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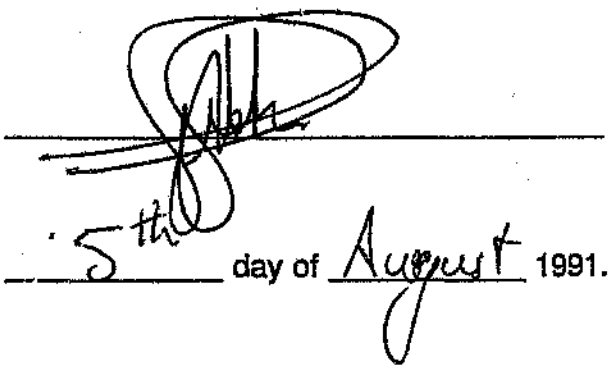
THE INFLUENCE OF TWO SOUTH AFRICAN FLY ASHES ON THE ENGINEERING PROPERTIES OF CONCRETE

Graham Robert Hugh Grieve

A thesis submitted to the Faculty of Engineering, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Doctor of Philosophy.

Johannesburg, 1991.

I declare that this thesis is my own unaided work. It is being submitted for the degree of Doctor of Philosophy in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.



5th day of August 1991.

CONTRIBUTION

This study has contributed to the advancement of the understanding of the performance of two sources of South African fly ash as cementitious extenders to cements of South African origin for use in concrete and/or mortar mixes.

The fly ashes used in the experimental work were those available as commercial products in South Africa during the period 1986–1991.

A wide spectrum of tests has been carried out to show the effect that the fly ashes have on the fresh and hardened properties of concrete and mortar. Particular attention has been given to the use of such concretes under the conditions of exposure peculiar to South African construction sites.

ABSTRACT

The South African cement producers would like to utilise cement extenders in cement to increase manufacturing capacity at a relatively low cost. An understanding of the implications such a step might have for the cement user was required.

A study was made of the performance of portland cement blends made with fly ash derived from the two commercial sources in South Africa that were being utilised by 1991. The performance of the blends was compared against the performance of ordinary portland cement, the cement type to which the majority of users in South Africa were exposed in the past.

An extensive literature study was provided which covered the latest research aspects of the use of fly ash in many other parts of the world as well as information from local South African research reports.

The ash concrete or mortar properties studied in the laboratory tests were as follows:

- workability
- rheology
- setting time
- bleeding
- heat of hydration

The following properties of hardened concrete were studied in laboratory and simulated site exposure tests:

- compressive strength
- flexural strength
- elastic modulus
- shrinkage
- creep
- permeability
- abrasion resistance
- carbonation

Some preliminary investigations were made into the effect that the use of fly ash had on the effectiveness of chemical admixtures, and into the compressive strength development of ternary (three component) blends.

As far as possible, use was made of standard SABS, BS, ASTM, DIN or RILEM test methods although it was necessary to use other non-standard or modified test methods in some cases to provide the necessary information. Appropriate references or details have been provided where methods have deviated from standard methods.

Recommendations were made regarding the level of fly ash replacement which was believed to be practical for site use for two categories of users, namely unsophisticated users with a low level of understanding of concrete technology and relatively crude methods of site batching and mixing, and sophisticated users with access to higher levels of technology and equipment.

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CHAPTER 1

1 INTRODUCTION

1.1 Expectations of cement performance

South Africa, in common with most other cement producing countries, has built up decades of experience with the use of portland cement in the manufacture of concrete, plaster and mortar and other cementitious products. This experience is held not only by the site staff of contractors, builders and concrete product manufacturers but also by the designers and owners of concrete structures.

Many applications of the use of portland cement are non–critical in that the consequence of failure is cosmetic rather than life–threatening. Nevertheless the owner will have certain expectations of quality and the supplier will try to meet these expectations with appropriate quality workmanship and materials. The supplier will rely heavily on experience of the behaviour of commonly used materials in trying to meet his customer's expectations. The supplier himself obviously has expectations of how his materials and workmen should perform.

A dilemma faces a producer attempting to introduce changes to a product that has many years of successful application behind it. If these changes are of such a magnitude that the user's expectations are no longer met then some problems can be expected during routine use of the product. These problems might occur even if the changes result in the product performance being superior to that which experience has led the user to anticipate.

The introduction of cement extenders such as ground granulated blastfurnace slag, fly ash or silica fume in cement blends is likely to cause such problems to the users if these blends perform in a way different to that expected by the user.

There have been many papers giving sound reasons why blended cement performance should not be compared against that of ordinary portland cement. Unfortunately when a blended cement is used by site or factory workmen then inevitably those immediately involved, unless specially trained in the use of the different product, will expect the performance given by the cement most commonly used. In South Africa this experience will most probably have been developed on ordinary portland cement, or in a smaller proportion of cases with a blend of ground granulated blastfurnace slag and portland cement.

Two options are open to the product manufacturer who wants to introduce blended cements with different properties:

- he can introduce the different product together with an education program, or
- he can try to manufacture the new product to meet the user expectations.

Both options present problems in South Africa. It would be a daunting prospect to try to reach and re-educate all cement users in South Africa.

The second option presents some interesting challenges to the cement chemist. This option is likely to lead to an increase in the production costs and would therefore tend to diminish the cost benefits that might normally accrue to the producer of a blended cement, and which could be passed on to the consumer.

1.2 Structural use of portland cement concrete

The techniques used to design concrete structures which will safely carry the loads and stresses intended by the designer have developed along with the increasing availability of the portland cement used in its manufacture. These techniques are largely based on empirical knowledge of the behaviour of concrete test specimens and how these results relate to the characteristics of the concrete in the structures.[1]

As this knowledge has, in the main, been developed using Ordinary Portland Cement (OPC) this has come to be regarded as the standard and it is common to find that when the use of other cementitious materials is considered the performance of these concretes is compared against that for OPC concrete to give the structural designer a feel for the new material.

Most civil engineers probably still regard compressive strength as the most important property of hardened concrete, although there is a growing awareness of the need to consider durability in the design process. The designer has commonly assumed adequate durability in the past. Now with some structures showing unexpectedly poor service life,[2] properties other than compressive strength are growing in importance.

In evaluating the use of new cementitious materials in concrete it is therefore necessary to measure the performance not only in terms of compressive strength but of many other characteristics which may have a bearing on the durability of such concrete when it is exposed to its service conditions.

Durability is not an easy property to measure. It is influenced by many different characteristics of the concrete and the environment and service conditions to which it is exposed. It is, furthermore, a property which influences the satisfaction of the long term needs of the owner – a lack of durability in existing structures is likely to introduce some doubts about the life expectancy of concrete when the owner comes to decide on the choice of structural material for his next structure.

1.3 Work needed to provide the necessary confidence

Substantial work by Stutterheim[3] and Fulton[4] preceded the adoption of the use of ground granulated blastfurnace slag (GGBS) as a partial substitute for portland cement in South Africa and made it possible for designers and concrete technologists to understand how to use the material. With 31 years of successful use of GGBS in

South Africa since its first introduction in 1958, it is evident that such research findings contributed to providing the necessary confidence to stimulate the use of the material.

It was therefore believed that this was an appropriate way to advance any further introductions of similar materials.

1.4 Proposed introduction of fly ash blended cement

In 1984 the South Africa cement producers made known their intention to consider producing a portland cement containing approximately 15 % of fly ash to be supplied to the Pretoria–Witwatersrand–Vereeniging (PWV) marketing area. This cement would be designated as a PC 15 FA, ie basically a portland cement with a maximum permitted fly ash content of 15 %.

Although the then National Building Research Institute (NBRI) of the Council for Scientific and Industrial Research (CSIR) had done a large amount of valuable research (as will be discussed later) it was felt that their work was of a very broad and general nature and that there was a need for more specific information applying to the particular combinations of fly ash and portland cement likely to be used in this marketing area. Other research work had been done overseas but there was concern that the findings of such researchers might not be applicable to South African materials.

The Portland Cement Institute (PCI) decided to undertake a research project to provide the necessary information which would permit more confident use of cements containing fly ash, and in particular a cement with up to 15 % of fly ash.

A survey was therefore undertaken of the intentions of the three cement producers supplying to the PWV market.[5] The companies were as follows:

- Anglo–Alpha Ltd. (A–A)
- Blue Circle Cement (Pty.) Ltd. (BC)
- Pretoria Portland Cement Company Ltd. (PPC)

Their expressed intentions could be summarized as follows:

Anglo–Alpha Limited stated that their intention was to blend portland cement with fly ash –if they decided to produce the product at all.[6] Blue Circle Cement (Pty) Limited wrote that they intended to produce a blended product.[7] Pretoria Portland Cement Company Ltd stated that they had not made a final decision between blending or intergrinding of fly ash nor whether they would produce such a cement.[8] The holder of the rights to Eskom's ash at the time, D & H Ash Resources confirmed that ash for any such product would be supplied from the Matla power station.

However during the course of the laboratory investigation for the evaluation of this particular fly ash the Lethabo Power Station was under construction for the South

African electricity utility company, Eskom. As this source of ash is also to be exploited for use in concrete and because it is likely to become the more commonly used source due to its closer proximity to the major PWV market some consideration has been given in the testing programme to this material too. Unfortunately as the classification equipment was only commissioned at the end of 1989 the ash from this source became available too late for substantial laboratory work to be done on its properties.

Having thus obtained the intentions of the producers involved the PCI research project could be started.

Before providing details of the properties of the materials used it is advisable to have a look at the history of the use of fly ash in other parts of the world and in South Africa. This aspect is covered in chapter 2.

CHAPTER 2

2 FLY ASH – THE MATERIAL, AND HISTORY OF ITS USE

2.1 Introduction

Fly ash is the waste product produced in modern coal burning plants when finely ground, milled or pulverized coal is burned and the fine residue, instead of being permitted to escape through the flue to atmosphere, is collected either by electrostatic precipitators or bag filters. This is a fairly wide definition and would encompass all fly ashes produced in South Africa including those produced by modern coal burning power generating facilities of the Electricity Supply Commission. This organisation was recently renamed Eskom.

In this particular study only two of Eskom's facilities are of interest, namely Matla Power Station in the Eastern Transvaal highveld near Witbank, and Lethabo Power Station situated in the Orange Free State near Vereeniging, Transvaal. Details of these two facilities and the fly ashes they produce are provided in later paragraphs of this chapter.

2.2 Coal – the fuel for the combustion process

South Africa is blessed with abundant reserves of coal. Much of this coal is however of too low a calorific value to make it suitable for export purposes. This is mainly due to the fact that the cost of transport per kilojoule of energy is too high. It is however possible to utilize this coal if it is not necessary to transport it too far. In an effort reserve the better quality coals for export purposes Eskom has opted to make use of these lower grade coals for electricity generation. This decision has forced Eskom into building their power generating facilities close to the coal sources. This is somewhat in contrast to the normal trend of having these close to the demand for electricity.

The details of only two of the many Eskom power stations are considered here as they are the only two from which fly ash is supplied for general cementitious use. The relevant stations are Matla and Lethabo.

