrete.

Ash Resources have also done extensive work locally on the subject of curing (4). They studied the effect of wet and dry curing on compressive strength and permeability. From this work it is stated that up to 30% fly ash in concrete does not increase the susceptibility to poor curing when considering either compressive strength or permeability. This conclusion contradicts most of the previous work on the subject and is probably due to the curing regimes that were chosen. In an attempt to model real life conditions their dry cured specimens were initially wet cured to simulate the likely site curing conditions. This method might be somewhat optimistic when there is poor curing on site. Modelling of site curing is however a very subjective question and makes comparisons with other work difficult.

Kelham, using a water absorption method, on both fully wet or dry cured samples found fly ash concrete to have significantly lower compressive strength and higher rates of water absorption when dry cured (5). This work was done with a 25% fly ash concrete and using 50 mm long by 150 mm diameter samples. Ho and Lewis also confirmed this trend using a water absorption or sorptivity test (6). They contend that concrete quality is influenced primarily by its pore structure as this determines how easily gases and liquids can enter the concrete. Since the curing regime affects the concrete pore structure good curing is fundamental to durability.

As poor curing is detrimental to concrete strength and impermeability, it would follow that other physical factors would also be affected. Carbonation for instance depends on the rate of ingress of carbon dioxide into the concrete pore structure, so one would expect it to increase when concrete is badly cured. Fattuhi showed that for plain concrete the carbonation rates decrease with an increase in the water curing period (7). This he ascribed to the continued hydration of the cement paste when wet cured which led to a reduction in the concrete porosity. This was confirmed by Hobbs who also showed that fly ash concrete of similar 28 day compressive strength to that of OPC concrete had slightly greater depths of carbonation when dry cured (8).

6.3 EXPERIMENTAL DETAILS

Given all the evidence of the detrimental effect of poor curing on fly ash concrete it was decided to do a comparative study of the subject. No attempt was made to model any real life curing regime but rather the extreme cases were used. Whilst it was realised that this might be extremely harsh it was hoped to establish any trends.

Initially only the compressive strength was used to determine the effect of curing. Compressive strength testing was done according to SABS 863 using 100mm cubes. Later the concrete sorptivity was also considered along with changes in the density. For the sorptivity work 300 mm long by 150 mm diameter cylinders were used. A description of the test is given in Chapter 5.

After casting, the specimens were stored in a fog room until they were demoulded at 24 hours and placed into their appropriate curing environment. All specimens were maintained in the same curing regime until being tested for compressive strength or sorptivity at the required age. The curing regimes were as follows :

Wet curing - fresh water at 20°C in a curing tank
Fog curing - 90% relative humidity and 23°C in a fog room
Dry curing - 50% relative humidity and 23°C in a drying room

The work done on the subject of curing can be divided into three sections:

6.3.1 Wet vs. dry curing

In this initial investigation the effect of curing was studied using two series of concrete specimens comprising 18 different concrete mixes each. These mixes varied in strength from 10 MPa to 50 MPa and in percentage fly ash from 0% to 70%. After either wet or dry curing the concrete was tested for compressive strength at 28 days only. The two mix series were identical except the first was over-sanded while the second was under-sanded. A table of the 18 individual mixes used for each series is shown below:

	PERCENTAGE FLY ASH				
CONCRETE GRADE	0%	15%	30%	50%	70%
10 MPa	X		X	X	X
20 MPa	X	X	X	X	X
30 MPa	X	X	X	X	
40 MPa	X	X	X		
50 MPa	X	X			

6.3.2 Wet vs. cyclical wet and dry curing

This work was done on one complete mix series of 18 mixes using a medium-sanded concrete. The concrete was subjected to 6 hour cycles of wet or dry curing. At 28 days the concrete was tested for compressive strength. The 6 hour intervals were chosen to model a tidal condition where concrete in the tidal zone is alternately wetted and dried.

6.3.3 Wet vs. fog vs. dry curing

Finally the effect of curing on compressive strength and sorptivity was investigated for wet, fog and dry curing. Only two grades of medium-sanded concrete were chosen and the percentage fly ash varied from 0% to 50%. Testing was done at 7, 28 and 90 days. The 8 different concrete mixes are shown below:

	PERCENTAGE FLY ASH			
CONCRETE GRADE	0%	15%	30%	50%
30 MPa	X	X	X	X
50 MPa	X	X	X	X

6.4 DISCUSSION OF RESULTS

6.4.1 Wet vs. dry curing

Results of this initial work clearly show the poor performance of dry cured fly ash concrete when compared with OPC concrete. Both the under- and over-sanded concrete mix series showed the trend of decreased performance with increasing fly ash. The ratio of the compressive strength of the dry cured specimens to that of their respective result for wet curing was used to indicate the effect of curing. This ratio expressed as a percentage was then plotted against the 28 day compressive strength for the wet cured concrete as shown in Fig. 6.1a and 6.1b below.

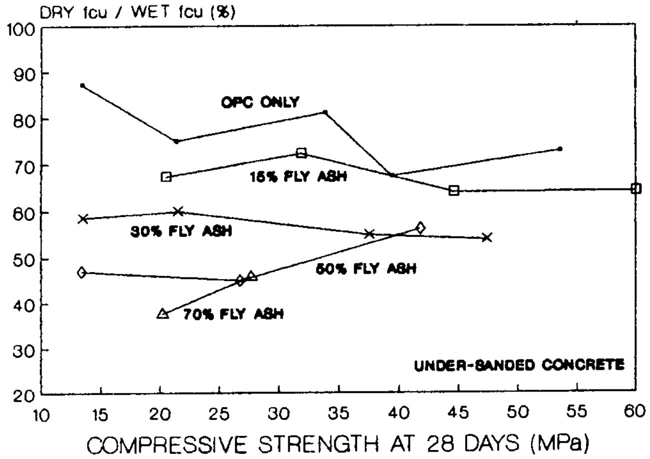


Fig. 6.1a: Strength ratios for under-sanded concrete

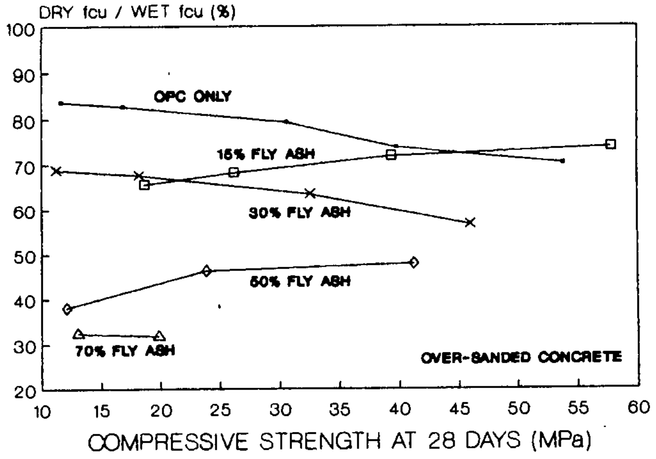


Fig. 6.1b: Strength ratios for over-sanded concrete

The graphs show that for high percentages of fly ash in concrete the effect of dry curing can be extremely adverse. Both the 50% and 70% fly ash concrete were found to have only half or less of the wet cured concrete's compressive strength. This is a major strength reduction, but it is unlikely that this type of concrete would ever be exposed to such harsh drying conditions being primarily intended for use as a mass concrete. The performance of the structural fly ash concrete was however also worse than OPC concrete. Concrete with only 15% fly ash showed similar, if somewhat lower, results to that of OPC concrete. With 30% fly ash in concrete the compressive strength performance was consistently lower than that of OPC concrete by between 10% and 25%.

No general trend was observed on the effect of curing with increasing strength for the various types of concrete. The OPC concrete showed more adverse effect from dry curing with increasing strength while the opposite was true of the 50% fly ash concrete. It was expected that the stronger a concrete was, the less susceptible it would be to the effects of dry curing. The reasoning was that the increase in strength and the advance of hydration would reduce the permeability and hence the drying rate. This would allow for rapid strength development before moisture losses had become significant.

6.4.2 Wet vs. cyclical wet and dry curing

As expected the cyclical wet and dry curing had only a slight effect on the compressive strength. On average the same trend as before was found with the higher percentage fly ash concretes being more susceptible to cyclical wet and dry curing. Generally the non-continuous water supply was not very significant in affecting the hydration of the cement and fly ash. In fact it was found that both the OPC and 15% fly ash concrete were on average stronger after wet and dry curing than the equivalent wet cured samples. After 6 hours of dry curing the concrete samples appeared surface dry but no appreciable drying of the interior was likely to have occurred in the short drying period. Fig. 6.2 summarises the results of this study.

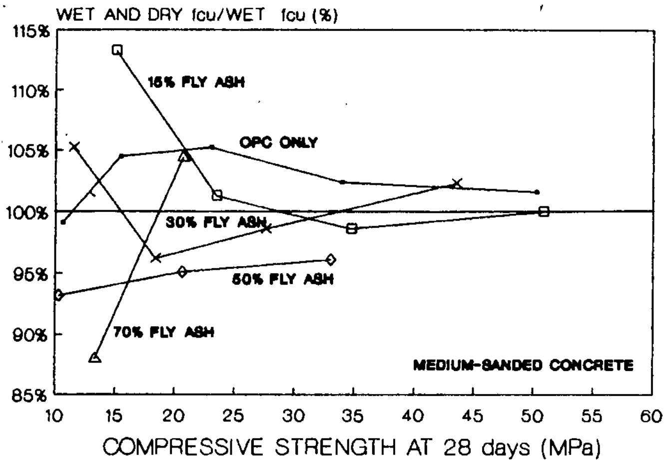
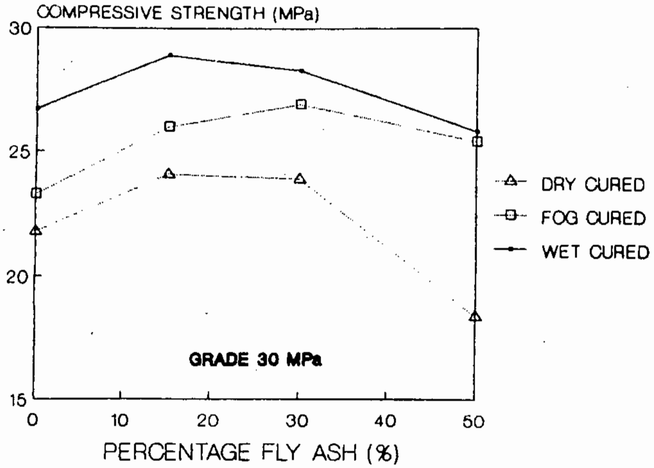


Fig. 6.2: Strength ratios for wet vs. cyclical wet and dry curing

6.4.3 Wet vs. fog vs. dry curing

Fog curing was found to be better than dry curing with regards to both compressive strength and sorptivity. Typical results are shown in Fig. 6.3a and 6.3b for grade 30 MPa concrete tested at 28 days. Due to the large number of parameters it was decided to concentrate on the results for the wet and dry cured specimens in this discussion. The results for the fog cured specimens were found to lie between those for the wet and dry cured specimens. Generally the compressive strength results for the fog cured specimens were closer to those for the wet cured specimens, while the sorptivity results were closer to those for the dry cured specimens.



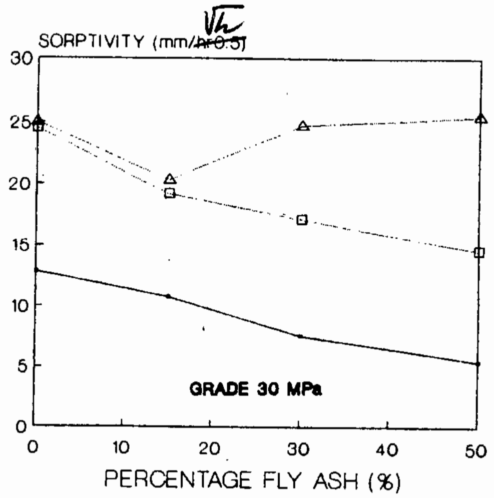
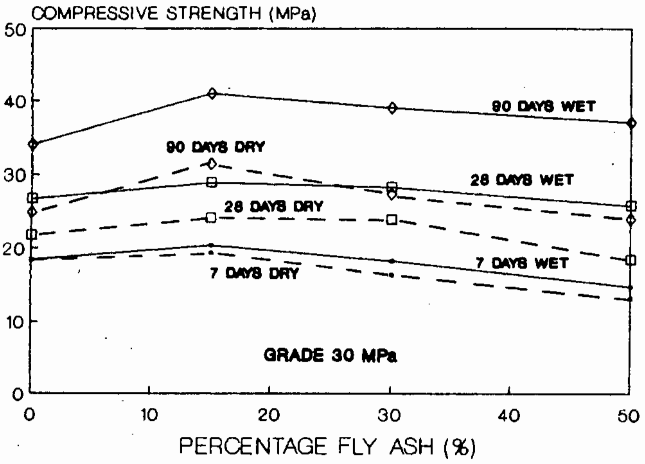


Fig. 6.3a: Wet vs. fog vs. dry curing - Compressive strength

Fig. 6.3b: Wet vs. fog vs. dry curing - Sorptivity

Considering the effect of wet vs. dry curing on compressive strength initially, it was clear that the gap between the wet and dry curing results widened with age. At 7 days there was hardly any difference in strength of concrete from the two curing regimes, while this difference was magnified at 90 days to nearly 40% in some cases. Another general observation was that the stronger grade concrete was less influenced by dry curing than the weaker concrete. These results are shown in Fig. 6.4a and 6.4b. for the grade 30 and grade 50 MPa concrete.



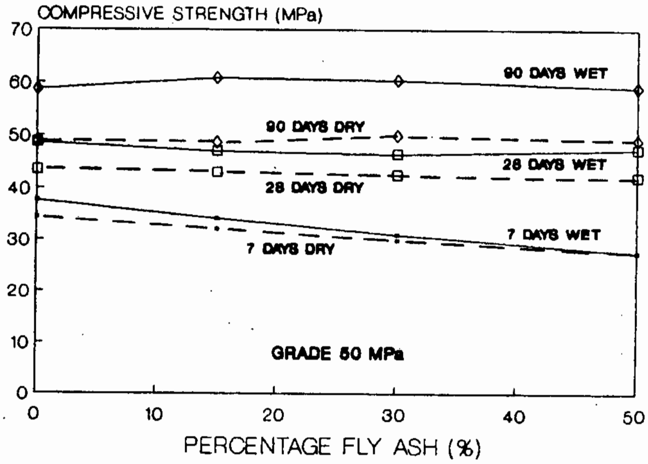


Fig. 6.4a: Wet vs. dry curing - Compressive strength

Fig. 6.4b: Wet vs. dry curing - Compressive strength

When comparing the compressive strength results for the dry vs. the wet cured specimens the trend of increasing strength difference with age can clearly be seen. On average the fly ash concrete was found to be more vulnerable to dry curing at all ages than was ordinary concrete. The results were not nearly as clear cut as in the earlier work with several of the lines crossing over. Fig.6.5a and 6.5b show these comparisons for the grade 30 and 50 MPa concrete.

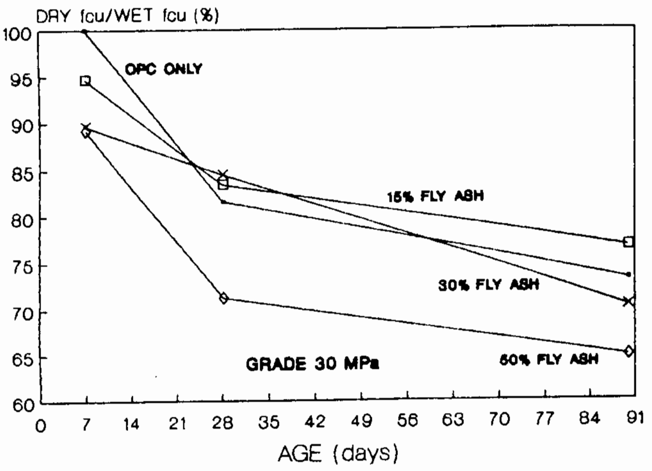


Fig. 6.5a: Compressive strength ratios - Grade 30 MPa

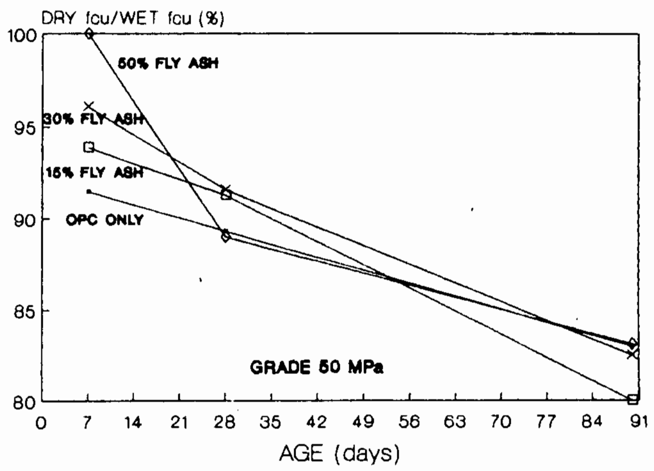


Fig. 6.5b: Compressive strength ratios - Grade 50 MPa

The grade 30 MPa concrete showed the trend of increasing effect of dry curing with increasing percentages of fly ash. The compressive strength of the 50% fly ash concrete in particular was found to be much lower than that of other concrete at all ages. With regard to the grade 50 MPa concrete it was difficult to make any clear comparisons between the various mixes as the results of all the tests fell within a very narrow range. Suffice to say that for up to 50% fly ash there was no substantial reduction in strength over that for OPC concrete when dry cured. It was thought that the scatter of results associated with the compressive strength test may have obscured the trend that was found with the grade 30 MPa concrete.

The results of the sorptivity work showed far more obvious trends than those found for compressive strength. The effect of dry curing was found to increase the sorptivity of all concrete mixes at all ages. Fig. 6.6a and 6.6b show these results for the grade 30 MPa and 50 MPa concrete. It should be noted that the sorptivity work was done with 300 mm long by 150 mm diameter cylinders which had a substantially lower surface area to volume ratio than the 100 mm cubes used for the compressive strength tests. The cylinders were cast vertically and stored in the same position until testing. A marked trend of decreasing sorptivity down the cylinder was observed when the six slices from each cylinder were tested. This was due to several factors such as the cement settling during vibration due to segregation, pockets of air entrapped in the concrete, bleeding and pore water migrating downwards during drying.

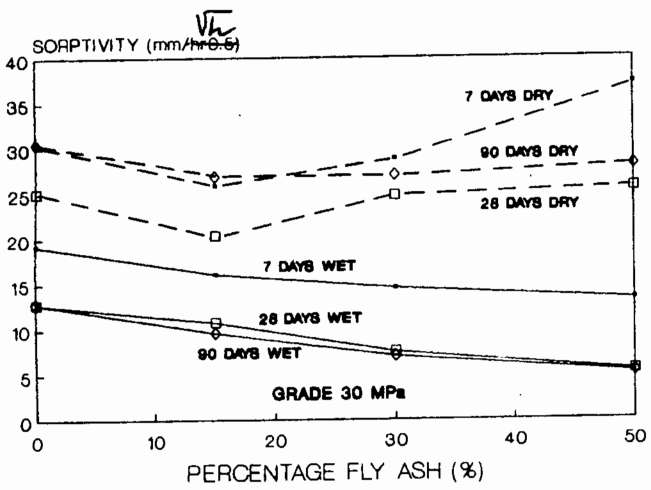


Fig. 6.6a: Wet vs. dry curing - Sorptivity

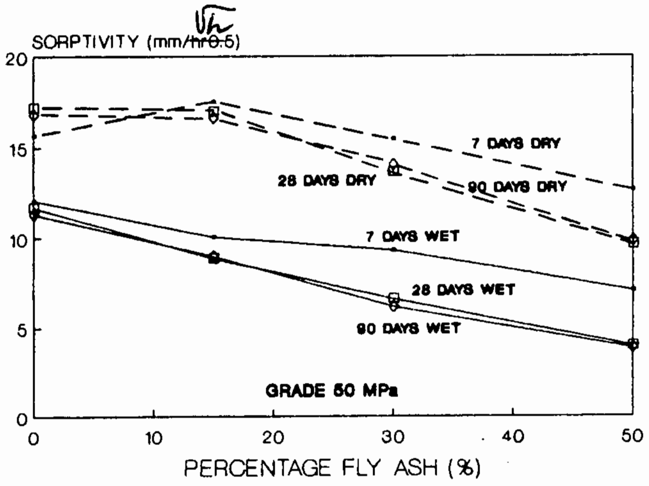


Fig. 6.6b: Wet vs. dry curing - Sorptivity

Several trends were immediately apparent when the results were compared. The sorptivity of the wet cured concrete was found to decrease with an increase in the percentage fly ash. This was also true for the dry cured 50 MPa concrete but not for the weaker 30 MPa concrete where the sorptivity fluctuated around the same level. The 28 day sorptivities for both wet and dry curing were found to be substantially lower than their equivalent 7 day sorptivities. Conversely the decrease in sorptivity from 28 to 90 days was minimal for both curing regimes. For the grade 30 MPa dry cured concrete the 90 day results are substantially higher than the equivalent 28 day results. This would indicate severe disruption to the pore structure due to drying.

By comparing the sorptivities for either wet or dry cured concrete it is immediately obvious how significant the effect of curing is on sorptivity. Fig. 6.7a and 6.7b shows this clearly with the discrepancy between wet and dry curing widening with age. Fly ash concrete was again found to be more vulnerable than ordinary concrete. The grade 30 MPa concrete was also found to be more severely influenced than the grade 50 MPa concrete.

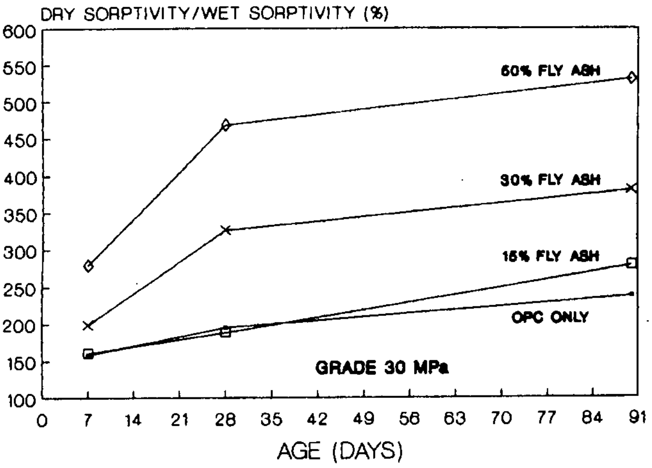


Fig. 6.7a: Sorptivity ratios - Grade 30 MPa

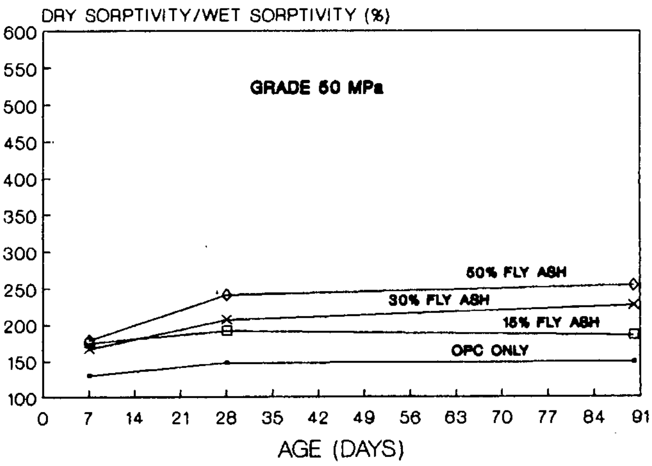


Fig. 6.7b: Sorptivity ratios - Grade 50 MPa

6.5 CONCLUSIONS

From the experimental results the following conclusions can be made :

1. Fly ash concrete was more vulnerable to poor curing than ordinary concrete of the same grade with regard to both compressive strength and sorptivity.
2. Stronger concrete was less adversely affected by dry curing for both OPC and fly ash concrete.
3. Cyclical wet and dry curing, such as that found in the tidal zone, had a negligible effect on the compressive strength of concrete.
4. Wet cured concrete had similar compressive strength to that of fog cured concrete but had far lower sorptivity values.

From the concluding remarks it is clear that the use of fly ash in concrete must be considered carefully when poor curing is possible. The trends reported here are not expected to occur on site to the same extent but should not be disregarded. It should also be remembered that even though a curing regime may be found not to affect the compressive strength detrimentally, it may affect other durability factors to a significant extent. This was seen with fog curing where the sorptivity was far higher than that for wet curing even though the compressive strengths were similar. In an aggressive environment this difference in sorptivity could influence the concrete durability to a noticeable extent.

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CHAPTER 7: MARINE DURABILITY.

7.1 INTRODUCTION.

Concrete in the marine environment often has a shorter useful life than expected. This is due either to poor design or material failure. Sea water attack may be particularly severe on concrete, both chemically and physically. The likely durability of concrete in such an environment is difficult to assess and only long-term exposure tests can confirm laboratory findings.

Due to the short time available for this work, it was only possible to expose concrete to the harmful effects of the marine environment for 10 months. It was hoped that even using such a short period, some trends might be found regarding the performance of fly ash concrete. It was accepted that little long term deterioration would be likely after 10 months of exposure.

A brief summary of current literature in the field of marine durability is presented below.

7.2 LITERATURE SURVEY.

The performance of concrete in the marine environment has been of interest for a long time. This is due to the aggressive nature of the sea where there are several forms of physical and chemical attack. The main cause of deterioration is due to the presence of sea water salts and in colder climates the repeated cycles of freezing and thawing. Other factors include wave action, physical abrasion, corrosion of reinforcement and wetting and drying cycles in the tidal zone.

Many long term studies using marine exposure sites have been started both locally and overseas. In the U.K. concrete test specimens are exposed to conditions in the spray, tidal and full immersion zones of the sea (1). This site at Shoeburyness on the Thames estuary averages roughly 35 freeze-thaw cycles each winter. Types of concrete being exposed are plain, fly ash and various forms of slag concrete. In the U.S.A. a natural weathering station at Treat Island, Maine has been in use for over 50 years (2). Here concrete specimens in the tidal zone are subjected to severe winters with over 100 cycles of freezing and thawing, and twice daily tide reversals. Recently fly ash and slag concrete has been included in the research project to complement the work already done on OPC concrete. Locally, work by the CSIR has just begun exposing different types of concrete to the marine environment in Durban harbour.

Sea water attack is largely dependent on the relative position of the concrete in the sea (3). Concrete above the high tide mark is mostly affected by the high concentrations of salts which crystallize in the pores. Due to evaporation of the sea water in the pores the salt concentrations may be far higher than those found in the sea. The reaction of these salts with the hydration products of cement form products which disrupt the pore structure of concrete due to their increased volume. In the tidal zone the concrete is subjected to alternate wetting and drying and often this zone is the most severe. Furthermore the damage is aggravated by frost, wave impact and abrasion. In the fully immersed zone concrete is generally attacked least, though at great depths the hydrostatic head may cause high levels of water penetration.

Gjorv found in a survey of marine structures that concrete in the tidal zone and especially concrete exposed to intermittent wetting and drying in the splash zone is most prone to deterioration (4). Two reasons advanced for this are: firstly, poor hydration of the cement paste due to the non-continuous water supply and secondly cracking caused by drying. Buenfeld and Newman stated that permeable inflow of sea water during the wetting phase of the wet and dry cycle causes greater ingress of ions than is caused by ionic diffusion alone (5). The rate of water penetration in this zone may be aided by capillary action of the concrete pore structure.

Chemical attack of concrete by sea water is usually a combination of sulphate and magnesium attack (6). The sulphates present in sea water mainly attack the tricalcium aluminate ~~silicate~~ hydrates in the hardened cement paste. The main product formed by this reaction is etteringite which, due to its high molecular volume, disrupts the concrete pore structure and allows further sulphate attack to take place. The magnesium present in sea water attacks the calcium silicate hydrates of the hardened cement paste indirectly. Magnesium reacts with $Ca(OH)_2$ produced by the cement hydrating and forms brucite [$Mg(OH)_2$] which reduces the pH of the pore solution of the hardened cement paste. This reduction in the pH makes the hydrated calcium silicate unstable which causes it to liberate lime to the solution in an attempt to re-establish the equilibrium pH. The calcium silicate therefore converts back to soluble products which can be removed by the sea water. Sea water attack is responsible for the breakdown of otherwise stable hydration products and this chemical attack may eventually cause general failure of the concrete structure as a whole.

Some of the products of chemical attack in the marine environment may help protect concrete. Recently, several researchers have found that some concretes exhibit a significant reduction in permeability on immersion in sea water (7). This has been generally ascribed to the magnesium salts present in sea water which react with the $Ca(OH)_2$ produced by the hydration of cement, forming the relatively insoluble brucite. This surface layer is extremely thin and may not help to protect concrete which is being severely abraded. Buenfeld and Newman report however that not only does a layer of insoluble salts form on the concrete surface but there is a more widespread constriction of the cement paste pore system (5). This constriction of the pore system would depend on the permeability of the concrete.