2.2.1 Matla Power Station

Matla power station is situated in the Eastern Transvaal in the vicinity of Witbank. It has a generating capacity of 3 600 Megawatt, produced from 6 boilers. The boilers are fired with finely milled coal, and each boiler consumes about 250 tons of coal per hour at peak load, burning at a temperature of about 1 500 °C. The coal is supplied by General Mining and Finance Corporation from their Matla underground colliery.[9]

The calorific value of this coal varies between 15,8 and 20,6 MJ/kg and the ash content lies between 17,5 % and 33,0 %. The coal is delivered to coal storage bunkers, 6 of which serve each boiler. The coal is supplied as a minus 25 mm size and this is further broken down in ball mills prior to being fed to the boiler in an air flow. The mills are required to produce the coal with a guaranteed fineness level of 99 %

finer than 300 micrometres, and 70 % finer than 75 micrometres.[10]

An analysis for the coal supplied to Matla is given in Table 2.1; these figures are the average for two analyses for 1989.[11]

At peak load each boiler will produce about 1400 tons of fly ash per day ie a total of 8 400 tons per day from the power station. At the same time each boiler produces 250 tons of bottom ash daily.

An analysis for the total ash, i.e. bottom + fly ash from Matla is given in Table 2.2. These figures are the average for two analyses for 1989.[11]

All ash not removed for further processing for cementitious or other purposes is sluiced away to an ash sump and subsequently to an ash dam. The water used to sluice the ash away is recovered and re-used in a closed cycle.

Fly ash required for other uses is removed from the precipitator hoppers. The fly ash required for cementitious use is then further processed through a British Rema air separator[12] to meet the 45 micrometre retention requirements of SABS 1491–1989 (South African Bureau of Standards, **Standard specification for Portland Cement Extenders**, SABS 1989 (1491–89)). Oversize material is rejected with this equipment while the fine material is selected for use. This is the current procedure followed at Matla; in the earlier days of supply of fly ash from Matla the practice was to select the fly ash from precipitator fields No. 2 to No. 4 and it was only when Eskom decided in 1987 to dump all the ash together that the classifier equipment became necessary. The change in selection procedure had some effect on the performance characteristics of this fly ash as will be discussed in a later chapter.

The process of separation or classification is necessary as fly ash fineness is an important parameter in determining its suitability for use in cementitious reactions.

2.2.2 Lethabo Power Station

Lethabo power station at the end of 1989 was still under construction. It is situated in the Orange Free State not far from the Transvaal town of Vereeniging. It has a generating capacity of 3 708 MW produced in 6 boiler–turbine sets. The boilers are fired with finely milled coal which is consumed at the rate of 350 to 400 tons per hour at peak load. The coal is supplied by Amcoal from its New Vaal colliery.[13] The calorific value of this coal is around 16 MJ/kg and the ash content is rather high at between 28 % and 42 %. Average figures for two analyses for 1989 are shown in comparison against those for Matla in Table 2.1.[14]

The coal is transported via storage silos to the boiler bunkers and mills. The coal is supplied as a –25 mm size and this is further broken down in ball/tube mills and then blown into the boilers where it is burned at a temperature of about 1450 °C to generate steam. The mills are required to produce coal with a guaranteed fineness of 99 % finer than 300 micrometres and 70 % finer than 75 micrometres. In practice these mills have produced 80 % finer than 75 micrometres during a commissioning test, and the

average level of fineness achieved during 6 months of operation in early 1986 was 78.2 % finer than 75 micrometre.[15]

At peak load each boiler will produce about 350 tons of coarse bottom ash and 3 400 tons of fly ash daily, ie a total production capacity of about 7.5 million tons of fly ash annually. The fly ash is collected in an array of 7 precipitators and is transported to ash bunkers from where, if it is not to be used for any other purpose, it is transported to be dumped in the mined–out open cast mine workings.

An average chemical analysis for the ash produced at Lethabo is given alongside the same figures for Matla in Table 2.2. These figures are the average for two analyses for 1989.[14]

When ash is required for cementitious use it is transported in a dry state to an air classifier which produces a product to meet SABS 1491–1989 requirements. This particular classifier is designed to be able to supply 400 000 tons of classified fly ash per annum.

2.3 History of the use of fly ash

In order to understand the use of a material such as fly ash it is necessary to go a long way back in history and look at the use of a natural pozzolan.

2.3.1 Fly ash as a pozzolan

The ACI defines a pozzolan as a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, react with calcium hydroxide to form compounds possessing cementitious properties.[16]

The first record of the use of a pozzolan dates back to the days of the Roman Empire when use was made of a natural pozzolan – a volcanic ash – obtained from a place called Puteoli situated near the volcano Vesuvius.[17] In this particular case the pozzolan was used together with building or hydrated lime and the users were surprised at how hard this particular mortar became.

Fly ash as the residue from the combustion of coal is similar to such natural pozzolans. It will react with calcium hydroxide to form cementitious products. The calcium hydroxide can be derived from hydrated lime or from the hydration of portland cement. Substantial quantities of calcium hydroxide are generated during the hydration of portland cement and this material does not contribute materially to the strength of the hydration products. Indeed portlandite, the crystalline form of calcium hydroxide, contributes to the susceptibility of hardened portland cement pastes to attack by various aggressive chemicals. In the process of the pozzolanic reaction the calcium hydroxide is consumed during the formation of further cementitious products in the form of calcium silicate hydrates.

2.3.2 The modern use of fly ash

An early investigation into the chemical similarity of coal ashes and natural pozzolans was published in the June 11 1914 issue of the USA publication Engineering News and subsequently referred to by Malhotra.[18] No significant fly ash utilization resulted from this article. Mielenz[19] in 1983 reported that in about 1932 fly ash was first used as a mineral admixture after research done by power utility companies. In 1937 Davis[20] published the first detailed scientific study of the use of fly ash based on work done at the University of California, Berkeley.

In 1942 the US Bureau of Reclamation used fly ash as an extender in tunnel spillway repair works at the Hoover dam. The same organization was responsible for the next significant step with between 24 % and 32 % fly ash in the concrete of the Hungry Horse dam in Montana. The use of fly ash in mass concrete became fairly routine in the USA up to the late 1960's. The oil crisis of the early 1970's provided the spur for wider use of fly ash in the USA, culminating in the use of 10 million tons of fly ash in 1988 from an available total of 45.4 million tons ie a utilisation of 22 %[21]. Malhotra[18] reports that current USA legislation requires the use of the highest possible proportion of recovered materials in work paid through federal funding.

In Canada the first use of fly ash was in the early 1950s in mass concrete applications. Subsequent use ran roughly parallel to the developments in the U.S.A. Current use is 1,1 million tons in 1988 from an available total of about 3,2 million tons, ie 34 % utilisation.[21]

Acceptance of the concept of using fly ash was slower in Europe than in America with the use in several European countries only starting in the late 1970's. As much of the fly ash used in Europe is in the form of factory blended cements this slow acceptance may have been due to the reluctance of vested interests to permit a competitive material onto the market. It is however notable that some European countries have extremely high levels of utilization of the fly ash they produce eg Austria 38 %, Belgium 68 %, Denmark 73 %, West Germany 76 %, Italy 57 %, and The Netherlands 97 %.[21] It is possible that these high levels of utilization are as a result of the importance these countries place on environmental protection and the high "cost" put on the dumping of waste materials.

Australia recorded their first use of fly ash in the 1950's with imported ash for mass concrete backfill. Only after a major research project's findings were published in 1966 was full scale commercial use of locally produced fly ash commenced.[22] Today Australian industry is reported to be using 0.56 million tons of an available 5.2 million tons ie about 10 %.[21]

2.3.3 History of Fly Ash in South Africa

In 1977 a company by the name of Saffic Resources concluded an agreement with Eskom awarding them the rights to all the PFA produced by Eskom.[23] (In those days the term Pulverised Fuel Ash PFA was the accepted terminology.) The owners of Saffic Resources were Messrs P Bates and P Newton-King. The operation started

with a small plant at the Grootvlei Power Station, and the plant was expanded in 1978–1979. Without technical backup however Saffic Resources met with little success.

In 1977 Randmix bought a 60 % interest in Saffic and not much later D & H bought Randmix thereby becoming majority shareholder of Saffic Resources. In 1978 D & H bought out Mr P Newton–King and the company name was changed to D & H Ash Resources. In 1980 D & H Ash Resources obtained a 100 % holding by buying the outstanding shares held by Mr Bates.

In 1980 D & H Ash Resources signed the first major contract for the sale of fly ash in South Africa with the Westonaria Gold Mine. Fly ash for this contract was supplied from Taaibos Highveld power station. The fly ash was used in grout packs for support of the hanging wall. In this case the fly ash was used in a 50/50 blend with ordinary portland cement. With the signing of this contract D & H injected skills and financial assistance into D & H Ash Resources. A facility with a capacity for handling 60 000 tons of fly ash per annum was erected at this power station. The plant was closed when Taaibos Highveld power station closed in 1986.

The handling facility at Grootvlei was enlarged in 1981. In 1981 a precast block manufacturer was a significant user of fly ash; this producer has been using a triple or ternary blend of fly ash, ordinary portland cement and ground granulated blastfurnace slag (ggbs) since 1981.

In 1982 a handling facility was installed at Matla Power Station with a capacity of 70 000 tons per year. This was increased in stages to the present capacity of 250 000 tons per year. The initial plant at Matla consisted of a selection plant, a 1 000 ton storage silo and a 750 ton loading silo at Oban station. In 1985 an air classification plant was installed.

In 1982 a Cape Town based ready mixed concrete producer started making use of fly ash in the concrete they produced. During the period up to 1983 the major users were mining companies and ready mixed concrete producers. In 1983 the contractor doing the Inanda–Wiggins tunnel in Durban elected to use fly ash in the concrete. The Nedbank centre, a prominent structure in Johannesburg, was built in 1984 using fly ash in the concrete. Also in 1984, customer demand from Vaal Reefs and other gold mines in the area prompted Pretoria Portland Cement (PPC) to start up a blending plant to produce a portland cement containing 30 % fly ash specifically for this group of customers. In 1985 Goldfields did a shaft lining using a 15 % fly ash concrete mix. This was the first time that fly ash had been used in an application where the 8 hour strength is a critical factor.

In 1985 Blue Circle introduced a portland cement with 15 % fly ash from their Industria depot using the trade name Readyblend.

The department of Water affairs spent a lot of time from 1983 to 1985 on research into the use of fly ash in dam construction. In 1984–5 the Bonnybrook dam was constructed near Amsterdam in the Eastern Transvaal. This was the first mass

concrete dam in South Africa to incorporate fly ash.

The Department of Water Affairs then undertook their first rollcrete dam construction projects at Zaaihoek near Standerton, and the DeMistkraal dam situated about 30 km south of Somerset East in the Cape Province. The former made use of a mix containing 70 % of ggbs, while the mix for the latter contained 50 % fly ash.

Structures constructed in the period 1986–7 and using fly ash included penstock towers at Bafokeng (30 % fly ash) and the first bridge for the National Transport Commission in which fly ash was used at Felixton near Richards Bay in Natal.