Fly ash concrete has only recently been investigated in the marine environment. The sulphate resistance of concrete has been found to be improved by the inclusion of fly ash. Larsen and Page reported that the corrosion protection properties of concrete were enhanced by fly ash (8). They found that the sulphate resisting properties of concrete can be improved by reducing the amount of tricalcium aluminate. The sulphate converts the insoluble hydration products into gypsum and etteringite which can then be leached out of the concrete. By replacing cement with fly ash which contains no tricalcium aluminate, a more sulphate resistant concrete can be produced. This was confirmed by Klieger and Gebler who observed this trend with air-entrained concrete (9). Fly ash concrete has been found to reduce the risk of alkali aggregate reaction which is a particularly prevalent problem in the Western Cape (10).

It is still too early to say with confidence how modern fly ash concrete will perform in the long term exposed to marine conditions. Already fly ash has been recommended for many marine applications because of its inherently good effects on concrete. Notable among these properties are reduced permeability, higher long-term strengths, better sulphate resistance and reduced expansion with alkali-reactive aggregate. Dhir regards fly ash concrete very highly for use in marine environments and anticipates good durability results for the material (11). His comments are made in the light of the many beneficial properties of fly ash concrete and from the results of fly ash exposed to various aggressive environments. This early optimism will hopefully be encouraged by the results of ongoing work at exposure sites and research laboratories.

7.3 EXPERIMENTAL METHOD.

Twelve concrete mixes of grades 30, 40 and 50 MPa were used for this work. Each concrete mix was made in one batch which was mixed in a 100 l drum mixer. The concrete mixes are described in more detail in Chapter 3. The concrete cube and cylinder samples were cured for 28 days in a fog room at 23°C and 95 % RH before being placed in one of four types of exposure conditions. The samples were placed in the various exposure sites in December 1988. To protect the concrete from physical damage in the sea the samples were stored in 1m long timber frames. Fig. 7.1 shows typical timber frames containing concrete samples in the tidal zone.

Fig. 7.1: Timber Protective Frames for Marine Exposure

The different types of exposure conditions are described below:

1. Submerged zone.

A tidal pool at Granger Bay was used for full immersion of the concrete samples. All samples were kept continuously wet even at low tide and were roughly 1m below water level. The timber frames were chained together in the tidal pool as the site was exposed to fairly rough sea. Fig. 7.2 shows the tidal pool with the timber frames partly obscured at the centre of the tidal pool.

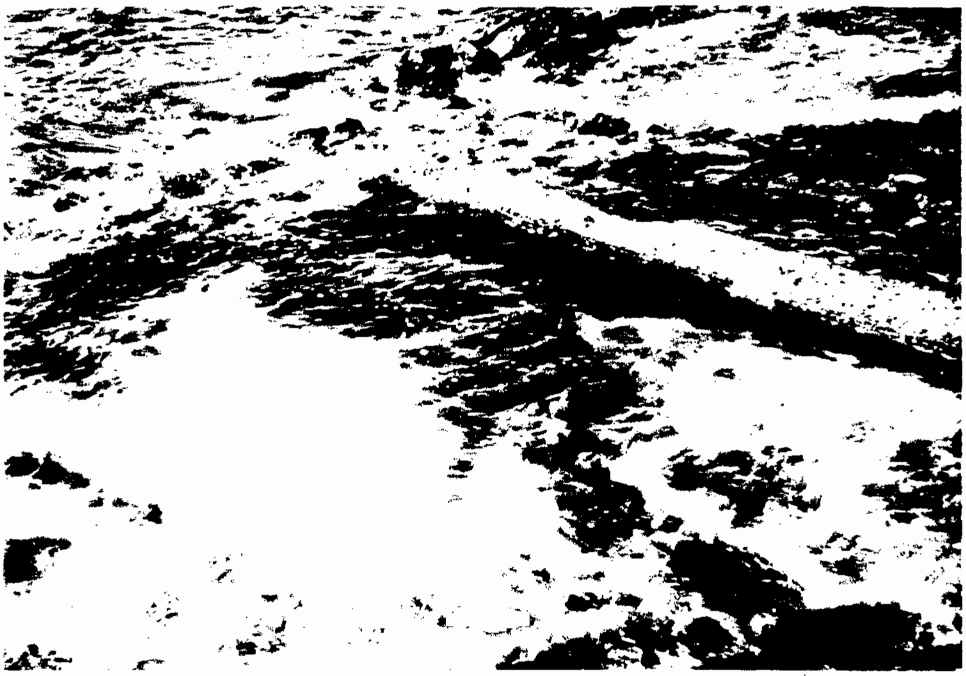

Fig. 7.2: Submerged Zone - Tidal Pool at Granger Bay

2. Spray Zone

Concrete samples in their protective timber frames were placed in the breakwater at Granger Bay. The samples were within 10 m of the sea, just above the high tide mark, but were occasionally wet when the sea was exceptionally rough. The timber frames were regularly monitored and moved so that all the samples were exposed to similar conditions. Fig. 7.3 shows the timber frames leaning against the breakwater at Granger Bay.

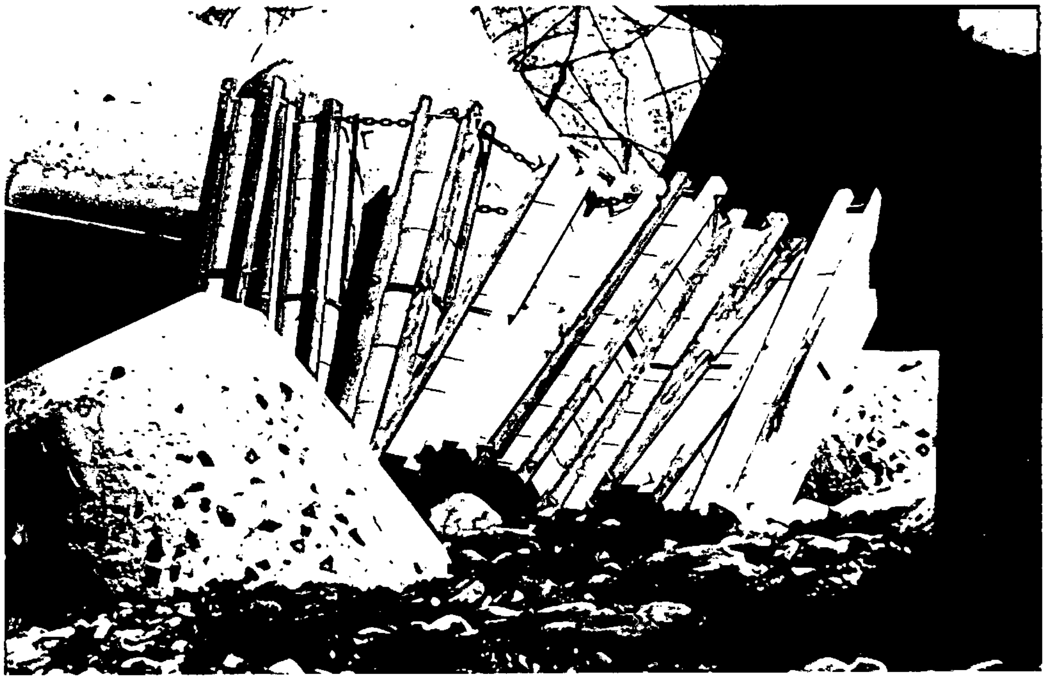

Fig. 7.3: Spray Zone Samples at Granger Bay

3. Tidal Zone.

A concrete ledge at A Berth end in Duncan Dock was used for the tidal zone exposure. The ledge was just below the high tide mark so that the concrete was fully wet at high tide. The timber frames were chained together and the chains were bolted down to the ledge. The concrete in the tidal zone was exposed to little oil pollution although the site was inside the docks. Fig. 7.4 shows the timber frames on the ledge at Duncan Docks.

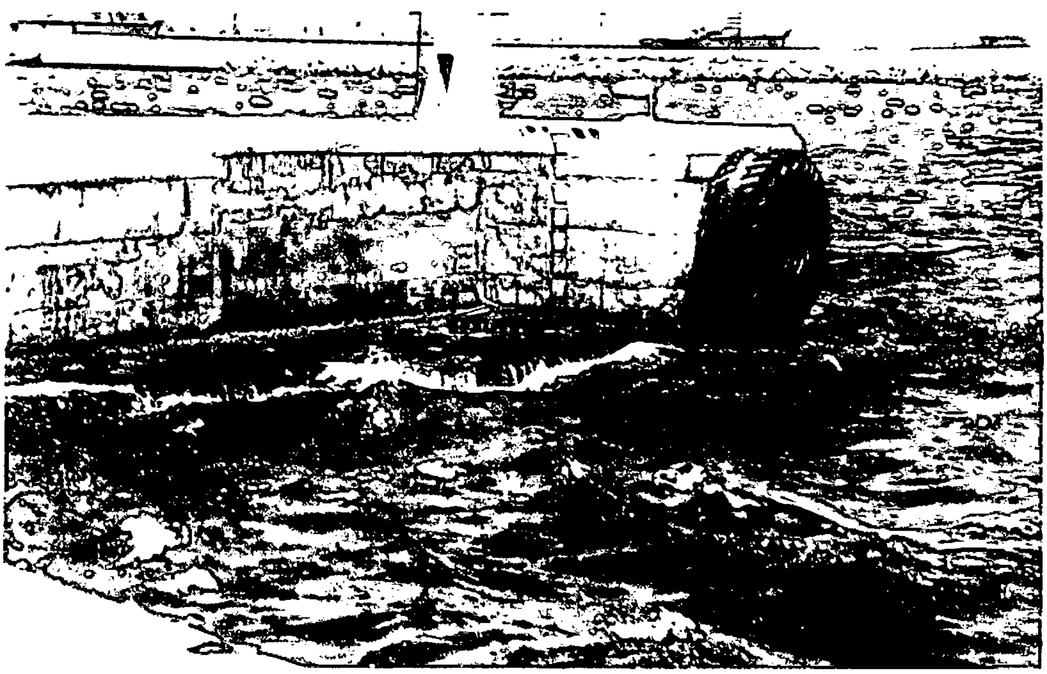

Fig. 7.4: Tidal Zone Samples at Duncan Docks

4. Controls.
Control samples were cured underwater in a curing tank at 20°C in the laboratory.

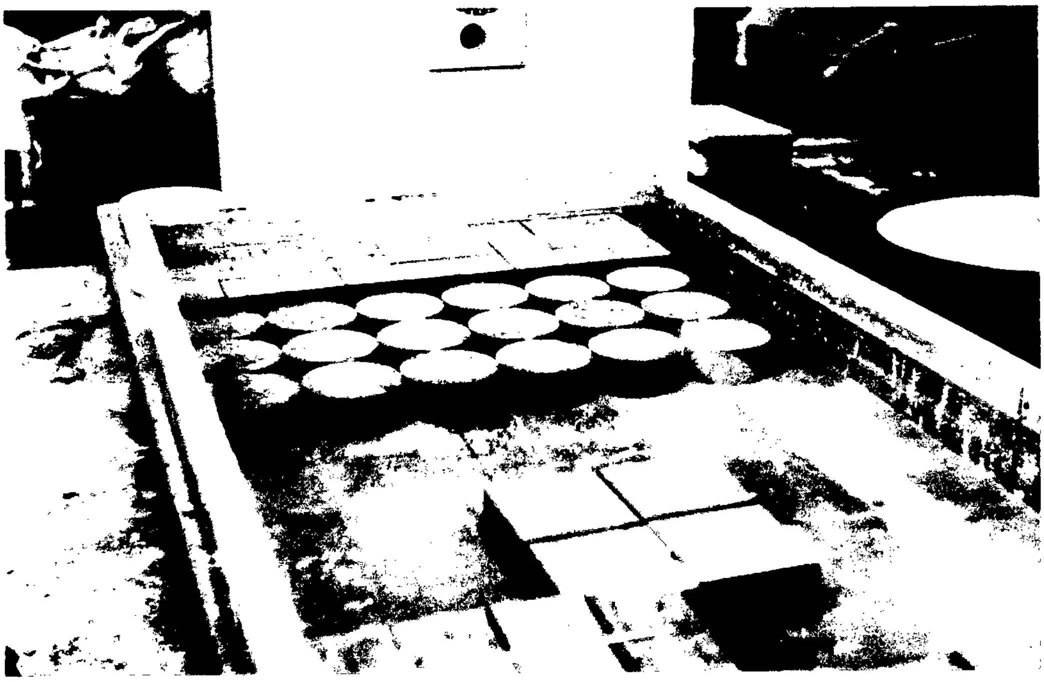

Fig. 7.5: Control Concrete in Curing Tank

The concrete was tested at age 28 days for compressive strength, sorptivity and density before being placed in each of the four environments. After 4 and 10 months, the samples were visually inspected and tested for compressive strength, sorptivity and density.

Compressive strength testing was done using 100 mm concrete cubes in accordance with SABS 863. Three cubes were used for each result at 28 days and 4 months, while at 10 months, 6 cubes were used for each test result.

Sorptivity testing of concrete was done using 150 diameter by 150 mm deep cylinders. The sorptivity test is described in more detail in Chapter 5. Three 40 mm thick disks were cut from each cylinder after the relevant exposure and tested at 28 days, 4 months and 10 months. The ends of the cylinder were cut off and discarded so that the interior sorptivity of concrete was tested using this method.

In addition to see how marine exposure affects the surface of the concrete with regard to the sorptivity, work was done using 150 diameter by 40 mm thick precut disks exposed in the tidal zone. Only grade 40 MPa concrete was used for this work with either 0, 15, 30 or 50% fly ash. These precut discs were stored in woven plastic sacks in the tidal zone at Duncan Dock. The concrete was cured underwater in the laboratory for 2 months before being placed in the tidal zone. Sorptivity tests were done after 14, 28 and 56 days of marine exposure. Buenfeld and Newman reported that the permeability of concrete was reduced by marine exposure due to the buildup of a layer of insoluble salts (5). To determine the effect of any surface layer three of the discs exposed to the marine environment were tested unaltered while three discs were wire brushed until they appeared rough. At the same times control concrete cured underwater in the laboratory was also tested for sorptivity.

7.4 RESULTS AND DISCUSSION.

7.4.1 Compressive Strength.

The compressive strength of both fly ash and OPC concrete was adversely affected by exposure to the marine environment. For all three grades of concrete it was found that the control samples cured under water in the laboratory had higher compressive strengths than similar concrete from the three marine exposure sites.

Results of compressive strength tests done at 4 months show that the control concrete had the highest strengths, followed by concrete in the spray, tidal and full immersion zones respectively. Fig. 7.6a-c shows the compressive strength results as tested at 4 months for grades 30, 40 and 50 MPa concrete for the four types of exposure conditions.

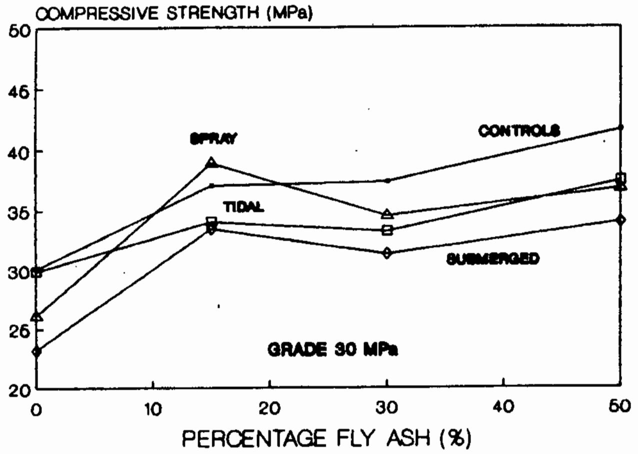

Fig. 7.6a: Compressive Strength at 4 months - Grade 30 MPa

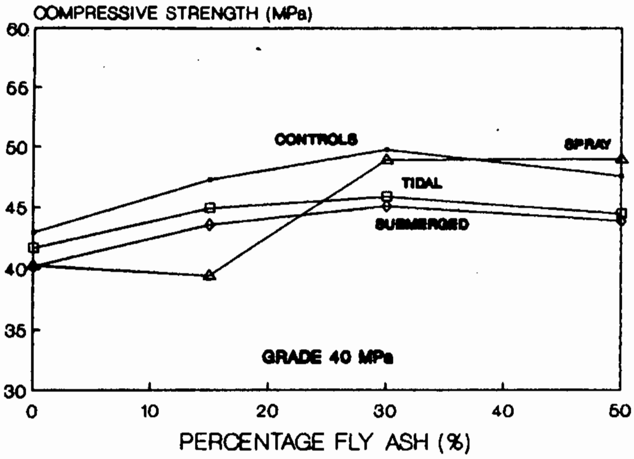

Fig. 7.6b: Compressive Strength at 4 months - Grade 40 MPa

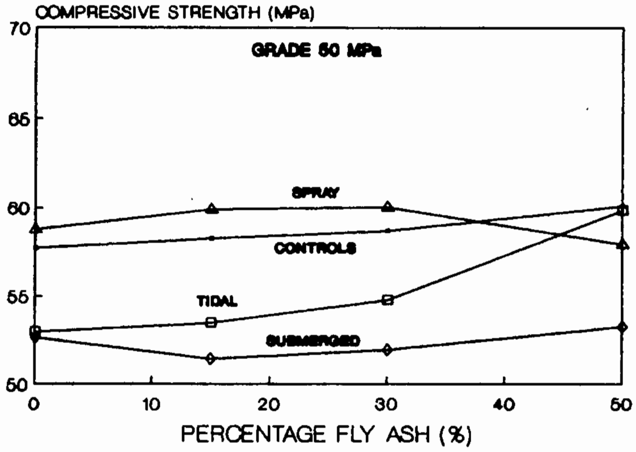

Fig. 7.6c: Compressive Strength at 4 months - Grade 50 MPa

Concrete in the submerged zone was found to have the lowest compressive strengths of the four exposure conditions. This was surprising as it was thought that the constant water supply would promote continuous hydration of the concrete and therefore high compressive strengths. The tidal pool was however exposed to the open sea and many of the timber frames were damaged. At 4 months the concrete cubes were found to have suffered considerable damage in the form of physical abrasion from rocks and sand in the tidal pool. Part of the reason for the low compressive strength results of concrete from the submerged zone must have been the physical damage suffered by the concrete due to wave action. This physical damage was much worse than that found in the tidal and spray zones. The water temperature was between 10 and 15°C.

Concrete in the tidal zone was found to show little significant physical damage after 4 months. Barnacles grew on the concrete within 1 month of exposure and may have protected the concrete from physical damage. Wave action was not a major factor at this site as the ledge was protected being inside the docks. Compressive strength results of concrete from the tidal zone were all significantly lower than those for similar control concrete. The temperature of the concrete samples in the tidal zone was likely to be close to that of the sea temperature of between 10 and 15°C. The samples were exposed to the sun in the late afternoon which was unlikely to heat up the concrete significantly.

Concrete from the spray zone had comparable compressive strengths to those of similar control concrete cured underwater in the laboratory. It was thought that the drier environment in the spray zone would adversely affect the compressive strength of the concrete due to poor curing. All spray zone samples had good compressive strength development however which indicates that water losses from the concrete did not significantly affect the strength at 4 months. As the samples were placed in the spray zone at the beginning of summer the effect of the sun heating up the concrete may have promoted more rapid strength development than that experienced by similar concrete in the sea. It is likely that the average temperature of concrete in the spray zone was between 25 and 30°C.

Fly ash concrete had better strength development than similar OPC concrete in all of the exposure zones. There was a general increase in compressive strength of concrete tested at 4 months with increasing percentages of fly ash.

When comparing compressive strengths of concrete from any of the three marine exposure sites to those of the control concrete no trend was found for increasing percentages of fly ash. The concrete was placed in the marine environment at 28 days so considerable strength development still took place before being tested at 4 months. Fig. 7.7 shows the averages of the compressive strength ratio of exposure to control concrete of grade 30, 40 and 50 MPa concrete for OPC and fly ash concrete.

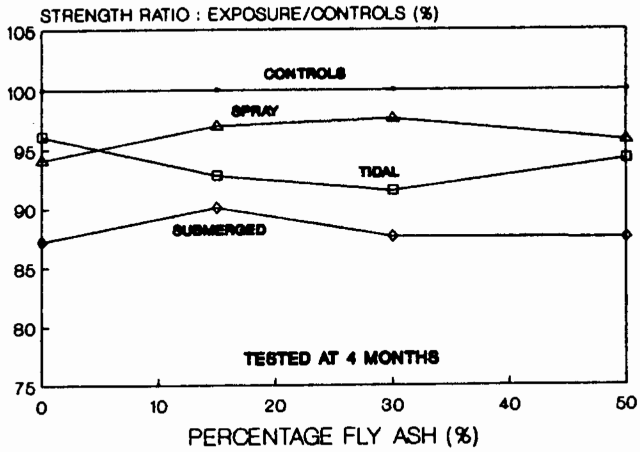

Fig. 7.7: Compressive Strength Ratio : Exposure/Control
Average for Grades 30, 40 and 50 MPa Concrete

After 10 months the remaining concrete cubes from the tidal and spray zones as well as control cubes from the laboratory were crushed. No testing was done on the submerged zone concrete cubes as these had either been lost or badly damaged during the winter storms. Fig. 7.8a-c shows the compressive results for the grade 30, 40 and 50 MPa concrete for the tidal and spray zones as well as the control concrete cured underwater in the laboratory.

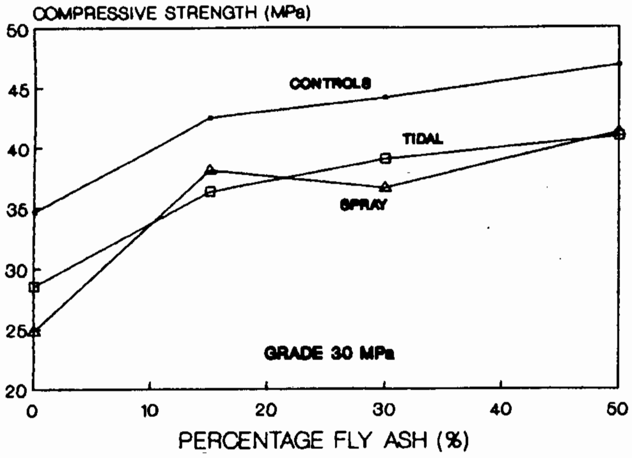

Fig. 7.8a: Compressive Strength at 10 months - Grade 30 MPa

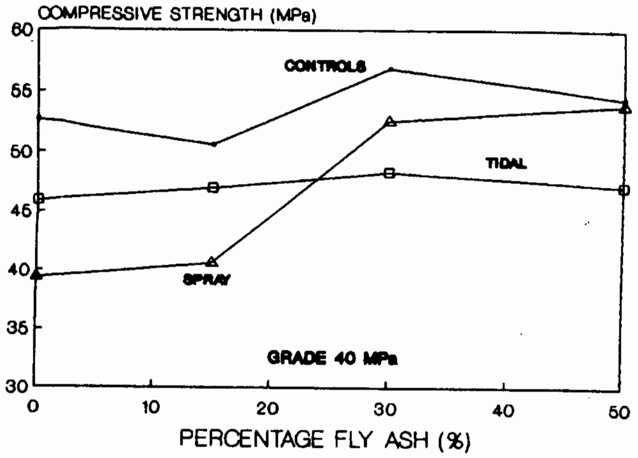

Fig. 7.8b: Compressive Strength at 10 months - Grade 40 MPa

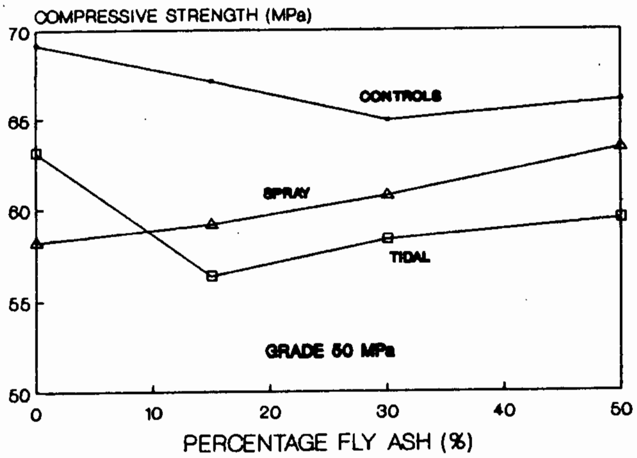

Fig. 7.8c: Compressive Strength at 10 months - Grade 50 MPa

Concrete in the tidal zone showed little sign of physical damage but some of the samples were polluted with oil. No sign of physical damage was observed on any of the spray zone samples and the timber frames were in good condition. The remaining concrete samples in the submerged zone were no longer in their timber frames, which had broken up due to severe wave action. The loose concrete cubes had been severely damaged with the aggregate exposed and the identification marks erased.

For all three grades of OPC concrete in the spray zone there was a loss in strength between 4 and 10 months. On the other hand fly ash concrete in the spray zone gained strength between 4 and 10 months and this gain in strength increased with increasing percentages of fly ash in concrete. The compressive strengths of all concrete from the spray zone were significantly lower than those for the control concrete at 10 months. The poor curing of concrete in the spray zone during the first four months of exposure was probably responsible for the low long-term strengths. This is discussed further in following section on sorptivity.

Concrete in the tidal zone gained strength between 4 and 10 months but this strength gain was less than that experienced by similar control concrete. There was a substantial buildup of barnacles on the concrete after 10 months in the tidal zone and some of the timber frames showed signs of damage. Fig. 7.9a and b shows timber frames from the spray and tidal zones after 10 months of marine exposure.

Fig. 7.9a: Timber Frame with Concrete Cylinders - Tidal Zone

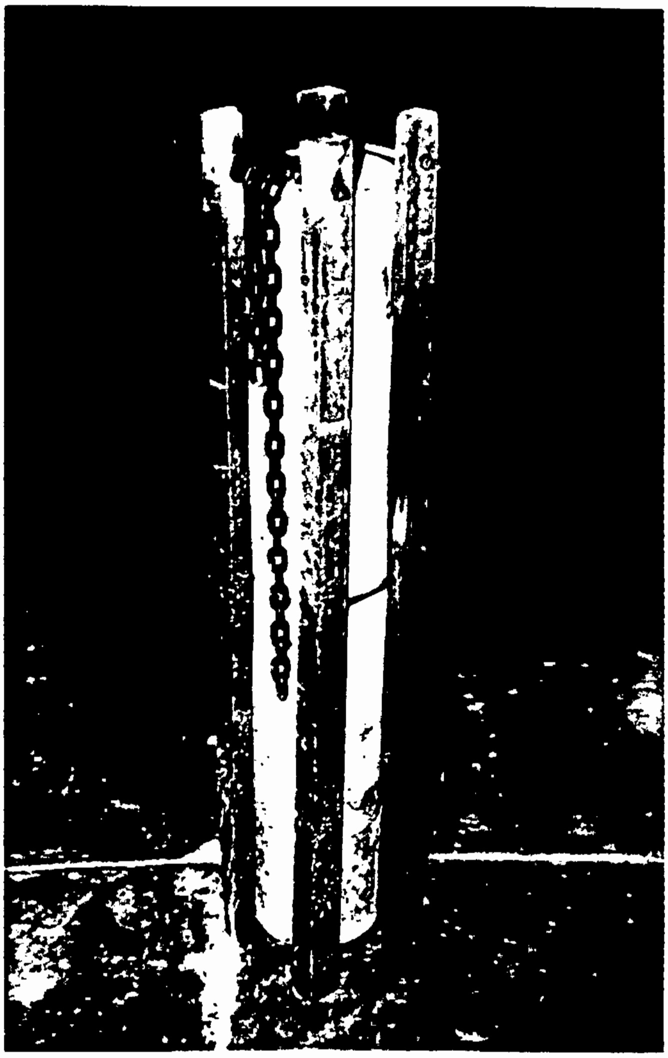

Fig. 7.9b: Timber Frame with Concrete Cylinders - Spray Zone

No trend with regard to long-term compressive strength development was found with increasing percentage fly ash in concrete from the tidal zone as was found for concrete from the spray zone. Fig. 7.10 shows the ratio of the exposed concrete compressive strength over that of the control concrete compressive strength for OPC and fly ash concrete. The results shown are the average of grade 30, 40 and 50 MPa concrete.

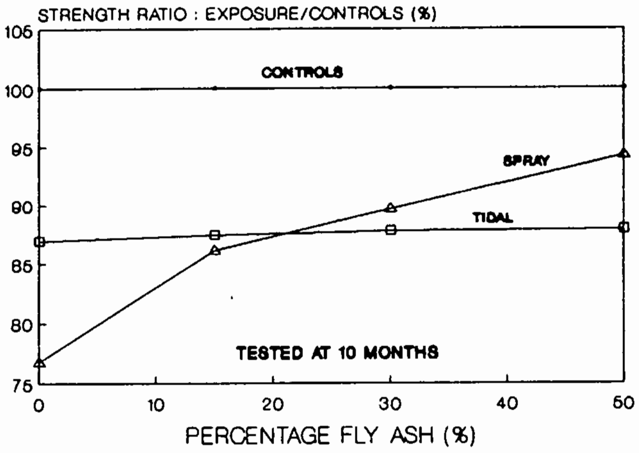

Fig. 7.10: Compressive Strength Ratio : Exposure/Control Average of Grades 30, 40 and 50 MPa Concrete

7.4.2 Sorptivity.

Sorptivity testing of concrete was carried out at the same time as compressive strength tests. Comments regarding exposure sites and conditions experienced by the concrete cubes are also relevant for the cylinders used for the sorptivity work.