D & H and Blue Circle merged in 1986 and D & H Materials became a wholly owned subsidiary of Blue Circle Materials. Subsequently the company became integrated with Blue Circle Cement and lost contact with Blue Circle Materials. The company name was changed to Ash Resources (Pty) Ltd.

In 1989, after negotiations lasting about 1 year, Ash Resources became a jointly owned company with 4 equal shareholders, namely Anglo–Alpha, Blue Circle, PPC and Eskom.

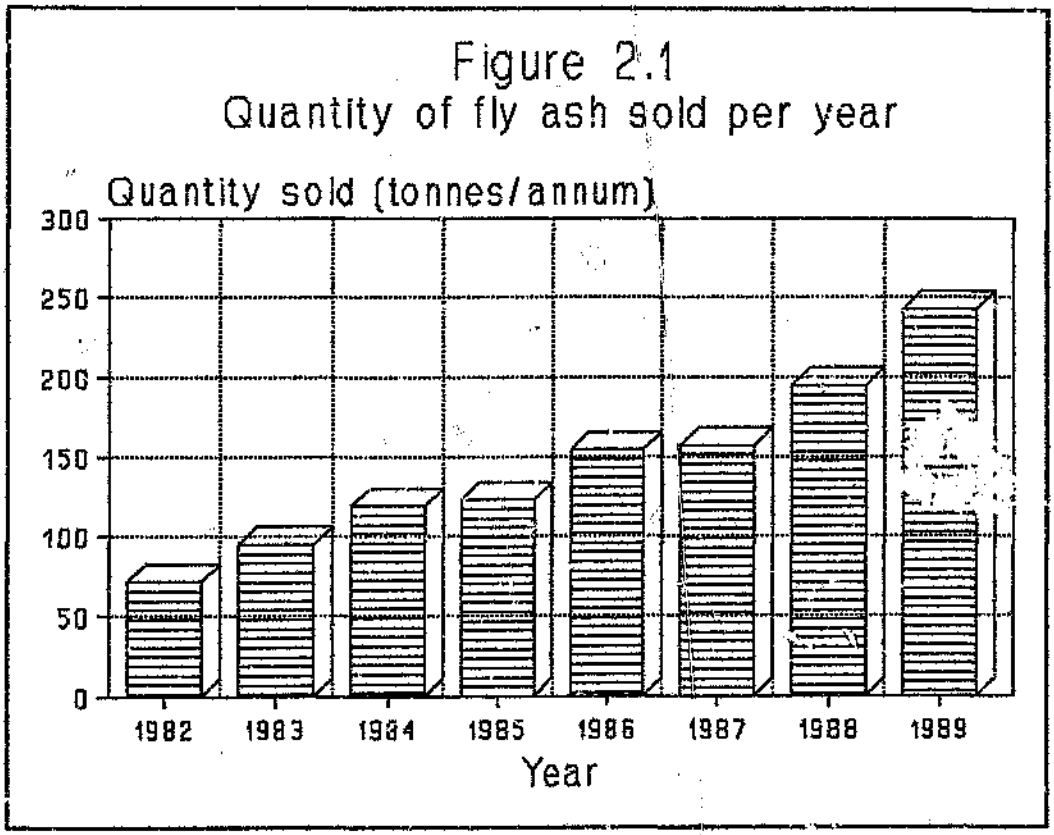
The Department of Water Affairs' first rollcrete arch dam, and in fact also a world first, was the Knellpoort dam near Bloemfontein. This dam was constructed in 1988. The world's second rollcrete arch dam is the Wolwedans dam near Mossel Bay which in 1990 was nearing completion. Both of these projects made use of fly ash; in the case of Wolwedans 70 % fly ash was used in the mix.

Petermix started producing a 30 % fly ash blend for the market in the Pietersburg area in 1988. A similar operation was started by Interafrica in Swaziland a year later.

The most recent fly ash production facility was due to be commissioned at the end of 1989 at Lethabo power station. It was designed to handle 400 000 tons per year but room was allowed for expansion. A 3 000 ton storage silo was provided. This plant uses an air separator for classifying the fly ash.

The introduction of fly ash into the field of structural concrete has apparently been slower than into the mining or ready mixed concrete fields. This has been attributed to a greater degree of conservatism amongst the designers involved.[23]

Table 2.3 gives the annual sales figures from Ash Resources (Pty) Ltd for the 8 years to 1989. These data are portrayed graphically in figure 2.1.



At the end of 1988 the consumption of fly ash in South Africa was about 0,5 % of the total fly ash produced[21]. About 30 % of this consumption is in cementitious applications while most of the balance is utilised in mine backfills.

This then is the picture as far as the history of the use of fly ash is concerned. The next chapter gives an impression of the extensive spectrum of published information on the technical aspects of the use of fly ash around the world.

Table 2.1

Ultimate analyses on coal samples

Parameter	Matla %	Lethabo %
Inherent moisture	4,95	5,90
Ash	23,20	36,45
Carbon	56,49	42,81
Hydrogen	3,46	2,68
Nitrogen	1,35	1,17
Total Sulphur	0,99	0,61
Carbonate(as CO_2)	1,66	1,43
Oxygen (difference)	7,94	8,96
Calorific Value (MJ/kg)	21,87	16,11

Table 2.2

Chemical analyses of typical ash samples from 2 sources (not representative of the samples used in this research)

Parameter	Matla %	Lethabo %
Silicon (as SiO_2)	50,85	52,55
Aluminium (as Al_2O_3)	26,40	29,75
Iron (as Fe_2O_3)	4,35	3,95
Titanium (as TiO_2)	1,35	1,55
Phosphorus (as P_2O_5)	0,95	0,45
Calcium (as CaO)	8,55	5,45
Magnesium (as MgO)	2,20	1,35
Sodium (as Na_2O)	0,50	0,20
Potassium (as K_2O)	0,95	0,50
Equiv Sodium (as Na_2O)	1,13	0,53
Sulphur (as SO_3)	1,95	2,10
Manganese (as MnO)	0,04	0,03

Table 2.3

Quantity of fly ash sold
(tonnes/annum)

YEAR	VOLUME (t/a)
1982	71482
1983	94741
1984	119052
1985	122760
1986	154248
1987	156948
1988	194176
1989	242708

CHAPTER 3

3 SURVEY OF RELEVANT LITERATURE

GLOSSARY OF TERMS
relating to methods of mix proportioning fly ash mixes

Replacement method. This is a direct mass replacement of fly ash for cement. This method will commonly result in a drop in strength at ages up to, and sometimes beyond 28 days. It is necessary to compensate for the lower relative density of the fly ash by modifying the sand content of the mix to correct the yield.

Addition method. This method involves incorporation of an additional mass of fly ash without reduction of the cement content. This method is used for lean mixes where the addition of fly ash improves workability and reduces bleeding and permeability. The sand content of such mixes will be reduced as the fly ash essentially replaces sand.

Partial replacement method. This method is commonly used when comparable performance to an ordinary portland cement concrete is desired and the typical target will be 28 day strength and equal slump. Again a correction should be made in the sand content to correct for the yield.

Independent proportioning method. Such methods start from the principle of meeting specific concrete properties and do not consider an ordinary portland cement control. They would endeavour to provide the most economical mix proportions with the available materials.

ASTM C 618-89[1] Type F fly ash. Fly ash produced by burning anthracite or bituminous coal, sometimes referred to as low-lime fly ash. South African fly ashes would generally fall in this category.

ASTM C 618-89 Type C fly ash. Fly ash produced by burning lignite or subbituminous coal, sometimes referred to as high-lime fly ash.

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[1] American Society for Testing and Materials. **Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete**, Philadelphia: ASTM., (1986). (C618-89).

3.1 Introduction

The research on which this thesis is based is presented in the following chapters using a sequence from fresh to hardened concrete or mortar characteristics. In order for the literature survey to form a coherent whole with the research work the same sequence is used for this chapter.

Section 3.2 covers the physical and chemical properties of ashes while sections 3.3 to 3.8 cover the effect that the use of fly ash has on concretes and mortars. Detailed discussions of the findings reported on are not given in this chapter as this will be done in later chapters in the discussion on the results generated for this study.

3.2 Physical and chemical properties

Characterization of fly ashes has received much attention as workers in the field soon became aware that not all fly ashes behaved in the same way when mixed with cement. An alphabetical list of these attributes is given in the following paragraphs.

3.2.1 Alkali Content

Some concern has been expressed about the relevance of the alkali content figures quoted for cements when the issue of alkali silica reaction is discussed. This is particularly important when alkali levels in fly ash are considered. The total alkali content, as determined by X-ray spectrometry, and the acid soluble alkali content determined by solution in acid, are less meaningful than the active alkali content that is produced by exposure to a calcium hydroxide solution for 28 days.[1] The ratio between active alkali to total alkali contents seems to be about 40 %.[2]

Barlow and Jackson[24] found that a significant proportion of the alkali present in fly ash is released when held in an aqueous solution with cement: in the ASTM C-311 test they found 33-39 % of the total fly ash alkalis were released, while in longer tests the alkalis contributed by the fly ash could increase to 50 % of the total alkali content of the fly ash. Nixon et al[25] showed that while the total alkali content of fly ash might be high the water soluble alkali content was low. Some of the alkalis are held in the glassy matrix and only become available once these glasses are dissolved by the calcium hydroxide released by the hydration of the cement. Generally they found fly ash to be a nett contributor of alkalis to the pore solution at 28 days. In contrast to this, Byfors[26] found that the pore solution pH decreased with fly ash addition.

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1 Obernolster, R. E. Alkali reactivity of siliceous rock aggregates: diagnosis of the reaction, testing of cement and aggregates and presentation of preventative measures, **Sixth International Conference, Alkalis in Concrete, Proceedings,** Copenhagen, Jun. 1983, pp. 419-433.

2 Davies, G. Personal Communication, Division of Building Technology, CSIR, Pretoria, Jul. 1991.

Kollek[27] suggested that about 17 % of the acid soluble alkalis in the fly ash become available for further reactions.

In summary therefore it seems that the quality of the ash may have some influence on the final pH of the pore solution and this may affect the durability of concretes which contain aggregates which are sensitive to alkalis.

3.2.2 Beneficiation

Beneficiation by means of an air classification process was shown to lead to selective removal of fine iron rich particles, the irregular shaped particles as well as large spheres and fragments of spherical particles, and to concentrate trace elements slighily in the finer fractions.[16]

Beneficiation by selection of fly ash from the second or subsequent fields will be shown in later sections of this chapter to reportedly have an influence on the water demand of fly ash mixes.

3.2.3 Calcium oxide content

Calcium oxide content of fly ash was shown by Valente et al[29,30] to be one of the main factors, along with particle size distribution, determining the mechanical behaviour of the fly ash in concrete. More information will be provided on this topic in the paragraphs on compressive strength.

3.2.4 Carbon content

Valente et al[29] gave the loss on ignition (LOI) at 750 degrees centigrade as a measure of burning efficiency as it determines what proportion of carbon is left unburned. Munn[31] noted that the LOI, the residue on the 45 micrometre sieve and the colour of the fly ash are used in the monitoring of fly ash quality.