At four months the submerged, tidal and control concrete had similar sorptivities while the concrete from the spray zone had higher sorptivities. The drier spray environment must have resulted in poorer log-term curing of the concrete, which caused higher sorptivities. The tidal zone concrete had similar sorptivities to those of the control concrete, even though the concrete had only intermittent wetting. Fig. 7.11a-c shows the sorptivities plotted against percentage fly ash for grades 30, 40 and 50 MPa concrete tested at 4 months.

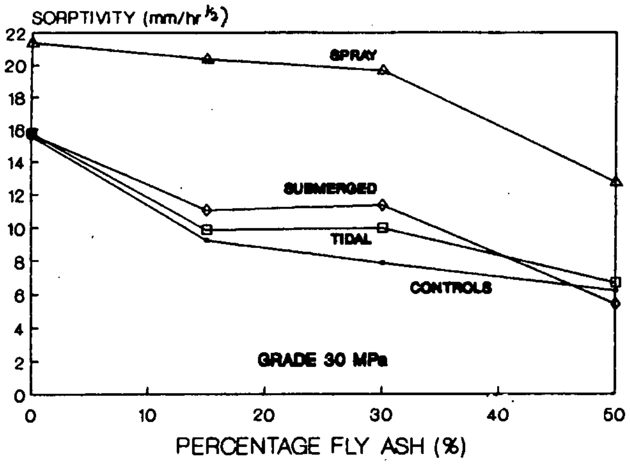

Fig. 7.11a: Sorptivity at 4 months - Grade 30 MPa

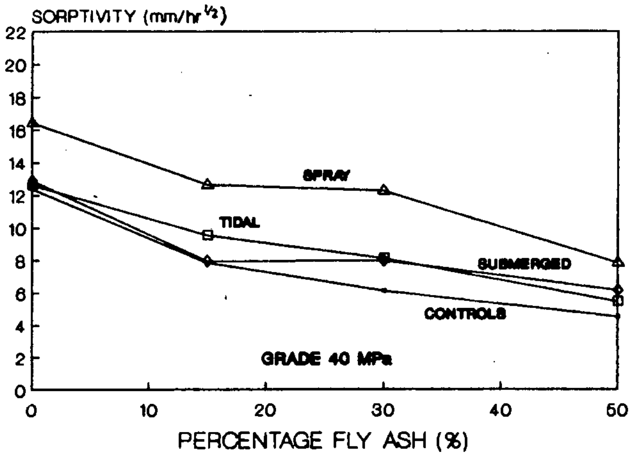

Fig. 7.11b: Sorptivity at 4 months - Grade 40 MPa

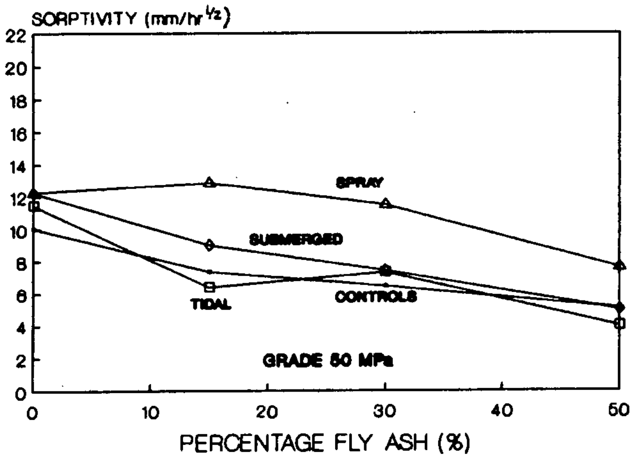

Fig. 7.11c: Sorptivity at 4 months - Grade 50 MPa

Fly ash reduced the sorptivity of concrete for all four types of exposure. The sorptivity of concrete reduced with increasing percentages of fly ash by up to 50% for 50% fly ash concrete compared to that of OPC concrete. Even in the spray zone, where the concrete had poor long-term curing, fly ash concrete had substantially lower sorptivities than similar OPC concrete.

Samples ~~Concrete~~ from the submerged zone concrete had slightly higher sorptivities than those of the control concrete. The difference in sorptivity may have been due to the lower temperature of the sea and internal crack damage caused by wave action.

When the concrete was tested at 10 months, the most apparent feature was the marked reduction in sorptivity of concrete from the spray zone. The tidal zone concrete and control concrete were again found to have very similar sorptivities. Fig. 7.12a-c show the sorptivities of grades 30, 40 and 50 MPa concrete, plotted against percentage fly ash, as tested at 10 months.

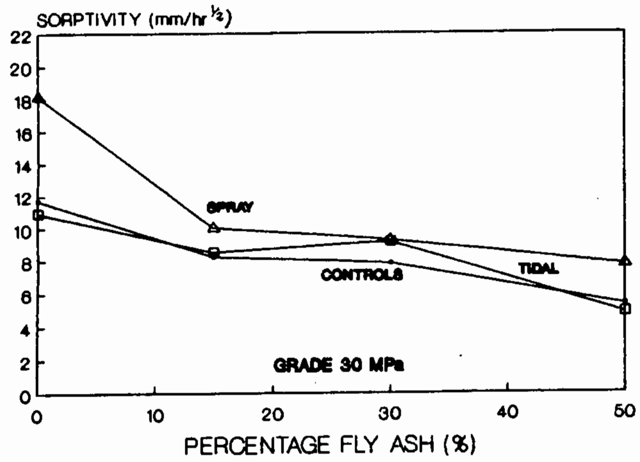

Fig. 7.12a: Sorptivity at 10 months - Grade 30 MPa

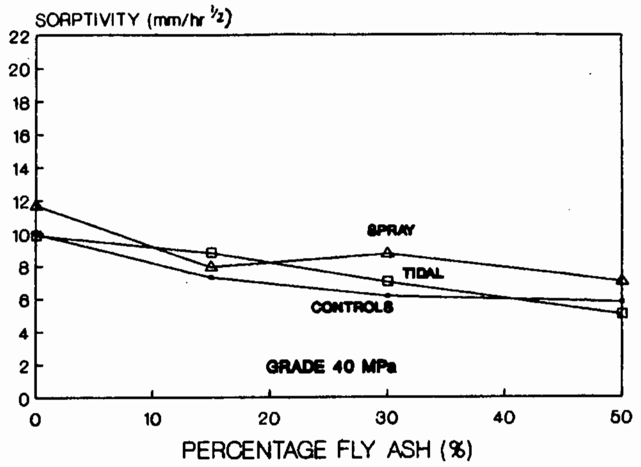

Fig. 7.12b: Sorptivity at 10 months - Grade 40 MPa

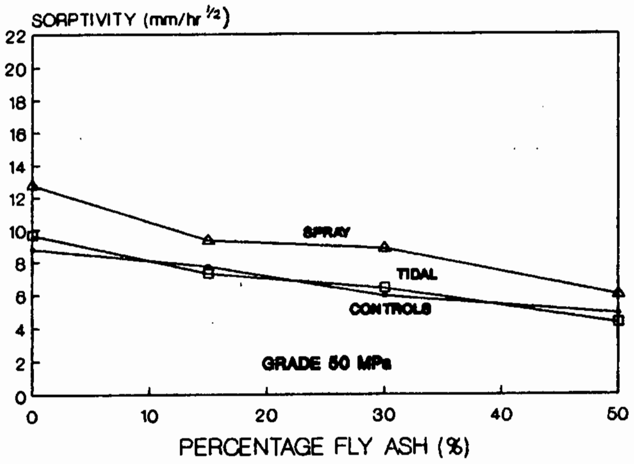

Fig. 7.12c: Sorptivity at 10 months - Grade 50 MPa

The large reduction in the sorptivity of concrete from the spray zone at 10 months was due to the wetter spray environment. The winter rainfall and the spray and splash from the winter storms kept the concrete in a near saturated state. Sorptivity reductions of over 50% between 4 and 10 months occurred for some concretes in the spray zone. The same concrete gained less than 10% in compressive strength during the same interval. The sorptivity of concrete from the spray zone was still higher than the control concrete tested at 10 months, particularly for OPC concrete. This higher sorptivity of OPC concrete, above that of similar fly ash concrete, agrees with the compressive strength losses of OPC concrete between 4 and 10 months.

Concrete in the tidal zone seemed to be largely unaffected by the sea with regard to sorptivity. For all three grades of concrete, the sorptivity of concrete from the tidal zone was roughly equal to that of concrete cured under water in the laboratory. The build up of barnacles and the oil pollution on the concrete may have helped to seal the concrete to some extent. The ends of the concrete cylinders were cut off after exposure, so this may have removed much of the surface concrete which was most affected by the tidal zone conditions.

To see how the sea affected the concrete surface in the tidal zone, precut disks were exposed to the marine environment. The sorptivity of this concrete, which had been in the tidal zone, was lower than similar concrete cured underwater in the laboratory. Concrete which had been wire-brushed after marine exposure, had similar sorptivities to the control concrete. This indicates that a surface layer was present on the concrete, which lowered the sorptivity. Fig. 7.13a-d show the sorptivities of grade 40 MPa concrete plotted against time for tidal zone concrete which was either wire-brushed, unbrushed or control concrete.

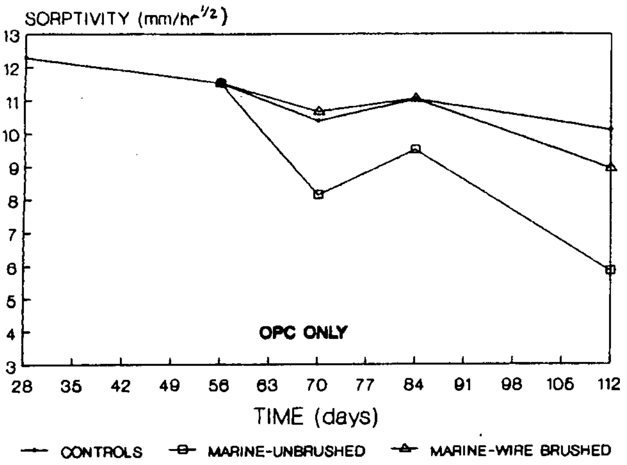

Fig. 7.13a: Sorptivity vs. Time - OPC Concrete

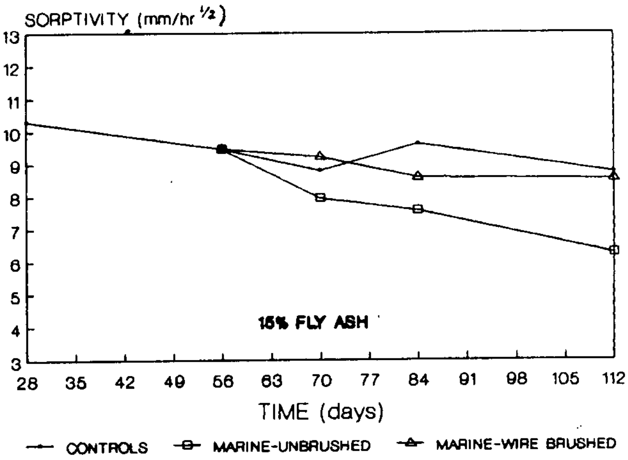

Fig. 7.13b: Sorptivity vs. Time - 15% Fly Ash Concrete

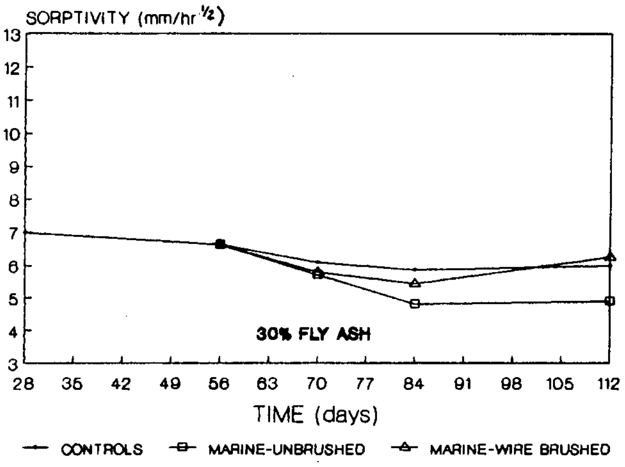

Fig. 7.13c: Sorptivity vs. Time - 30% Fly Ash Concrete

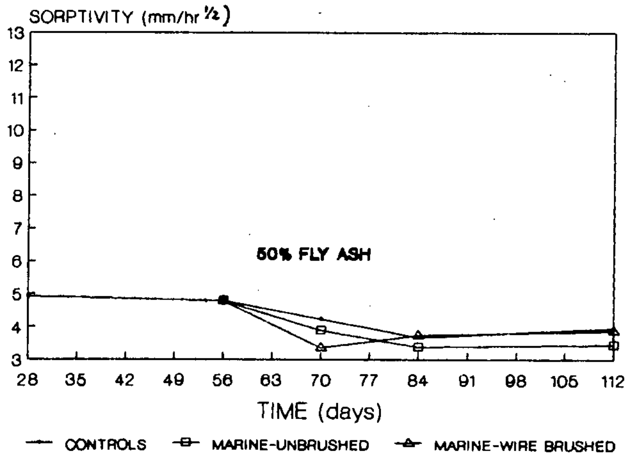

Fig. 7.13d: Sorptivity vs. Time - 50% Fly Ash Concrete

For all four types of concrete the sorptivity of tidal zone samples was lower than the control samples, and the difference in sorptivity increased with increasing time of exposure. This indicates the build up of some kind of impermeable layer on the concrete surface. The fact that a simple wire-brushing of the concrete layer returns the sorptivity to levels similar to those shown by the control concrete, means that the impermeable layer is relatively thin.

A possible explanation for the impermeable layer on the concrete is that oil found in the docks, blocks up the concrete pores on the surface. Several factors contradict this argument, however:

1. Heating the concrete discs to 105° C for 7 days would probably drive off most of the oil from the concrete surface.
2. The concrete discs were stored in tightly woven plastic sacks which allowed water to pass through, but kept most of the heavy oil out.
3. The surface layer reduced the sorptivity of the OPC concrete by up to 40% while a 50% fly ash concrete was reduced by only 13%

These factors would indicate a build up of some chemical deposit on the concrete due to the effect of the sea. Of particular interest is the fact that the sorptivity of OPC concrete was reduced much more than fly ash concrete after exposure to the sea. Fig. 7.14 shows the percentage reduction in sorptivity of the OPC and fly ash concrete with increased time of exposure.