Mehta[32] recommended that a single figure for LOI of 6 % be used for all extenders as the only mandatory chemical requirement.

Kruger et al[33] showed carbon content of fly ash to influence the water demand of the mix but as South African fly ashes have loss on ignition figures of between 1 and 5 % he suggested that the effect can be regarded as negligible for local ashes. Valente et al[29] gave high values for carbon contents of fly ashes derived from South African coal but ascribed this to poor burning efficiencies of the Italian power stations.

Dunstan[34] however showed that high carbon ashes can be used successfully in high fly ash concretes, and Valente et al reported on a fine fly ash with 13 % LOI that had been used successfully.[30]

Costa and Massazza[35] reported that the carbon content is a factor in determining the rheological behaviour of fly ash mixes. This may be due to Diamond's contention that the Swiss–cheese–like non–spherical particles are found to be composed of

incompletely oxidized coal and melted organic material.[36] The carbon content of fly ashes is also reported to influence the measurement of surface area.[37]

Alstead Nielsen[38] pointed out that the carbon in fly ash is undesirable due to its effect on colour and the tendency it has to absorb chemical admixtures. The South African CSIR showed that the carbon content of a fly ash is dependent on the rate of combustion, the air/fuel ratio and the fineness of the coal.[39]

Osback[40] found that the carbon content of fly ash influenced both water demand and strength development of fly ash mixes.

There is thus some consensus regarding the fact that carbon is an undesirable component of fly ash, but the presence of small quantities of carbon do not necessarily make the fly ash unsuitable.

3.2.5 Cenospheres

Dhir et al[41] described cenospheres as hollow fly ash particles that float on water. They concluded after using heavy liquid separation techniques that a major part (97,6–99,9 %) of the fly ashes tested were cenospheres. Local researchers concur with the belief that the majority of particles appear hollow.[42]

The ACI pointed out that the presence of cenospheres influences the apparent specific gravity of the fly ash.[43] Dhir et al[44] showed the cenospheres to be hydrophillic and noted that a high proportion of unreacted cenospheres could be detected in mature fly ash concrete.

There seems little doubt that a fairly substantial proportion of cenospheres occurs in most fly ashes but the significance of this to the suitability of fly ash use in cementitious mixes is not clear.

3.2.6 Chemical composition

Diamond[36] contended that the overall chemical analysis of fly ash is meaningless other than to give an indication of the statistical average composition. Nevertheless many authors have undertaken extensive analyses in attempts to classify the fly ashes being worked with. A few papers are cited here to give an idea of the spectrum, but commonly a chemical analysis would form part of a research paper.

Some researchers[39] found that sub-bituminous coals produce fly ashes with more CaO and less Fe_2O_3 than those derived from bituminous coals: they pointed out that the bulk of the particles are glassy but that some crystalline quartz and mullite may be present. They also noted that the quartz content decreased with increasing precipitator field number.[42] Manz[45] listed the crystalline minerals as quartz, mullite, magnetite or ferrite spinel together with calcium sulphate and alkali sulphates and agreed that there is little correlation between oxide composition and reactivity. Munn,[31] on the other hand, found that the chemical composition depends to a degree on the operating load of the power station. The major change, as could be expected, was the loss on

ignition, or carbon content, with other oxides changing only in proportion to the dilution effect of the carbon. The ACI committee ascribed the presence of glassy particles to the rapid cooling that the particles undergo.[43]

Dhir et al pointed out that the chemical composition of the fly ash does not define the pozzolanicity of the ash, and noted that the mullite and amorphous components are derived from the melting of the incombustible illite and kaolinite in the coal.[44]

Mehta[32] noted that the aspect of calcium and magnesium unsoundness is easily determined using the le Chatelier test and that it was not necessary to carry out an autoclave test.

Willis et al[45] found a marked effect of the particle size of fly ash on the concentration of volatile trace elements – this changes through the bank of precipitators. Comparisons have been given between different South African sources and also against values from the USA.

Commonly it seems that the chemical composition from a particular source plays a relatively insignificant role in determining the suitability of the fly ash. There may however be an impact on some of the characteristics of the fresh mixes but this will be discussed in later paragraphs.

3.2.7 Environment: Disposal and energy saving

Valente[29] indicated in his paper that when the fly ash content exceeds 10 % of the mass of the coal burned the disposal or utilization becomes an environmental problem. In Italy the power stations burning South African coal use a relatively high grade coal when the ash content is compared against the levels at Matla (17,5–33,0 %)[9] and Lethabo (28–42 %).[13] The disposal problem is therefore a proportionately larger one in South Africa.

Dunstan[34] pointed out that the use of fly ash in concrete reduces the energy consumption of the concrete as fly ash requires less energy to produce than ordinary portland cement. Souerbren[47] mentioned that the dumping of fly ash presents an environmental hazard due to the leaching of soluble toxins, and this was therefore an option that was no longer considered in Holland due to the lack of space. However, also in the Netherlands, ENCI[48] indicated that the health hazard on exposure to fly ash dust was no greater than that on exposure to ordinary portland cement. Van der Schaaf et al[49] showed further that exposure to fly ash dust posed no dangers from silicosis, toxicity, radioactivity or carcinogenicity.

There are thus two environmental benefits to be had by utilizing fly ash in concrete; an energy saving and a reduction in the quantity of a potential pollutant that needs to be dumped.

3.2.8 Flow

Alstead Nielsen[38] pointed out that the flow characteristics of dry fly ash powder are superior to those of ordinary portland cement, and less difficulty can therefore be expected in transporting the material.

3.2.9 Glass content

Valente et al[29,30] indicated that the glass content of fly ash is not an important parameter for it's mechanical properties when used in concrete or mortar. Fraay et al[50] postulated that the glass had to go into solution before any pozzolanic effects were noted and this required about 14 days and a pH of greater than 13,2. They noted that the temperature is of great importance in this process. The glass eventually all reacts leaving the mullite lattices behind.

Berry et al[28] indicated that beneficiation appeared to increase glassy particle content as fineness increases with an accompanying drop in quartz and mullite content.

While the glass component of fly ash is important it seems that within the range of glass contents commonly found in fly ash there is little effect on its suitability for use in concrete or mortar.

3.2.10 Gypsum and sulphate content

Some fly ashes have a high SO_3 content – this allows a reduction in the gypsum content of a cement during manufacture of a blended cement but can cause a complication in that the optimum gypsum content is no longer as clearly defined according to Haque et al.[51] Giergiczny and Werynska[52] came to similar conclusions but found that the gypsum could be omitted altogether in some cases.

Ravina[53] indicated that the fly ash particles become coated with sulphates as they cool in the boilers; these lead to early expansion in a mix with extra formation of ettringite. Idorn[54] said that the sulphates in the liquid phase are activators and create complex secondary hydrates. Mehta[32] showed that fly ash with high sodium oxide and sulphate content tends to accelerate the setting and hardening of fly ash concrete. Manz[55] showed that three fly ashes with sulphate contents in excess of ASTM limits had been used successfully in high replacement fly ash concrete.

Associated with sulphates is calcium trisulphoaluminate hydrate (ettringite). Jun-yuan et al[56] showed that the use of fly ash allows the conversion of ettringite to the monosulphate before 7 days while in the control mix this only happened at about 28 days, but noted that this might only occur with fly ashes having low sulphate contents. This conversion is accompanied by an increase in microstructure density.

Berry et al[28] noted that the fly ash particles provide nucleation sites for C–S–H gel and ettringite with a slowing in the rate of formation of calcium hydroxide and acceleration in the rate of formation of ettringite. Saito et al[57] found that ettringite normally occurs at the aggregate/paste interface, but the use of fly ash restricts this.

This would appear to be an example where the chemical composition of the fly ash can be significant in determining the suitability of the fly ash for use in blended cements where these are required to meet setting time and sulphate content requirements. The control that the use of fly ash places on the formation of ettringite at the aggregate interface may improve the aggregate/paste bond.

3.2.11 Particle size distribution and surface area

Valente et al[30] showed that the particle size distribution and the calcium oxide content of fly ashes are the main characteristics influencing the mechanical behaviour of concrete or mortar mixes incorporating fly ash. Schiessl and Hardtl[58] found that an improvement of the particle size distribution of a fly ash by classification or grinding had a positive influence on the workability, early strength and pozzolanic reaction of a mortar. They also noted that fly ash efficiency could be improved if the particle size distribution could be made to compliment the grading of the cement and aggregates. Some authors[42,59] had similar findings on the degree of reactivity after grinding, although others disagreed.[62] Dhir et al[41] showed that only the coarsest of particles are broken down during grinding. Osborne and Nixon noted that intergrinding of a cement with a fine ash leads to little improvement in performance.[59]

Pat et al[67] recorded the particle size distribution of fly ash using a sedigraph and found a range from 1,5 to 90 micrometre with about 10 % exceeding 45 micrometre. Manz[45] gave a size range from 0,1 micrometre to 1,0 mm and found the nitrogen absorption surface area to lie in the range of 300–500 m^2/kg.

The carbon content of fly ash is reported to influence the assessment of specific surface of the ash.[42] Butler warned that due to the fly ash particle density being highly variable (from 0,7 to 3,0) the specific surface of fly ash should be expressed by volume.[61] This phenomenon could affect the measurement of particle size distribution too.

Idorn and Thaulow[62] noted that the fineness of fly ash should at least match that of the cement as most coarse fly ash particles do not react but merely act as micro–aggregate particles. Many authors confirm the significance of the fineness of the ash as measured by the retention on the 45 micrometre sieve as being a good guide to the performance of the ash, with low retention values being advantageous.[30,31,32,42,44,61,63] However, the fineness cannot predict the reduction of water demand that may occur,[64] nor does it have much influence on the degree of retardation of setting time.[65]

Gopalan and Haque[66] noted how a fly ash becomes finer as it proceeds through the different stages of the electrostatic precipitator.

The particle size distribution together with the fly ash fineness appear to be important characteristics of quality, but the grading of the ash should be compatible with the overall grading of the other components of the mix so as to provide a smooth grading for the total mix.

3.2.12 Specifications for fly ash

Fly ash is a material whose composition and cementitious properties depend to some extent on the physical and chemical characteristics:not all fly ashes work well in cementitious mixes. In an attempt to provide guidelines as to which fly ashes are suitable, many countries have compiled specifications for the physical and chemical requirements of the fly ashes.

The South African CSIR summarized the specification requirements for various countries,[67] and commented on the various desirable (eg. 45 micrometre residue and water requirement test results) and undesirable clauses (eg. pozzolanicity indices and free magnesium and calcium oxide contents).[68]

Mehta noted that there is general dissatisfaction with the various specifications on fly ash and slag as there are too many requirements which have been found to be unnecessary,[69] and indicated that the specifications should be performance–based rather than prescriptive.[32] Manz[63] had similar views and added that the division of class F, and class C should be in terms of the degree of self–hydraulicity rather than on the calcium oxide content.

Potter noted that the Australian specifications have changed with time and there are moves towards monitoring the variability of cement and subsequently that of fly ash.[70]

The tests for pozzolanicity of fly ashes have been criticized as taking too long when done with cement and being irrelevant when done with lime.[71]

The general view has been well summed up by Brizzi[72] when he stated that it seems inappropriate to rely on many prescriptive requirements for fly ash when they have little bearing on the performance in concrete.

3.2.13 Variability of composition

Dunstan,[34]looking at the macro–variability of fly ash pointed out that the variability in quality causes more problems than using fly ashes which do not comply with the British Standards specification. D & H Ash Resources showed that the inclusion of the selected fly ash available in South Africa at the time did not increase the variability of the strength results from the tests done.[73]

Diamond[36] looked at the issue of variability on a microscopic level. He said that the fly ash constitutes the particulate residue of the responses of individual particles of ground coal to brief exposure to high temperature oxidising conditions. Each particle is therefore likely to differ slightly from the next, but on a macroscopic scale this will probably have little impact on the performance of the fly ash.

Macroscopic variability of fly ash is thus likely to lead to noticeable changes in the behaviour of mixes incorporating fly ash. In South Africa the vast quantity of fly ash available for use allows the producer of cementitious grade fly ash to be very selective. The likelihood of macroscopic variation should, given a commitment to uniform quality by the producers, therefore be less of a problem in South Africa.

3.3 Rheology, setting time and bleeding

The impact that incorporation of fly ash has on the level of flow or workability of a mix is of considerable importance in determining the economic feasibility of the use of fly ash. For this reason the problem is approached in a number of ways in the following paragraphs.

3.3.1 Rheology

Rheology is defined as "the science of the deformation and flow of matter" and is thus concerned with the relationships between stress, strain, rate of strain and time.[74]

For the concrete technologist or the site foreman this characteristic is the one which determines how easily the mix can be placed and compacted on site; the water content of the mix is a critical aspect of this property. The most commonly used test on site is the slump test, and this allows the mixer operator some control of the water content. This aspect of the measurement of the flow characteristics of the mix is discussed first.

3.3.1.1 Assessment of workability with the slump test

Many authors[34,41,75] have noted that the slump test gives a poor reflection of the improvement in the mobility and ease of compaction of mixes using fly ash. While some researchers attributed part of the improvement to the spherical shape of the fly ash particles,[42] Dhir et al[41] suggested that the effect is brought about by influence of the fly ash on the agglomeration of the mix. Kruger et al[33] indicated that the increase in mix cohesion helps improve the workability.

The improvement of the workability is more commonly measured by the amount of water that can be removed from the mix and still give the same slump as the control mix (which has no addition of fly ash). This is also referred to as a reduction in the water demand of the mix ie the quantity of water (litres) required per cubic metre of the mix. Hobbs for example indicated that the water demand increases when fly ash is used as an addition to a mix, although he suggested that interground cements might have lower water demands.[76] Other authors believed that milling of fly ash to increase fineness makes little difference to the water demand of mortar mixes.[42] Van Zyl[77] found no reduction in water demand for an increase in fineness of an interground fly ash cement.

The area of fly ash use that has received the most attention is that of partial replacement. Hobbs[76] stated that the reason for the water reducing effect is that an active component (cement) is being replaced by one that is inert at early ages (fly ash). Hobbs further reported that the general order of water reduction lies between 7 % and 12 % (or 2-4 % for each 10 % of fly ash used) although this effect apparently disappears above a total cementitious content of 450 kg/m^3.

Dhir et al[41] said that the water demand reduction is proportional to the product of fineness (45 micrometre retention) and loss on ignition of the fly ash.

Other authors ascribed the water demand reduction to the smooth spherical shape of the fly ash particles.[42] They found that water demand of mixes decreases along with the number of precipitator fields that the ash has passed through before selection and use. Carbon content was shown in this study to affect the water demand – high carbon content as revealed by the loss on ignition being associated with high water demand.

Ravina and Mehta[78] found that the reduction in water demand permitted an increase in cement water ratio without increasing cement content. In another paper[79] these authors found a water demand reduction of 10–15 litres/m^3 for 50 % fly ash content and 15–20 litres in the case of 75 % fly ash mixes.

Van Zyl found fly ash from a particular source to increase the water demand[80] although the other source investigated showed a reduction.[76] Dunstan[34] also determined that the quality of the fly ash had an effect on the magnitude of the reduction in water demand and found that a high quality ash permitted mix proportions with a lower cementitious material content than was the case with a poor quality ash. The ACI committee 225 concurred by noting that the use of fly ash normally allows a reduction in water content.[43]

Olek and Diamond used a different approach and determined how much extra aggregate could be added to a mix without reducing the slump when various proportions of fly ash were used.[81] A substantial addition of aggregate was found possible for 15 % fly ash but the quantity of the additional aggregate was found to reduce if the fly ash content was increased to 25 %.

In contrast to this study Thomas et al[82] found the magnitude of the water demand reduction to increase consistently with fly ash content, varying from 8 litres at 15 % fly ash, 15 litres at 30 %, to 26 litres at 50 %.

Berry et al[26] found that the proportion of fly ash particles larger than 45 micrometre adversely influences the water demand and these particles contribute little to the compressive strength. Dahl[83] found that the intergrinding of a poor fly ash allowed little reduction in the water demand. Butler[61] showed that most fly ashes will permit a water reduction but pointed out that the cement used plays an important role; he found that a high water demand cement will give greater water demand reductions than a cement with a lower water demand.

Samarin, working with mortars with constant ASTM C–109 flow values found that the water demand decreased or increased depending on the proportion of fly ash used.[84] The flow reached a minimum value at between 2 and 3 % (by mass of mortar) fly ash content, but increased steadily with increased fly ash content beyond this point.

Helmuth[85] suggested that the water reduction is due to the adsorption of the finest fly ash particles onto the cement grains which prevents their flocculation in a manner similar to a water reducing agent. The improved mobility of the mix he ascribed to the ability of the increased paste volume to separate the aggregate particles but pointed out that as there is a possibility of aggregate interference with coarse ashes the

greatest water reductions are found with the fly ashes having the highest specific surfaces. Roy[86] reported that the floc structure of fresh cement paste is interrupted by fly ash thus creating smaller units and leading to greater workability.

Brizzi et al[72] found the only attribute of fly ash to correlate well with reduction in water demand was the carbon content. The correlation was only good for fly ash with carbon contents greater than 12 %. Cornelissen et al[87] found that substitution of fly ash for cement generally improved workability. Schiessl and Hardtl[58] reported that if the incorporation of fly ash improved the particle size distribution of the cementitious fraction then the water demand reduced. Air classification was reported to improve the rheology of the mix. Theissing[71] stated that an improvement in the shape of the grading of all the solid materials in the concrete brought about by using fly ash may also contribute to reducing the water demand of the concrete.

Two ENCI papers reported that fly ash replacement of cement improves workability,[88] and that the water demand is reduced by 5–11 litres for a 25 % fly ash content.[48] Rivera reported that using 30 % fly ash and a superplasticiser permitted a cement saving of 40–50 %.[89]

Tikalski et al[90] reported that fly ash mixes exhibited a greater degree of slump loss which they ascribed to the lower water content permitted by the use of the ash. Rivera had similar findings and commented that this occurred irrespective of the temperature of the mix.[91] Ionescu and Ispas[92] provided contrary evidence where the fly ash mix lost slump at the same rate as the control mix, but as it started at a higher slump, the fly ash mix took longer to get to the lowest acceptable slump.

The consensus of opinion would therefore seem to be that fly ash will improve the workability of a mix in which it is incorporated on a partial replacement basis but that the quality of the fly ash and the cement used will determine the magnitude of the change. The changes measured in the slump test may not be a true reflection of all the modifications that have occurred in the placeability or compactibility of the mix.

3.3.1.2 Viscosity measurement

The technologist in a laboratory has more sophisticated means of measuring the rheology of the mix or of some of its constituents than the relatively crude slump test, and this topic has had substantial coverage in the literature. In laboratory assessment of rheology the most commonly used apparatus seems to be the coaxial cylinders viscometer.

Atzeni et al[93] pointed out that the fundamental role played by the experimental conditions has sometimes led to gross discrepancies in the results obtained. As the results of paste viscosity tests are rather sensitive to the method adopted, and because no standard method seems to exist,[94] some references are provided to illustrate the spectrum of results obtained in ordinary portland cement mixes as well as those incorporating fly ash. The majority of the work reported on here has been done on pastes, although there is some mention of flow or other tests on mortars.

Atzeni et al[93] evaluated a number of mathematical models to see which most closely represented the viscous flow behaviour of cementitious pastes. While the Bingham model is commonly accepted as being representative of the behaviour of pastes they showed other models to more closely simulate the actual flow measured. The mixing cycle used in Atzeni's[93] work was 3 minutes of hand mixing with a spatula using a range of water cement ratios (w/c) from 0,3 to 0,45.

In another paper, Atzeni et al[94] indicated that the rheology of pastes represented by the yield shear strength correlates reasonably well with the slump and flow tests on mortars. The mortars tested were mixed using an apparent standard test for mortar testing, ie the Hobart mixer with the ASTM standard method C–305, while the pastes were mixed by hand using a spatula for a total of 3 minutes as before. The range of w/c ratios tested by Atzeni et al[94] ran from 0,3 to 0,6.

In contrast to this method of paste mixing Costa and Massazza[95] used a high speed rotary blade mixer for 90 seconds in the preparation of their 0,45 w/c pastes. They showed the same shape of hysteresis cycle on a plot of angular velocity against torque as Atzeni et al, but noted that the fly ashes used in some of the tests had a limited effect relative to the results shown by the cement mixes.

Banfill and Rudzinski[95] used a mixing cycle of 500 revs/min in a laboratory mixer for a range of w/c ratios from 0,3 to 0,4. They too, found similar shaped hysteresis loops, in this case on non–shrink cement pastes.

Diamond and Tattersall[96] used a range of w/c ratios from 0,28 to 0,34 but gave no details of the mixing cycle used. They showed that while different types of behaviour could be obtained using a smooth coaxial cylinders viscometer the variability was not found when serrated cylinders were used. In all the above cases the hysteresis loop had shown a reduction of torque on the down curve, ie strain softening or thixotropic behaviour.

Wolter[97] showed that with time the hysteresis loops change from thixotropic to antithixotropic (strain stiffening) behaviour. Most of his work was done at a w/c ratio of 0,5. He noted that the viscous behaviour of cement from any source changed from one shipment to the next.

Ralgelj[98] working with mortars with a w/c range from 0,3 to 0,6 found thixotropic behaviour in a vane shear apparatus. Mixing was done to ASTM C–305.

Rudzinski[99] made mixes of varying proportions of cement and fly ash using 2 minutes of spatula mixing followed by 3 minutes of 50 rev/min machine mixing. He worked with w/c ratios of 0,6 and 0,65. He found the behaviour of the hysteresis loop to change from thixotropic to antithixotropic as the fly ash content increased. The shear stress values were also seen to increase with the increase in fly ash content.