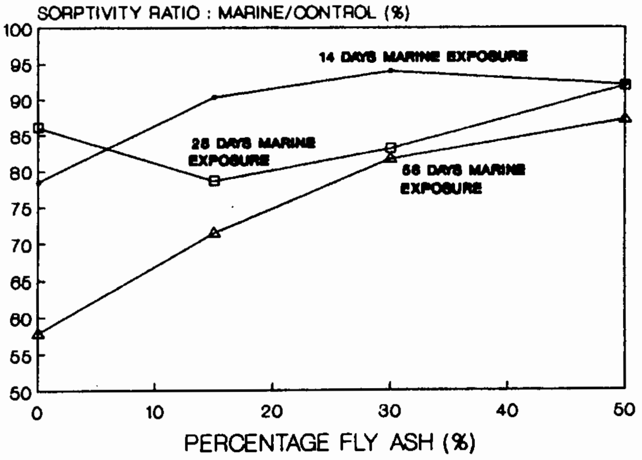

Fig. 7.14: Sorptivity Ratio : Marine/Control
vs. Percentage Fly Ash

After 2 months of marine exposure, OPC concrete had a reduction in sorptivity of over 40%, while the 50% fly ash concrete had only a 13% reduction in sorptivity. The deposit of brucite [$Mg(OH)_2$] on the concrete surface would explain the variable results of the sorptivity for the different types of concrete. The amount of brucite deposited on the concrete surface would depend on the amount of $Ca(OH)_2$ available from the concrete, as the sea could provide limitless Mg^{2+} ions. Fly ash is known to combine with $Ca(OH)_2$ to form insoluble products, thus depleting the $Ca(OH)_2$ produced by the cement. The greater amounts of $Ca(OH)_2$ in OPC concrete available to combine with Mg^{2+}ions would explain the thicker build up of brucite on the concrete surface. Buenfeld and Newman reported that the surface layer of brucite, formed after 18 weeks marine exposure, was less than 100 μm thick (5). This explains why wire-brushing the concrete was able to remove the impermeable layer.

The magnesium salts present in the sea water react with $Ca(OH)_2$ to form brucite in the following manner:

$$MgCl_2 + Ca(OH)_2 \longrightarrow Mg(OH)_2 + CaCl_2$$

$$MgSO_4 + Ca(OH)_2 \longrightarrow Mg(OH)_2 + CaSO_4 + 2H_2O$$

It is thought that aragonite [$Ca(CO_3)_2$] may also be deposited on the concrete surface, which would contribute to the lower sorptivities(5).

Results for the concrete which had been wire-brushed after marine exposure prove that only the surface of the concrete is affected, with the interior pore structure remaining unchanged. This may have been due to the fact that the concrete was only exposed to the marine environment after 2 months, and was thus already fairly impermeable. The concrete was only tested for 2 months exposure time, which may have been too short a time for the significant changes to the concrete interior to take place. The concrete may also have been too impermeable when exposed to the marine environment for the internal pore structure to be affected significantly.

More work is needed to establish exactly what is happening to the concrete surface in the marine environment. From the limited work done here, it would appear the deposit of brucite and aragonite helps to seal OPC concrete, and thus reduces sorptivity. This reduction in sorptivity was much less for fly ash concrete. It is not known whether the deposit of insoluble salts on fly ash takes place for a longer period than OPC concrete, thus developing similar final brucite/aragonite deposits. If the insoluble layer formed on fly ash concrete, after marine exposure, is not as great as that of OPC concrete then this could have serious implications on fly ash durability. The assumption that fly ash concrete will perform better than OPC concrete in the marine environment because of its intrinsic lower permeability may prove to be invalid.

7.5 CONCLUSIONS.

The following conclusions can be made about the performance of fly ash concrete in the marine environment:

1. Fly ash concrete had higher long-term compressive strengths than similar OPC concrete after marine exposure.
2. Fly ash concrete had lower sorptivities than similar OPC concrete after marine exposure.
3. Fly ash concrete performed better than similar OPC concrete in the spray zone with regard to compressive strength and sorptivity.
4. Fly ash concrete and OPC concrete from the tidal zone had similar compressive strength and sorptivity results.
5. Concrete from the submerged zone in the sea gave inconclusive results, but the results obtained were worse than those of the control concrete cured in the laboratory.
6. Concrete from the tidal zone showed a marked reduction in sorptivity due to the build up of insoluble salts on the concrete surface.
7. The reduction in sorptivity due to the build up of insoluble salts was more marked for OPC concrete than it was for fly ash concrete.

The use of fly ash concrete for above ground marine structures is recommended as it is clear that the durability of fly ash concrete should be better than similar OPC concrete. For marine structures in and below the tidal zone, fly ash concrete would appear to be useful, but with some reservations. The nature of the build up of insoluble salts on the concrete surface needs to be investigated thoroughly with regard to fly ash concrete. Also the performance of the fly ash concrete over a longer period of time needs to be investigated. This is presently being undertaken by the CSIR.

It should be remembered that the fly ash used for this work on marine durability was Lethabo field 2 fly ash. This was found to have lower than expected long-term strength development. The results found may thus not be truly representative of fly ash concrete used in practice. It is thought that the trends observed here would however be generally applicable to most fly ash concrete used in the marine environment.

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CHAPTER 8. SOFTWATER DURABILITY

8.1 INTRODUCTION

Concrete due to its alkaline nature has little resistance to attack by acids and pure waters (1). The aggressiveness of natural softwater is dependent not only on its pH but also on the temporary hardness and the free carbon dioxide content. Water may be "soft" due to the low soluble salt content of the ground through which it flows or due to the vegetation it flows through.

Very pure water has a low dissolved calcium bicarbonate content and is said to have a low temporary hardness. Softwater requires only a small portion of the dissolved carbon dioxide to stabilize the calcium bicarbonate present in the water. The remainder of the carbon dioxide is free and is extremely aggressive towards concrete. By solvent action it can leach out the free lime and sometimes the cement binder from the concrete.

Softwater may also be aggressive due to its acidity from the influence of humic acid and other acids derived from decomposed plant matter. These softwaters, also referred to as brown or peaty waters, occur in poorly drained areas rich in vegetation. The pH of these softwaters may be as low as 4.0 but any water with a pH of below 7.0 may be considered to be potentially aggressive.

A brief literature survey of the effect of softwater attack on concrete is given below.

8.2 LITERATURE SURVEY

Aggressive agents can attack hardened cement paste chemically either by a process of dissolution or by chemical transformation. Czernin stated that softwater can attack hardened cement paste by the process of dissolution (2). This is because cement contains up to two thirds lime, either combined with silica, alumina or ferric oxide or as the hydration product of calcium hydroxide. The action of softwater causes dissolution of calcium hydroxide which is fairly soluble in water and so can be leached out by pure water. The insoluble hydration products of cement are only stable in aqueous solutions containing a certain minimum concentration of calcium hydroxide. Leaching of calcium hydroxide out of concrete by pure water causes the decomposition of the hydration products as they attempt to restore the calcium hydroxide concentration by releasing combined lime into solution. This process can proceed in theory until all the combined lime has been removed leaving a mushy mass.

Acidic water dissolves hardened cement by converting its constituents into soluble salts. Biczok stated that the rate of acid corrosion of any particular concrete is controlled by the type of acid, the pH and the solubility of the calcium salts formed by exchange reactions with the salts dissolved in water (3). If the calcium salts are soluble in water they will be leached from the concrete and therefore the rate of concrete corrosion will increase. He claimed that calcium humate formed as a result of the exchange reaction with humic acid and the calcium products of concrete seals the pores of concrete due to it being highly insoluble in water. This protective layer of calcium humate is easily wash away so that the concrete surface will be exposed to further attack.

Humic acid, formed by the decay of plant matter, has a high molecular weight and is relatively insoluble in water. The concentration of humic acid in water depends on the type of vegetation, the season and the type of soil. A saturated solution of humic acid in water will have a pH of between 3.6-4.1. Lea states that water containing humic acid is not as aggressive as pure water or softwater containing aggressive carbon dioxide.

Fraser found that concrete exposed to peaty water for 1 year suffered compressive strength and weight losses (4). This work was done with OPC concrete, either with or without air-entrainment. It was found that air-entrained concrete was more resistant to softwater attack. The softwater used for his research was high in humic acid and had a pH of as low as 4,0.

Several researchers have done work using artificial softwater, which is produced by bubbling CO_2 through tap water. This produces a very aggressive softwater with a pH of around 5,0 and a concentration of about 500 ppm CO_2 in the water. Kruger reported that autoclaved fibre reinforced concrete pipes containing fly ash, had better softwater resistance than similar OPC concrete pipes (5). The resistance to softwater attack was determined by measuring the amount of weight loss of samples with time. Kruger found that fly ash concrete cured underwater for 28 days suffered greater weight loss than similar OPC concrete after 20 weeks of softwater exposure.

Dhir reported that fly ash concrete was used on the Dinorwic Pumped Storage Scheme in the U.K. because of its increased resistance to aggressive water (6). The general consensus of opinion is that fly ash should be used in concrete exposed to softwater because the pozzoalan reduces the free calcium hydroxide in the concrete (7). This reduction in free calcium hydroxide, which might otherwise be removed by the softwater, is thought to improve the resistance to softwater attack.

Little is known about the long-term performance of concrete in softwater environments, apart from case studies of failures due to softwater attack. Even less is known about the performance of fly ash concrete exposed to softwater attack, although indications are that fly ash concrete may have better resistance to softwater than similar OPC concrete.

8.3 EXPERIMENTAL METHOD

Twelve concrete mixes of grades 30, 40 and 50 MPa were used for this work. The concrete mixes are described in detail in Chapter 3. The concrete cubes and cylinders were initially fog cured at 23°C and 95% R.H. for 7 days before being placed into either the softwater environment or cured in tap water in the laboratory. The concrete was placed in the two exposure environments in October 1988.

The two exposure environments are described below :

1. Softwater environment

   Concrete samples were placed in a curing tank at Constantia Nek Water Treatment Plant. The samples were exposed to untreated softwater which came directly from the reservoirs on Table Mountain. The softwater in the tank was changed daily and pH reading taken at regular intervals. The average pH of softwater at Constantia Nek was 4.8. Fig. 8.1 shows the tank containing softwater at Constantia Nek.

Fig. 8.1: Softwater tank at Constantia Nek

After 4 months of exposure to softwater at Constantia Nek the concrete was removed as the plant closed down at the end of January 1989. The concrete samples and curing tank were then moved to Steenbras Water Treatment Plant. At Steenbras it was possible to get a continuous through-flow of softwater in the tank. It was estimated that the water in the tank was replaced four times a day. The average pH of the softwater at Steenbras was 5.3 .

2. Control concrete

   Concrete samples were also cured in tap water at 20°C in the laboratory.

Concrete from the softwater exposure and control concrete cured in the laboratory were tested for compressive strength, sorptivity and weight loss at 4 and 10 months. Compressive testing of concrete was done in accordance with SABS 863 with three 100 mm concrete cubes being used for each test result. The sorptivity of concrete was tested using three 150 diameter by 40 mm thick discs cut from each concrete cylinder. The ends of the cylinders were discarded so the sorptivity of the interior concrete was measured. The weight changes of the concrete in softwater and of the control concrete were monitored throughout the 10 months of exposure.

The chemical analysis of softwater from Constantia Nek is given below.

Average pH		4.8	
Organic Content		17.1	mg/l
Colour		180.0	Plat. Std
Hardness		9.8	mg/l $CaCO_3$
Mineral Content	- Cl	18.5	mg/l
	- SO_2	4.5	mg/l
	- Ca	1.87	mg/l
	- Mg	1.24	mg/l
	- Na	8.8	mg/l
	- K	0.65	mg/l
	- Al	0.61	mg/l
	- Fe	0.32	mg/l
	- Mn	0.03	mg/l

8.4 RESULTS AND DISCUSSION

8.4.1 Compressive Strength

Concrete exposed to softwater had similar compressive strength development to that of the control concrete cured in tap water. The compressive strength results of concrete exposed to softwater were generally lower than those of the control concrete but this difference was usually less than 10% The compressive strength of fly ash concrete was generally higher than that of similar OPC concrete. Fig. 8.2 shows the compressive strength results for grade 30, 40 and 50 MPa concrete plotted against percentage fly ash for the softwater and control concrete.

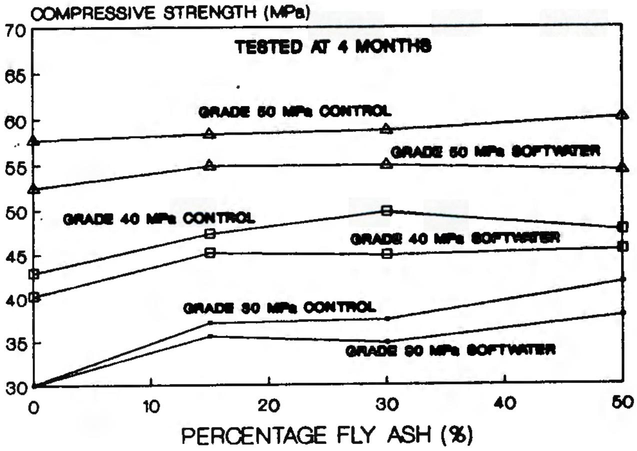

Fig 8.2: Compressive Strength vs. Percentage Fly Ash
Grade 30, 40 and 50 MPa - Tested at 4 months

Regular measurement of the softwater pH in the tank at Constantia Nek showed that daily water changes were not sufficient to maintain a low pH. Within a few hours of changing the water the pH of the softwater in the tank had stabilized to a level of between 10 and 11. The softwater environment could have been much more aggressive towards the concrete if there was a constant through-flow of water. Given a sufficiently fast through-flow of water the pH of the water could have been maintained at a value of below 5.0.

After 4 months of exposure to softwater the concrete showed little sign of physical deterioration. The effect of softwater on concrete strength development can be determined by comparing the compressive strength of the softwater concrete over that of the control concrete. Fig. 8.3 shows the ratio of softwater concrete strength to that of control concrete strength for grades 30, 40 and 50 MPa tested at 4 months.