Odler et al[100] found they needed to use cement finer than Blaine specific surface 450 m^2/kg in order to prevent too much sedimentation occurring. He worked with a range of paste w/c ratios from 0,375 to 0,55 and made use of the ASTM C–305 mixer at 285

rpm for 3 minutes; they found antithixotropic pseudoplastic behaviour. They associated the antithixotropic behaviour with mechanical agitation of the paste during hydration, but noted that the viscosity also depended on the fineness of the solids in the paste.

Nessim and Wajda[101] used a cycle of 6 minutes of hand mixing with a spatula in pastes of w/c around 0,3. They monitored temperature during the testing and concluded that a 1,6 degree change resulted in little change in the results. They found thixotropic behaviour in the hysteresis loop.

Massidda and Sanna[102] used 2 minutes of hand mixing for pastes of w/c from 0,35 to 0,45 and incorporated from 20 % to 40 % of fly ash in the mixes. A very fine cement (Blaine of 490 m^2/kg) was used. They found pseudoplastic thixotropic behaviour with the fly ash resulting in reductions in the peak viscosity levels reached.

Lapasin et al[103] used a cycle of some hand and some mechanical mixing with three w/c ratios of 0,35, 0,40 and 0,45. The cement was moderately fine (Blaine = 360 m^2/kg).They found a partially thixotropic behaviour, and noted that if smooth cylinders are used on the viscometer then the viscosity measured is that of the liquid and not the homogenous suspension.

Ish–Shalom and Greenberg[104] found the predominant kind of behaviour to be thixotropic but did measure antithixotropic behaviour when the mixes had been vigorously agitated and allowed to hydrate a little. They used three minutes of vigorous mixing (under vacuum to avoid air entrainment) on pastes with a range of w/c ratios from 0,4 to 0,8. They found that reproducible results could be obtained if the test conditions were kept constant, and stated that the temperature did not play much of a role in the early viscosity results. The results indicated that the viscosity is proportional to the surface area of the solids, and also to the C_3A content where this was above 4 %, and that the antithixotropic behaviour was dependent on the C_3A content.

Helmuth[85] ascribed the increased resistance to flow of mixes with finer cements to the tendency of the smaller particles to flocculate. Destroying these flocs will increase flow. He stated that fly ash is thought to deflocculate the cement by adsorption onto the cement grains resulting in improved flow.

With the wide range of different mixing techniques used it is not altogether surprising that widely differing results have been reported. A good example is the totally different behaviour reported by Rudzinski[99] and Massidda[102] when fly ash is incorporated in the mix. Unfortunately insufficient information has been given on the various fly ashes used to be able to offer any explanation as to why one set of results indicates an increase in shear stress with incorporation of fly ash,[99] while the other indicates a decrease.[102] An important factor to be noted is that the test conditions need to be kept as constant as possible to ensure reasonably repeatable results.

3.3.2 Setting time

The influence that fly ash has on the setting times of cementitious mixes has received a substantial amount of attention because of the potential impact that an increase in these times could have on the construction techniques used on site.

Ravina and Mehta[85] recorded increases in both initial and final setting times: the increases ranged from 20 minutes to 260 minutes in initial set, and 60 minutes to 327 minutes in the final set. They noted that the delays in setting times with partial replacement of cement with fly ash were smaller than was the case if the mix was made with only the ordinary portland cement in the cement + fly ash mix proportions. They also found that class C fly ashes gave greater delays than was the case with class F fly ashes. They suggested that the delays could be as a result of sulphate ions from the fly ash retarding the hydration of the tricalcium aluminate. In another paper[79] they noted that the increase in setting time was proportional to the quantity of fly ash used. They felt that fly ashes with high alkali contents could accelerate the setting times.

Haque et al[51] also found retardation of setting and further noted that the peak temperature in the heat evolution curve was depressed by the incorporation of fly ash. They supported the idea of sulphates in the fly ash causing delayed setting and reported that the optimum gypsum content for a cement was altered by the incorporation of fly ash.

Giaccio and Malhotra[105] noted that the setting time of fly ash mixes depended to some extent on the type of cement used. There was little difference in setting time between beneficiated fly ash mixes and as-received fly ash mixes with ASTM Type I cement but the setting time showed greater retardation with a ASTM Type III cement and as-received fly ash. They noted that opc/fa/sf mixes were retarded far less than the opc/fa mixes. In contrast to this Baoyu et al[106] found dramatic increases of about 1000 minutes in both initial and final setting times with similar mixes, but, as they were aiming at producing a low heat concrete, this is probably not surprising.

Dodson[107] reported that when a fly ash concrete is designed to give a compressive strength at a particular age equal to a control ordinary portland cement mix, the setting time of the fly ash mix will show some retardation. He introduced the Omega Index Factor (OIF) which he maintained indicated whether the retardation caused by the use of fly ash is due to a chemical or physical reaction. The OIF is computed as the cement content of the mix (kg/m^3) divided by the water cement ratio of the mix. In the calculation of the OIF the presence of the fly ash is ignored in both the cement content and the water/cement ratio. Dodsc found a linear relationship between OIF and setting time. He remarked that fly ashes that gave acceleration in setting time are high calcium ashes while those that retard commonly have high sulphate contents. Munn[91] however reported that class F fly ash gave reduced setting times while Class C fly ash gave severe retardation.

The ACI[45] noted that the incorporation of fly ash in a mix generally causes increased initial and final setting times.

Sivasundaram et al[108] found that the initial set was retarded slightly in a high volume fly ash mix (≈ 60 % fly ash) but final set was retarded by more than 3 hours. They noted that the retardation was not expected to cause problems on site as site concrete was seen to have set within 12 hours of casting. Sri Ravindrarajah and Tam[109] showed setting time to be increased by about 2 hours at 40 % fly ash replacement level.

Gebler and Klieger[110] found slight to significant delays in both initial and final setting times for most of the fly ash mixes they made: these included both class F and class C fly ashes. Rivera[91] found that temperature affects the degree of retardation measured with high temperatures reducing the relative retardation, and low temperatures increasing it. His work was done on class F fly ash.

Carette and Malhotra[111] tested a range of eleven fly ashes and found that most (9) caused retardation to both initial (30–180 min) and final (60–240 min) setting times. The two ashes tested that did not retard caused no change in the setting times. They ascribed the retardation in setting times to the dilution effect, but conceded that some chemical effects might be influencing setting times too.

Lin and Hwang[112] reported retardation in both initial and final setting times for mixes containing 20 % of fly ash and found the degree of retardation to be proportional to the content of the class F fly ash they used in their tests. Rodway and Ferdirko[113] found severe retardation of initial set in the superplasticised class C fly ash mixes they made in a site evaluation. The retardation for a 76 % fly ash mix was 35,5 hours.

Kasai et al[114] found there to be a great deal of difference between the setting time retardations caused by fly ashes from different sources. They reported a good correlation of retardation against boron content as well as against the concentration of the so called fly ash fluxing agents, sodium and potassium. They also noted that the degree of retardation caused by any one fly ash was proportional to the fly ash content. Naik and Ramme[115] concurred with this last observation.

Samarin et al,[116] in reporting on the use of fly ash in Australia noted that the effect of fly ash on the setting times is insignificant in comparison with what happens when the water/cement ratio is changed. This they found to be the case for a wide range of mix temperatures. In contrast Korac and Ukraincik[117] found that when they used 50 % fly ash in the concrete for a dam construction project it was not necessary to use a retarding admixture as the setting times were sufficiently retarded by the fly ash.

Costa and Massazza[65] found that the addition of fly ash prolonged both initial and final setting times but that the degree of retardation was diminished by an increase in cement fineness. Changing the fineness of the fly ash by grinding had no influence on the change in setting times. Roy[96] noted setting time retardation with fly ash with class C retarding more than class F. She reported that in both cases there would still be appreciable quantities of unreacted ash at later ages.

Collepardi[118] commented that in winter, when the greatest quantities of fly ash are available in Italy, the retarding effects of the use of fly ash are most noticeable. He

commented however that when fly ash is added to a mix without any reduction in cement content the setting time is reduced.

It would appear to be fair to state that the incorporation of fly ash in a cementitious mix is likely to extend the initial and final setting times. The degree to which these times increase seems to depend not only on the quantity of fly ash used but also on the source and quality of the fly ash and ordinary portland cement used, and on the mix proportions used. The method adopted for fly ash incorporation (eg addition, replacement or partial replacement) also plays a role. The data presented by these authors seem to contradict earlier statements that the chemical composition of fly ash is not an important factor in determining its suitability, unless setting time is regarded as being of no consequence on a particular project.

3.3.3 Bleeding

The formation of a layer of clear water on the top surface of newly compacted concrete or mortar is known as bleeding.[119] It is caused by the settling of the solid particles in the mix through the water and the rate of settlement determines the rate of bleeding. The rate of settlement will, according to Stokes law, depend on the specific surface of the solid materials in the mix, so an increase in the quantity of fine material (such as cement or fly ash) in the mix will slow the rate of bleeding due to the effect that the fine particles have on the rate of settlement.

The total volume of water that comes to the surface is known as the bleed volume. The process will continue until the mix has set sufficiently to prevent any further settlement. Therefore any changes to the mix that result in changes in the setting time will probably impact on the bleed volume.

Giaccio and Giovambattista[120] pointed out that for the concrete tested, a bleed capacity (ie total bleed volume as a proportion of the water content of the mix) of 8 % should be considered as dangerous as it could lead to a compressive strength reduction of about 30 % due to the formation of voids such as bleed channels and fissures. They noted that bleeding capacities of 3–3,5 % make little impact on the concrete properties.

Dhir et al[41] reported a reduction of bleeding brought about by fly ash in concrete. In contrast, Ravina and Mehta[79] noted that fly ash concrete had an increased bleed rate and volume relative to the control ordinary portland cement concrete, with a fine ash bleeding less than a coarse ash. They also showed that different fly ashes influenced bleeding to different degrees.

Van Zyl[75] found a reduction in bleeding when fly ash was used in a mix containing South African Cape flats sand as fine aggregate. Kruger et al[33] also found a reduction in bleeding with improved pumpability and placeability as additional benefits. Idorn and Thaulow[62] reported that by replacing 20 % of the cement by fly ash bleeding of a concrete was successfully controlled.

Mehta[69] found that in high volume fly ash mixes the bleeding is almost non–existent as the initial water content is relatively low.

Munn[31] noted that the mix proportioning procedure used influences the bleeding; using the Australian procedure the bleeding rate and volume is reduced, but if a mix is poorly proportioned then the use of fly ash can lead to increased bleeding.

Gebler and Klieger[110] reported reduced bleeding capacity with the use of fly ash. Dhir et al[44] mentioned reduced bleeding of fly ash mixes and stated that the phenomenon was dependant on the specific surface of the fly ash used. This property is commonly measured by the retention on the 45 micrometre sieve.

Carette et al[111] reported similar or slightly increased bleeding for fly ash mixes but explained that there had been no control of slump in these tests. Lin and Hwang[112] noted an increase in bleeding which was proportional to the fly ash content.

Pat et al[60] reported that a mix using rapid hardening cement with 25 % fly ash gave lower bleeding than an ordinary portland cement control mix. Samarin and Munn[116] noted that typical partial replacement fly ash mixes gave less bleeding than the control mixes.