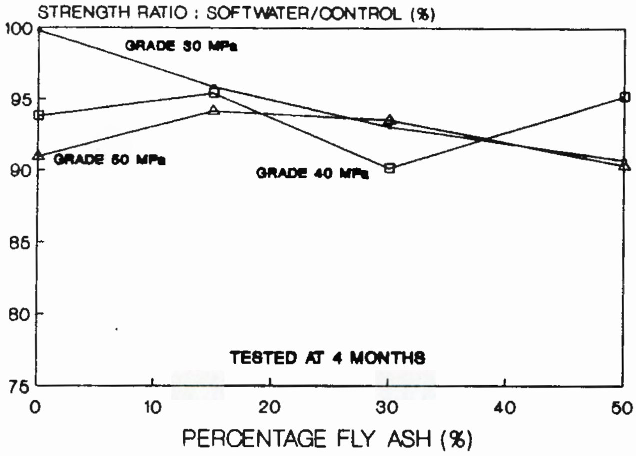

Fig. 8.3: Compressive Strength Ratio : Softwater/Control
Grade 30, 40 and 50 MPa - Tested at 4 months

Concrete exposed to softwater at Steenbras for a further 6 months showed signs of softwater attack after 10 months of total exposure. All concrete cubes had some degree of pitting of the concrete surface. In more severe cases sufficient mortar had been dissolved to expose the aggregate. A close up view of a control cube and a cube from softwater exposure is shown in Fig. 8.4.

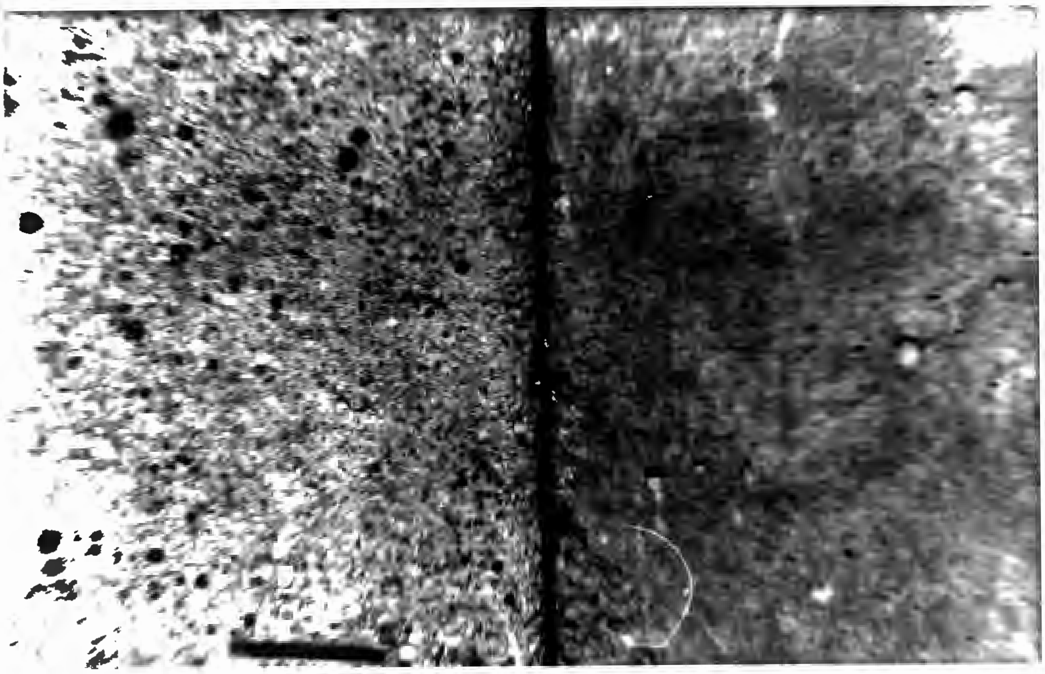

Fig. 8.4: Close up View of Concrete Surface
Left - Softwater   Right - Control

Compressive strength results at 10 months indicate that the softwater environment at Steenbras was more aggressive than at Constantia Nek. This must have been due mostly to the constant through-flow of softwater, which maintained a pH below 7,0. The large differences in compressive strength at 10 months between the control concrete and concrete exposed to softwater are shown in Fig. 8.5.

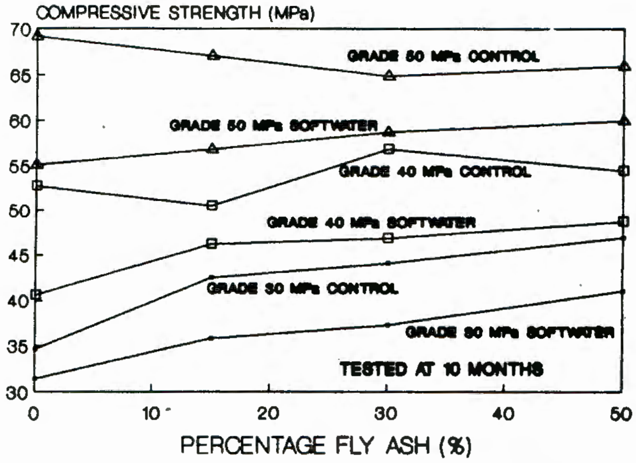

Fig. 8.5: Compressive Strength vs. Percentage Fly Ash
Grade 30, 40 and 50 MPa - Tested at 10 months

The ratio of softwater concrete strength to control concrete strength at 10 months shows the adverse effect of the softwater. Compressive strength of concrete exposed to softwater were between 10 and 20% lower than similar control concrete. Fig. 8.6 shows the compressive strength ratio of softwater concrete to control concrete as tested at 10 months.

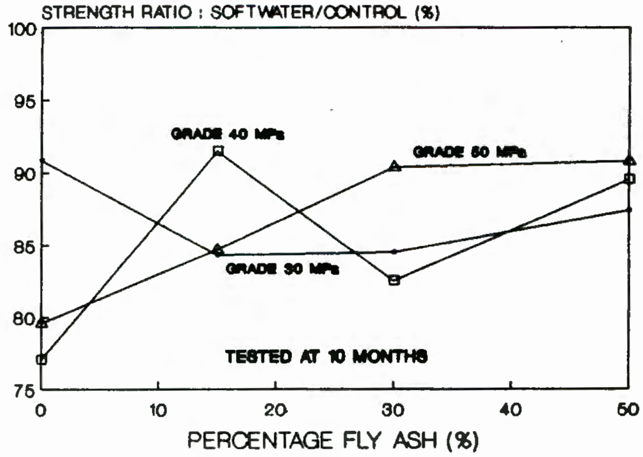

Fig. 8.6: Compressive Strength Ratio : Softwater/Control
Grade 30, 40 and 50 MPa - Tested at 10 months

Fly ash concrete exposed to softwater was generally less affected with regard to compressive strength than similar OPC concrete. The better long-term strength development of fly ash concrete could explain this trend. This is contradicted however by the unusually low long-term strength development of Lethabo field 2 fly ash concrete. Compressive strength results of control concrete showed that OPC concrete actually gained more strength between 4 and 10 months than similar fly ash concrete. At the same time, fly ash concrete exposed to softwater was found to develop more compressive strength than similar OPC concrete. The average compressive strength development of OPC and fly ash concrete exposed to softwater or cured in tap water is shown in Fig. 8.7.

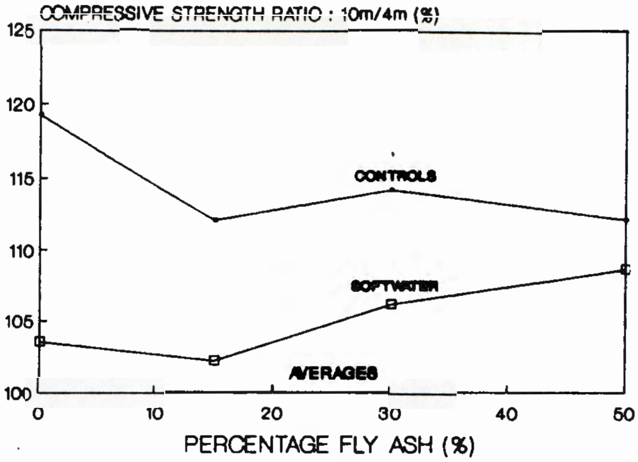

Fig. 8.7: Compressive Strength Development Between 4 and 10 months - Averages

Exposure to the softwater environment caused some retardation in concrete strength development. No concrete was found however to have deteriorated between 4 and 10 months, though OPC concretes showed little strength development during the period. Trends were not obvious due to the mild softwater exposure and short time of exposure.

8.4.2 Sorptivity.

Fly ash concrete exposed to softwater for 4 months had substantially lower sorptivity than similar OPC concrete. There was a definite decrease in sorptivity for increasing percentages of fly ash in concrete. Fig. 8.8 shows the sorptivity plotted against percentage fly ash for grade 30, 40 and 50 MPa concrete exposed to softwater for 4 months.

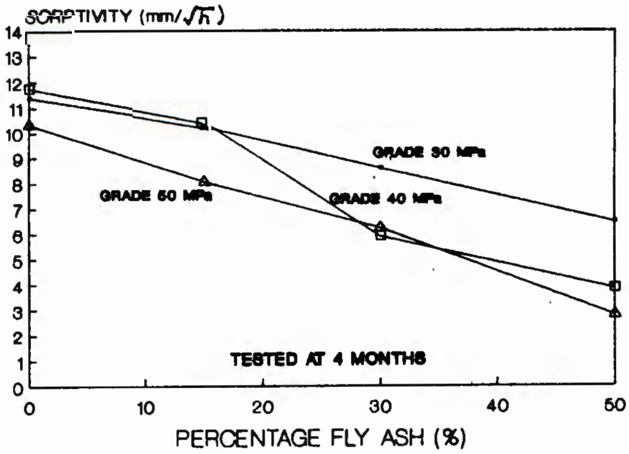

Fig. 8.8: Sorptivity vs. Percentage Fly Ash Grade 30, 40 and 50 MPa - Tested at 4 months

Sorptivity results of concrete tested at 10 months show that fly ash concrete has much lower sorptivity than those for similar OPC concrete. Exposure to softwater increased the sorptivity of many types of concrete compared to the sorptivity measured at 4 months. Fig. 8.9 shows the sorptivity plotted against percentage fly ash for grades 30, 40 and 50 MPa exposed to softwater for 10 months.

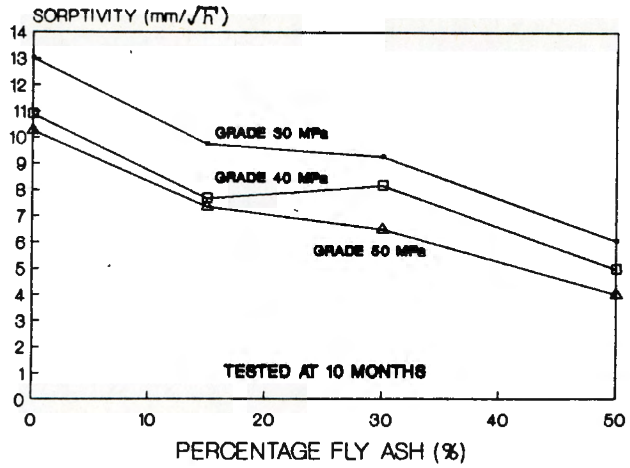

Fig. 8.9: Sorptivity vs. Percentage Fly Ash
Grade 30, 40 and 50 MPa - Tested at 10 months

If the sorptivity development of concrete between 4 and 10 months is compared, the effect of softwater exposure can be seen. High percentage fly ash concrete exposed to softwater had an increase in sorptivity while OPC concrete sorptivity remained almost constant. By comparison, control concrete had a reduction in sorptivity between 4 and 10 months. The sorptivity development of OPC and fly ash concrete, from either softwater exposure or control concrete, is shown in Fig. 8.10.

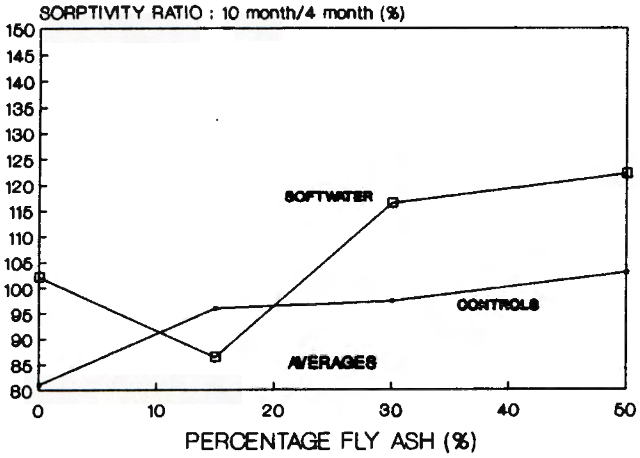

Fig. 8.10: Sorptivity Development
Between 4 and 10 months

The trends established for concrete sorptivity may be slightly misleading as the results fell within a narrow range and the sorptivity measured was that of interior concrete. It was clear that after 10 months of softwater exposure, fly ash concrete had lower sorptivity than similar OPC concrete. The lower sorptivity of fly ash concrete will help protect the concrete from softwater attack.

8.4.3 Weight Loss.

Weight measurements of concrete cubes were complicated by the build up of humic material on the concrete samples exposed to softwater. The continued hydration of concrete in softwater also caused the initial weight reading to increase. At 10 months, considerable weight loss was recorded for concrete exposed to softwater as compared to similar control concrete. Fig. 8.11 shows the average weight loss of grades 30, 40 and 50 MPa concrete plotted against percentage fly ash.

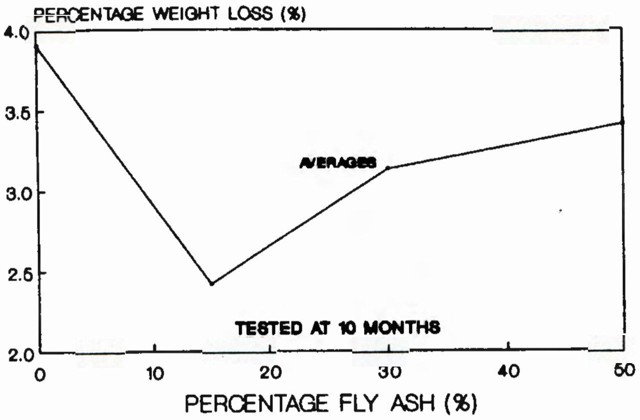

Fig. 8.11: Percentage Weight Loss
Averages - Tested at 10 months

Mass losses of over 100g were recorded for some concrete cubes after 10 months of softwater exposure. Due to the controlled flow of softwater through the tank and careful handling of samples, it is assumed that no weight loss was caused by physical damage. Fly ash concrete had lower percentages of weight loss than OPC concrete, though there is no clear trend for increasing percentage of fly ash.