There appear to be two distinct schools of thought on the effect that fly ash has on bleeding; the one side believes that there is an increase, and the other a decrease. It is probable that both parties are correct under the conditions of test in each case. It is also likely that the particle size distribution of the fly ash, cement and aggregates and the way they combine to form an overall grading curve play an important role. There is no way of confirming this contention regarding the above papers as seldom, if ever, have the authors provided the full particle size distributions of all the materials used.

3.4 Heat of hydration

The heat of hydration refers to the rise in temperature generated by the exothermic chemical reaction between water and cementitious materials. The phenomenon can cause problems when the heat cannot readily be dissipated, in, for example, mass concrete pours, as the heat can cause expansion in the plastic concrete. The expansion is easily accommodated at this stage, but once the concrete has hardened and starts to cool then cracking may occur in the now stiff concrete. Reduction of the rate and magnitude of the heat generation is thus desirable in mass concrete applications, but the same reduction may result in such mixes being sensitive to low ambient temperatures when used in thin sections. The degree to which fly ash influences the heat generation is discussed in the following paragraphs.

Owens[121] mentioned the impact that the heat of hydration can have; he pointed out that for every 10 °C rise in temperature the rate of the hydration reaction can be expected to double, this in itself causing further heat generation. He noted that when this occurs in an ordinary portland cement concrete the long term strength is depressed, while in a fly ash mix the strength is increased.

The CSIR[122] found a significantly lower heat of hydration when fly ash was incorporated in a mix. They made use of the BS 1370 Heat of Solution method and determined that fly ashes with high free calcium oxide contents developed higher temperatures than those with low calcium oxide contents. Kruger et al[33] in another paper concluded that the heat is reduced by about half the percentage of fly ash used. Idorn and Henriksen[54] found that when 30 % fly ash was used in a site concrete the heat of hydration was reduced to between 60 and 80 % of the ordinary portland cement control.

Fajun et al[123] showed that the heat evolution for a 40 % fly ash mix was lower than that for the control ordinary portland cement mix even when the reduction in cement content was taken into account. Leaching out water soluble chemicals from the fly ash samples prior to mixing reduced the temperatures further. Retardation of the initial reactions was a further contributory factor to the reduction in heat. The authors suggested that the retardation is due to the fly ash particles acting as calcium sinks depressing the concentration of calcium in solution during the first 6 hours or so, resulting in a longer induction period during which the reaction rate is slow. Jun-yuan et al[58] showed the retardation of the hydration to be as much as 10 hours, and also noted that the crystalline calcium hydroxide content of fly ash mixes was decreased relative to the control.

Tokyay[124] found the heat of hydration to be reduced when low-calcium fly ash was used, but noted little change when a high-calcium fly ash was used. It is not clear in this paper on what basis the fly ash was used. The author concluded that high levels of fly ash substitution are required for significant reductions in the heat evolution.

Shartsis and Newman[125] pointed out some of the difficulties of the Heat of Solution method of test, and suggested modifications to the ASTM method. Such modifications were subsequently made to the ASTM method.[126]

Coole[127] noted that the fly ashes in the United Kingdom are well established as heat reducing agents after his adiabatic calorimeter studies. He pointed out that he had found a slag that gave a greater heat of hydration than ordinary portland cement in his apparatus; this would not have been shown if isothermal testing had been done. In another paper[128] he reported that where the heat of hydration raises the concrete temperature above 40 degrees the fly ash reacts more readily.

Mehta[69] reported a 15 % reduction in temperature of mass concrete in a dam when 30 % of the ordinary portland cement is replaced by fly ash. Barrow et al[129] found a 7,5 degree reduction for 27,5 % volume replacement of fly ash. Baoyu et al[106] noted a 18 % reduction in the heat generation for a 38 % reduction in ordinary portland cement content, this being replaced with fly ash. The 90 day strength levels of fly ash mix and control were both about 30 MPa.

Dahl and Meland[93] showed that there was little difference in the heat evolution curves for ordinary portland cement and two 20 % fly ash blended cements. Ryan[130] reported on the use of fly ash mixes for major raft foundations in order to control the heat

development, and Munn,[91] also referring to work in Australia, mentioned that fly ash was used to reduce peak temperatures in thick members.

Tenoutasse and Marion,[131] reporting on Belgian fly ashes noted that increasing fly ash content helps reduce the heat of hydration and also retards the initial hydration of cement. Rodway and Fedirko[113] reported on the temperatures recorded in some large blocks cast using 3 different high-calcium fly ash contents; the peak temperatures dropped by 7, 19, and 20 degrees for 56, 68 and 76 % fly ash content, and were delayed in time by 18, 28 and 38 hours respectively.

Douglas et al[132] showed that the use of fly ash compared well against slag in reducing heat, and noted that a 50 % fly ash mix gives reasonable strength development and low heat. They noted that the fly ash retards the heat evolution of the tricalcium aluminate.

Langley et al[133] found that the peak temperature of a 55 % fly ash mix was reduced by 25 °C relative to the control mix and the peak was delayed by about 60 hours. These tests were done on concrete blocks of about 28 m^3 volume.

ENCI[134] reported that the heat generated by a fly ash cement made with 20 % fly ash in rapid hardening cement was equivalent to that of an ordinary portland cement with comparable strength performance. In matching the performance of the ordinary portland cement with the blended cement they have sacrificed the advantage in heat evolution. Van der Schaaf[48] indicated that the magnitude of the reduction in heat development depends on the fineness of the cement – the coarser the cement the smaller the change that the fly ash makes.

Sturrup et al[135] reported a reduction in temperature of about 15 °C for a 30 % fly ash mix. Samarin et al[116] gave figures of between 13 and 17 °C drop for 25 and 30 % fly ash mixes in 15 cubic meter blocks. The peaks were delayed by about 12 hours. Korac and Ukrainclk[117] found a 14 °C drop for a 50 % fly ash cement relative to a 15 %/5 % slag/pozzolan cement, with the peak delayed by about 24 hours. Costa and Massazza[65] showed the total heat generated in 28 days to be reduced by about 12 % in a series of tests on 30 % fly ash mixes.

A reasonable rule of thumb would appear to be a reduction in peak temperature of about 0,5 x F where F equals the percentage of fly ash in the mix. This presupposes that the cement is of average quality and that the fly ash is of good quality. It is obvious that a great deal of care is needed in the selection of the test method for determining the heat development of a cement or blend.

3.5 Compressive and flexural strength

Compressive strength, because it is used as the control measure of quality of site concrete, often receives an inordinate amount of attention, sometimes to the detriment of other properties such as durability. In order to study the effect that fly ash has on the compressive strength of cementitious mixes it is first necessary to study the best way to proportion the mixes when the fly ash is incorporated in order to achieve parity

of one or more of the properties of the control ordinary portland cement mix with which the users are familiar.

3.5.1 Mix design procedure

The CSIR[136] proposed a method of mix proportioning using a cement efficiency factor (k) and thereafter basically following the method given in SABS 0100[3]. The efficiency factor is a measure of how reactive the fly ash is and what proportion of its mass can be regarded as true cement replacement. Use of such a factor is a recognition that fly ash modifies some of the properties of fresh and hardened concrete. They gave the k value for Matla fly ash with PPC Hercules ordinary portland cement as 0,4.

Munn[31] defined 4 different philosophies for the use of fly ash in cementitious mixes. The replacement method is where a mass of cement is removed from a mix and replaced by an equal mass of fly ash; a subsequent adjustment is made to the proportions to correct the yield. The addition method involves adding a mass of fly ash without removing any cement; the fly ash replaces sand and/or stone and again the yield is corrected. The replacement/addition or partial replacement method refers to the practice of replacing some of the cement with a greater mass of fly ash and correcting for yield. The final category is that of independent proportioning where conventional methods are ignored; a substantial bank of data is necessary to enable a computer model to be set up, but in using such a method it is possible to design very economical mixes. The CSIR method proposed above[136] is an example of the partial replacement method.

A great deal has been written on the partial replacement method, particularly on the issue of cement efficiency factors. Hobbs[76] noted that the value of k decreases as the fly ash content or the total cementitious content increases. He stated also that the magnitude of k is dependent on the source of fly ash and ordinary portland cement used. He found for a 30 % fly ash mix that the k value varied between 0,18 to 0,45 with an average of 0,35. He further noted that the k value is dependent on the age at which the comparison is made. Barlow and Jackson[24] confirmed the tendency for the k value to increase with decreasing fly ash content, as did the CSIR.[42]

Barker[137] also confirmed that the k value was sensitive to the source of fly ash and cement used and that it changed as the age changed. Butler[51] noted that k is not constant and depends on many things including cement, replacement level, strength level and aggregate quality. He found that the 45 micrometre retention of a fly ash sample was a poor predictor of the k value. The k value did however correlate well with the water requirement of the mixes. Potter[70] also found the k value to vary with cement used and the test procedure applied. Dhir et al[44] concurred but added that the value of k becomes insensitive with rich mixes and this makes it difficult to find the optimum fly ash content.

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[3] South African Bureau of Standards, **The Structural Use of Concrete. Part II Materials and Execution of Work**, Pretoria: South African Bureau of Standards (1980)(SABS 0100 Part II).

Cornelissen et al[97] found that k increased with age for fly ash cements containing up to 15 % fly ash, but decreased with age in a PBFC/fly ash blend. Munday et al[138] mentioned an additional factor that influences the value of k, ie the curing conditions used. They suggested that the fly ash concrete should be proportioned without reference to an ordinary portland cement concrete, and proposed a simple design procedure for this.

Warris[139] produced a formula for strength at a given age which included an efficiency factor. While the formula is based on European cements and probably works adequately with these cements, it is possible, in view of some of the remarks above, that the formula will not be universally applicable. Gopalan and Haque[58] found that the k value depended on the fly ash content of the mix.

There would therefore seem to be some difficulties in working with cementing efficiency factors and there may be good reason to consider the fourth type of approach suggested by Munn,[31] ie the independent method. While the data gathered on local ashes may be insufficient to permit computer modelling, it has permitted an alternative approach for local materials.[140] This method does not consider efficiency factors; curves have been developed for local cement/fly ash combinations and allow selection of suitable water/cementitious ratios for the specified strength level at a number of different fly ash levels. The only other modification made to the conventional ordinary portland cement mix design method is to modify the stone content.

It is extremely important to remember these different methods of proportioning mixes, as the method used can have a considerable influence on the behaviour of the mix. It is possible that some of the contradictory findings in earlier paragraphs owe part of their differences to the fact that the mixes have been proportioned differently; this will have been done in good faith as the different methods are used for different purposes. The different purposes, previously detailed in the glossary to this chapter, are summarized again below, for convenience.[31]

Replacement method. This is a direct mass replacement of fly ash for cement and is used for mixes with an adequate level of strength reserve. This method will commonly result in a drop in strength at ages up to, and sometimes beyond 28 days.

Addition method. This method involves incorporation of an additional mass of fly ash without reduction of the cement content. This method is used for lean mixes where the addition of fly ash improves workability and reduces bleeding and permeability.