8.5 CONCLUSIONS.

The following conclusions can be made about the performance of fly ash concrete in a softwater environment:

1. Fly ash concrete had higher compressive strength than similar OPC concrete after 10 months of softwater exposure.
3. Fly ash concrete had lower sorptivity than OPC concrete after 10 months of softwater exposure.
3. OPC concrete had better sorptivity reduction between 4 and 10 months than similar fly ash concrete.
4. After 10 months of softwater exposure, OPC concrete suffered greater percentages of weight loss than similar fly ash concrete.
5. All types of concrete were adversely affected with regard to compressive strength, sorptivity and weight loss by exposure to softwater.

The performance of fly ash concrete in a softwater environment was promising, even accepting the limited nature of the work done. Further work needs to be done over a longer period of time, exposing concrete to a more aggressive environment. Had the concrete samples been exposed to a rapid flow situation with some physical abrasion, it is thought that more obvious trends might have been established. It should be noted that even though fly ash performed better than OPC concrete, it was still quite severely affected by softwater attack.

Some of the trends observed in this study may be specific only to Lethabo field 2 fly ash concrete. Work should be done using a commercially available fly ash in concrete to confirm these trends.

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CHAPTER 9: CONCLUSIONS

A summary of the conclusions from previous chapters is given below. These conclusions are discussed with regard to their influence on concrete durability.

9.1 FRESH PROPERTIES.

Lethabo field 2 fly ash reduced the bleed rate and bleed capacity of concrete. This should improve the durability of concrete particularly when excessive bleeding is prevalent, such as when using a poorly graded sand such as Cape Flats dune sand. High bleed rates cause vertical bleed channels to form and produce a weaker concrete surface. The reduction in bleeding caused by Lethabo field 2 fly ash was larger than expected because of the high quality of the fly ash.

The early ~~set times~~ setting of concrete were retarded by Lethabo field 2 fly ash. The delays in setting time of Lethabo field 2 fly ash concrete were not as significant as those of Matla classified fly ash concrete. The slower setting of fly ash concrete is not a problem in mass concrete structures where concrete is poured continuously. in fact the slower setting of concrete and consequent lower heat of hydration may be beneficial for mass concrete to reduce the risk of thermal cracking. In concrete structures where setting time is of importance the use of up to 30% fly ash will not cause significant delays in setting times.

The improved workability of fly ash concrete will produce better compacted concrete which in turn should improve the concrete durability. Concrete that is poorly compacted will contain large voids which will not only affect the structural integrity but will also allow easy access for aggressive agents. Concrete will be vulnerable to attack in marine and softwater environments if poorly compacted no matter how impermeable the concrete is.

9.2 COMPRESSIVE STRENGTH.

All three types of fly ash concrete had higher long-term compressive strengths than similar OPC concrete. Lethabo field 2 fly ash concrete had exceptionally great early strength development but lower than expected long-term strength development. By comparison Lethabo classified and Matla classified fly ash concrete had lower early strength development but greater long-term strength development than Lethabo field 2 fly ash concrete. Even with these variations all mature fly ash concrete should have higher compressive strengths than OPC concrete if well cured.

The continued long-term strength development of Lethabo classified and Matla classified fly ash concrete make these concretes suitable for applications where early strength development is not so critical. In concrete structures where early strength is required, fly ash concrete may compare unfavourably with similar OPC concrete.

Compressive strength remains one of the best indicators of concrete quality. The performance of concrete with time can be determined by measuring the compressive strength at intervals. Using test specimens such as 100 mm cubes does however introduce size effects which makes direct comparisons with large mass concrete structures difficult. The compressive strength of concrete is also influenced by external factors which need to be monitored carefully. The influence of these factors needs to be considered before comparisons can be made between different types of concrete.

9.3 MIX ECONOMICS.

The substantial reduction in water requirements found with the Lethabo field 2 fly ash concrete reduced the total cementitious material needed for any cement water ratio. This, coupled with the good early strength development of Lethabo field 2 fly ash concrete, made most fly ash concrete cheaper in terms of material costs than OPC concrete at 28 days. This was found even though fly ash costs virtually the same as OPC in the Western Cape.

Lethabo classified and Matla classified fly ash concrete had higher water requirements and lower 28 day compressive strengths than those of Lethabo field 2 fly ash concrete. This resulted in classified fly ash concrete being slightly more expensive than similar OPC concrete at 28 days. This slight disadvantage in mix economics of fly ash concrete is however counteracted by other improved concrete properties. In an aggressive environment, the impermeability may be seen as the most important factor for good durability of concrete. The material cost of a fly ash concrete will be much lower than that of an OPC concrete of equal permeability.

9.4 DRY CURING.

Lethabo field 2 fly ash concrete was more vulnerable to poor curing than similar OPC concrete. In slender reinforced concrete structures the use of fly ash must be considered carefully if proper curing cannot be guaranteed. In mass concrete structures the problem of curing is negligible, particularly in wet environments such as the sea or underground. It should be realised however that the outer layer of concrete may still cure poorly and some deterioration of the surface can be expected.

The slower compressive strength development of Lethabo classified and Matla classified fly ash concrete will increase the likelihood of these concretes being adversely affected by poor curing. The slower strength development allows increased water loss from the concrete due to drying. This causes the pozzolanic reaction of the fly ash to be curtailed resulting in lower long-term strengths and higher permeability.

9.5 WATER ABSORPTION AND PERMEABILITY.

The inclusion of fly ash in concrete was found to substantially reduce the rate of water absorption and permeability of mature concrete. The constriction of the pore structure due to the pozzolanic reaction was related to the compressive strength development. The slow reduction of permeability of fly ash concrete with time means that fly ash concrete may be vulnerable to aggressive attack at early ages. In the longer term however, fly ash concrete will retard the infiltration of aggressive agents.

The permeability of mature concrete is of the utmost importance for concrete exposed to aggressive attack over an extended period of time. In mass concrete structures, where the full potential of hydration of cement and fly ash concrete is commonly realised, the lower permeability of fly ash concrete will enhance the durability of the material.

9.6 MARINE ENVIRONMENT.

Lethabo field 2 fly ash performed better in the spray zone than similar OPC concrete. In the tidal and submerged zones Lethabo field 2 fly ash concrete had results similar to those for OPC concrete. The more rapid strength development and sorptivity reductions of Lethabo field 2 fly ash may have helped enhance the performance of fly ash concrete. The better long-term compressive strength development and sorptivity reductions of Lethabo classified and Matla classified fly ash concrete will however produce similar ultimate strength and sorptivities as Lethabo field 2 fly ash. Assuming that the classified fly ashes suffer no rapid short-term deterioration, all three types of fly ash should produce concrete with good long-term durability.

Concrete in the tidal zone had a build-up of insoluble material after exposure to the marine environment for two months. The insoluble layer was confined to the surface and reduced the sorptivity of concrete. This sealing of the concrete surface may help to protect the concrete from infiltration by harmful agents and therefore improve the durability in aggressive environments. OPC concrete had higher reductions in sorptivity due to the chemical build-up than similar fly ash concretes. It is difficult to draw conclusions about the effect of the insoluble layer due to the limited number of tests done and the relatively short time of exposure. A reassessment of the durability prospects of fly ash concrete will however have to be made if the decrease in permeability of OPC concrete in the marine environment is not found for fly ash concrete.

9.7 SOFTWATER ENVIRONMENT.

As in the marine environment, Lethabo field 2 fly ash concrete performed better than similar OPC concrete. Compressive strength and resistance to weight loss of fly ash concrete were better than for similar OPC concrete while the sorptivity results were inconclusive. This would indicate that fly ash concrete is potentially suitable for use in softwater environments. The concrete was however exposed to a fairly mild softwater environment which resulted in little deterioration over the 10 months of exposure.

9.8 SUMMARY

Fly ash concrete confirmed its good durability potential after exposure in the marine and softwater environments. The favourable performance of fly ash concrete must however be seen in the light of the following considerations.

1. Lethabo field 2 fly ash concrete behaves differently to Lethabo classified and Matla classified fly ash with regard to compressive strength development. Some of the characteristics found for Lethabo field 2 fly ash concrete may not apply to concrete made with air-classified fly ash.
2. The size of the exposure samples may have some influence on the results recorded due to their high surface area to volume ratio.
3. The time the concrete was exposed to the marine or softwater environments was too short to cause significant amounts of deterioration. The long-term performance of fly ash concrete in the marine or softwater environment can only be predicted confidently by long-term exposure tests.

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APPENDIX - CONCRETE MIXES

1. AVERAGE-SANDED CONCRETE

TARGET 28 DAY STRENGTH (MPa)		PERCENTAGE FLY ASH (%)				
		0%	15%	30%	50%	70%
10 MPa	CEMENT	192		134	95	75
	FLY ASH	0		57	95	175
	SAND	879		881	878	865
	STONE	1050		1102	1127	1151
	WATER	210		182	172	143
20 MPa	CEMENT	239	201	170	136	95
	FLY ASH	0	35	73	136	221
	SAND	864	855	854	838	806
	STONE	1050	1083	1102	1127	1151
	WATER	202	188	175	154	137
30 MPa	CEMENT	296	245	207	168	
	FLY ASH	0	43	89	168	
	SAND	837	838	829	803	
	STONE	1050	1083	1102	1127	
	WATER	196	182	168	147	
40 MPa	CEMENT	348	287	243		
	FLY ASH	0	51	104		
	SAND	812	808	797		
	STONE	1050	1083	1102		
	WATER	190	175	162		
50 MPa	CEMENT	416	344			
	FLY ASH	0	61			
	SAND	766	760			
	STONE	1050	1083			
	WATER	187	171			

2. UNDER-SANDED CONCRETE

TARGET 28 DAY STRENGTH (MPa)		PERCENTAGE FLY ASH (%)				
		0%	15%	30%	50%	70%
10 MPa	CEMENT	173		123	87	75
	FLY ASH	0		53	87	175
	SAND	784		760	758	682
	STONE	1220		1280	1309	1338
	WATER	193		172	160	141
20 MPa	CEMENT	219	185	154	126	93
	FLY ASH	0	33	66	126	217
	SAND	758	738	745	710	633
	STONE	1220	1259	1280	1309	1338
	WATER	188	175	164	148	138
30 MPa	CEMENT	275	232	194	166	
	FLY ASH	0	41	83	166	
	SAND	725	702	701	634	
	STONE	1220	1259	1280	1309	
	WATER	180	170	156	147	
40 MPa	CEMENT	328	274	239		
	FLY ASH	0	48	102		
	SAND	691	670	636		
	STONE	1220	1259	1280		
	WATER	178	167	158		
50 MPa	CEMENT	398	326			
	FLY ASH	0	57			
	SAND	635	630			
	STONE	1220	1259			
	WATER	176	164			

3. OVER-SANDED CONCRETE

TARGET 28 DAY STRENGTH (MPa)		PERCENTAGE FLY ASH (%)				
		0%	15%	30%	50%	70%
10 MPa	CEMENT	202		142	103	79
	FLY ASH	0		61	103	184
	SAND	940		942	931	942
	STONE	950		997	1019	1042
	WATER	226		199	191	159
20 MPa	CEMENT	252	213	179	145	92
	FLY ASH	0	38	77	145	216
	SAND	922	911	922	896	929
	STONE	950	980	997	1019	1042
	WATER	218	201	191	172	149
30 MPa	CEMENT	307	264	223	185	
	FLY ASH	0	47	96	185	
	SAND	908	883	877	836	
	STONE	950	980	997	1019	
	WATER	205	195	181	159	
40 MPa	CEMENT	372	307	263		
	FLY ASH	0	54	113		
	SAND	856	857	841		
	STONE	950	980	997		
	WATER	206	188	175		
50 MPa	CEMENT	450	379			
	FLY ASH	0	67			
	SAND	796	798			
	STONE	950	980			
	WATER	198	181			

4. SOFTWATER EXPOSURE CONCRETE

TARGET 28 DAY STRENGTH (MPa)		PERCENTAGE FLY ASH (%)			
		0%	15%	30%	50%
30 MPa	CEMENT	297	252	202	150
	FLY ASH	0	45	87	150
	SAND	851	840	851	839
	STONE	1050	1083	1102	1127
	WATER	201	188	175	160
40 MPa	CEMENT	353	295	232	171
	FLY ASH	0	52	100	171
	SAND	817	804	824	813
	STONE	1050	1083	1102	1127
	WATER	196	185	170	154
50 MPa	CEMENT	406	338	260	196
	FLY ASH	0	60	112	196
	SAND	785	769	800	780
	STONE	1050	1083	1102	1127
	WATER	191	181	165	148

5. MARINE EXPOSURE CONCRETE

TARGET 28 DAY STRENGTH (MPa)		PERCENTAGE FLY ASH (%)			
		0%	15%	30%	50%
30 MPa	CEMENT	306	259	203	151
	FLY ASH	0	46	87	151
	SAND	827	820	847	834
	STONE	1050	1083	1102	1127
	WATER	207	193	176	161
40 MPa	CEMENT	364	302	236	173
	FLY ASH	0	53	101	173
	SAND	791	786	812	804
	STONE	1050	1083	1102	1127
	WATER	202	189	173	156
50 MPa	CEMENT	420	346	268	203
	FLY ASH	0	61	115	203
	SAND	757	750	777	752
	STONE	1050	1083	1102	1127
	WATER	197	185	170	153

6. LETHABO CLASSIFIED FLY ASH CONCRETE MIXES

TARGET 28 DAY STRENGTH (MPa)		PERCENTAGE FLY ASH (%)			
		0%	15%	30%	50%
30 MPa	CEMENT	312	264	208	156
	FLY ASH	0	47	89	156
	SAND	807	801	825	805
	STONE	1050	1083	1102	1127
	WATER	211	196	180	166
40 MPa	CEMENT	371	312	243	179
	FLY ASH	0	55	104	179
	SAND	744	753	783	772
	STONE	1050	1083	1102	1127
	WATER	206	195	178	161
50 MPa	CEMENT	429	353	277	212
	FLY ASH	0	62	119	212
	SAND	733	726	742	708
	STONE	1050	1083	1102	1127
	WATER	201	189	176	160

7. MATLA CLASSIFIED FLY ASH CONCRETE MIXES

TARGET 28 DAY STRENGTH (MPa)		PERCENTAGE FLY ASH (%)			
		0%	15%	30%	50%
30 MPa	CEMENT	312	264	209	162
	FLY ASH	0	47	90	162
	SAND	807	801	820	777
	STONE	1050	1083	1102	1127
	WATER	211	196	181	172
40 MPa	CEMENT	371	312	250	188
	FLY ASH	0	55	107	188
	SAND	744	753	760	732
	STONE	1050	1083	1102	1127
	WATER	206	195	183	169
50 MPa	CEMENT	431	359	284	223
	FLY ASH	0	63	122	223
	SAND	729	712	721	664
	STONE	1050	1083	1102	1127
	WATER	202	192	180	168