Partial replacement method. This method is commonly used when comparable performance to an ordinary portland cement concrete is desired and the typical target will be 28 day strength and equal slump.

Independent proportioning method. Such methods start from the principle of meeting specific concrete properties and do not consider an ordinary portland cement

control. They would endeavour to provide the most economical mix proportions with the available materials.

With these different philosophies in mind it is now possible to consider the issue of the influence of fly ash on compressive strength.

3.5.2 Influence on compressive and flexural strength

Hobbs[76] used the partial replacement method with a common 28 day target strength and common slump for the fly ash and opc control mixes. He found the 91 day fly ash concrete strength to be 15–20 % higher than the control and at 1 year the difference was 30–50 %. In another paper he used the replacement method for some of the tests and found compressive strength parity for 35 % fly ash only at about 91 days with a fly ash complying with the requirements of BS 3892: Part 1[4]. At 28 days the fly ash mix fell about 20 % short of the strength of the control mix.

Tikalski et al[90] stated that compressive strength parity can be achieved at either 7 or 28 days using appropriately proportioned fly ash concrete, but noted that using the replacement method with class C fly ash they recorded slightly reduced early age compressive and flexural strengths under moist curing conditions. Under both elevated and low temperature curing conditions class F fly ash mixes were found to equal or exceed the performance of the ordinary portland cement concrete.

The CSIR[42] used the replacement method and found compressive strength parity between 28 and 91 days for interground or blended 20 % fly ash mixes. In 30 % fly ash mixes the interground cement reached parity between 28 and 91 days whereas the blended cement had not reached the control strength even at 180 days.

Ravina and Mehta[78] stated that the contribution of fly ash to strength development is generally at a slower rate than the cement replaced, and that fly ash is regarded as having a compressive strength reducing effect. Kruger et al[33] using the partial replacement method found lower early strengths and higher compressive strengths after 28 days if the moist curing was continued. In the case of dry curing the fly ash mixes will not reach the same level of compressive strength before 91 days.

Owens[121] warned that the laboratory determination of compressive strength is dangerously misleading as the specimen size is too small to simulate the heat of hydration effects that occur in site concrete; he found that while ordinary portland cement concrete had its compressive strength reduced by exposure to higher curing temperatures the opposite was true for fly ash concrete. This is a point well worth considering as the majority of work reported here is based on the testing of small laboratory specimens.

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[4] British Standards Institution, **Specification for Pulverised-Fuel Ash for Use as a Cementitious Component in Structural Concrete**, London: British Standards Institution, (1982)(BS 3892 Part I).

Osborn and Nixon[59] found when using blended or interground fly ash cements in the replacement method that the early strengths of both 5 % and 20 % fly ash cements were lower than the ordinary portland cement control with the compressive strengths up to 7 days being similar to that achieved by mixes containing the same percentages of sand instead of fly ash.

Rasheeduzzaffar et al[141] used the replacement method and found that compressive strengths only reached the levels of the control mixes at about 80 days; replacement levels ran in steps of 10 % from 0 to 40 %. Mehta[69] notes that whichever method of proportioning is used, fly ash makes little contribution to compressive strength in the first 7 days, but contributes considerably after that.

Giergiczny and Werynska[52] used the replacement method with 30 % fly ash cements and found that even at 90 days most of the cements could not match the control performance. Only where the fly ash was ground beyond about 400 m^2/kg did the compressive strengths approach the control at 90 days. Ravindrarajah and Tam[109] used the replacement method at 20 and 40 % fly ash contents and found compressive strength parity at about 91 days for a nominal 25 MPa concrete but this occurred earlier in a 35 MPa concrete. They commented that the fly ash cements in their hot climate performed like an ordinary portland cement in a temperate climate. Thomas et al[62] used the partial replacement method and found comparable results at 28 days, but at earlier ages the fly ash mixes gave lower results. They pointed out that beyond 28 days the fly ash mixes developed compressive strength at a faster rate than the control. Barrow et al[129] found reduced strength at 28 days with between 20 and 35 % replacement.

Ryan[130] reported that early practice in Australia was simple replacement but this was found to depress 28 day strengths, and particularly 3 and 7 day strengths. The ready mixed concrete companies then switched to a partial replacement system which helped to overcome some of the problems.

Devalsto[142] did experiments with the addition method and found that fly ash mixes with up to 28 % ash reached strength parity before 60 days. The early age strengths were reported to be lower than the control. Tse et al[143] found that class F and class C fly ashes gave different early age behaviour with class C ash (about 26 % calcium oxide) contributing significantly to early age strength development and giving in excess of the control mix strength at 28 days with as much as 75 % fly ash present. In the case of the Class F ash (about 14 % calcium oxide) only the 25 % fly ash mix approached the same level of 28 day compressive strength, while at 75 % fly ash the strength level was scarcely 15 % of the control.

Popovics[144] showed that when plotted on a scale of log of compressive strength to the water/cementitious ratio it is possible to draw straight lines through the plot of the results for the fly ash mixes, thus confirming that the fly ash mixes follow Duff Abrams law both qualitatively and quantitatively. His work was based on the replacement method. His lines showed the fly ash mixes to have lower compressive strengths at ages up to 90 days, although at low w/c+f ratios the differences were smaller than at high w/c+f ratios.

Swamy and Mahmud[145] using what they called replacement of 50 % of the cement with fly ash produced concrete with good early strength characteristics, although there was no control to compare against. The method used was probably a partial replacement method as the water/cementitious ratios used were lower than normal for the grades of concrete used. They found under wet curing that the compressive strength of the fly ash mixes increased by between 50–100 % from 28 days to 1 year compared with 18–25 % for plain concrete. They further noted that under poor curing conditions the high fly ash mixes performed better than the normal performance of ordinary portland cement concretes.

Dhir et al[44] used their own design method and at about 40 % fly ash they found very similar levels of strength development to the control at ages up to 28 days. The increase from 28 days to 1 year of moist curing was about 85 % compared with about 45 % for the ordinary portland cement control mix. The fly ash mixes were found to be no more affected by poor curing than the control mix.

Carette and Malhotra[111] showed that 20 % replacement fly ash mixes did not reach the level of compressive strength of the control mix at 28 days and that the actual level reached was dependent on the quality of the ash used. Poor fly ash did not even match the strength of the control at 1 year. Vom Berg[146] worked with a 20 % replacement and found that the drop in strength at early ages was small relative to the control when the results were expressed as a percentage of the compressive strength achieved by each mix at 28 days. He showed a strength reduction for 25 % fly ash mixes which was greater than that of the control under drying conditions although he points out that the specimens had a very adverse surface area to volume ratio. The CSIR[147] found that when using a partial replacement method the 3 and 7 day compressive strengths were about 15 % lower than the control when the same 28 days values were obtained. When dry cured the fly ash mixes showed slightly poorer performance than the control although at 1 year the difference was small. They showed that under exposed curing conditions the fly ash mixes performed better than the control.

Rodway and Fedirko[113] used their own design method and found that under laboratory conditions some of the high fly ash content mixes exceeded the control compressive strength even at 28 days. The 3 and 7 day strengths were lower than the control. Cores drilled from large (1 cubic meter) blocks showed the fly ash concrete did not perform as well as in the laboratory tests while the control was less affected. Carse and Dux[148] used about 20 % replacement with 3 different fly ashes but augmented the alkali content of the mixes to a constant 10,4 kg/m^3. Very little difference was found between the fly ash and control mixes at ages of 3, 28 and 90 days.

Giaccio et al[149] used a partial replacement method but also kept the w/c+f ratio constant. They found that with one fly ash the strength parity level was only reached some time after 1 year while with another fly ash this occurred at between 90 and 180 days. The less reactive of the ashes was very much coarser than would normally be considered for use in South Africa. Ionescu and Ispas[92] used replacement of cement by fly ash at various replacement levels. At age 28 days mixes with up to 30 % fly ash

had reached the same strength as the control while higher replacement levels had lower 28 day strengths; all fly ash mixes had lower early strengths.

Brooks and Farrugia[150] found for 30 and 70 % replacement that the compressive strengths of the fly ash mixes were well below the control up to 28 days, with the 70 % mix showing greater reductions than the 30 % mix. Douglas et al[132] used 3 levels of replacement for two fly ashes and found compressive strength lower than the control up to 28 days. The finer ash (Blaine of 326 against 289 m^2/kg) proved more reactive in the short time scale provided in these tests even though it had a much lower calcium oxide content (1,3 against 12,5 %). Berry et al[151] showed for a 58 % fly ash replacement that it took a year for the fly ash mix to catch up to the control compressive strength level.

Naik and Ramme[116] found that in using a partial replacement method with fly ash levels up to 60 % and higher, the early strengths of the fly ash mixes were lower than the control even where the 28 day strengths exceeded that of the control. By 56 days even the 60 % fly ash mixes had overtaken the control. Langley et al[133] used a 55 % replacement but modified the w/c+f ratio. They found that the laboratory results of the fly ash mix were lower than the control up to 7 days; the 28 days results were about equal. The laboratory results were confirmed by core results taken from the 3,05 metre cubes cast on site. Site results from another experiment on a 1,5 metre cube with 55 % replacement showed a continuous increase in compressive strength up to 3,5 years.

Theissing[37] found for 30 % replacement that the early strength was lower but after 3 months the strengths normally exceed those of the control. He confirmed that the same could be said for dry curing conditions. Van der Schaaf[49] noted that it took varying times for a 20 % fly ash mix to reach strength equality with the control; at temperatures in excess of 50 °C the strength of the fly ash mixes matched that of the control even at very early ages.

Samarin et al[116] reported on replacement mixes where decreased strengths were found for the first few months, with the magnitude of decrease increasing with increase in fly ash content. Costa and Massazza[65] stated that at 30 % replacement the 1 day strength was reduced by about 50 % which is similar to the drop when ground limestone is used to replace cement. There is a marked difference between fly ash and limestone mixes however as early as 3 days. The fly ash mix will exceed control strength levels between 28 and 90 days.

Yuan and Cook[152] found no slow early strength gain for the class C fly ash (30,3 % calcium oxide) used at up to 30 % replacement, although at 50 % replacement some drop was evident before 28 days. (Note: this level of calcium oxide is similar to that of South African slags.)

Dhir et al[153] reported finding the typical ratio of 1:10 for tensile (flexural) to compressive strength for the designed fly ash mix and stated that it can be assumed that the fly ash makes no difference to the flexural strength. Carette and Malhotra[111] used partial replacement of 20 % fly ash and found that in accordance with the compressive

strength behaviour, the flexural strength was consistently lower than the control at ages up to 28 days, and even at 91 days was lower by some 5–10 %.

Samarin et al[116] stated that the performance of the flexural strength of fly ash mixes was consistent and predictable from the compressive strength. Fly ash was shown to have no influence on the relationship between flexural and compressive strength. As in this work the replacement method was used, the flexural strength of the fly ash mixes was lower than that of the control at ages up to about 90 days. In contrast to this Costa and Massazza[55] found the flexural strength increases faster in fly ash mixes (30 % replacement) than is the case with compressive strength and reaches parity with the control at 90 days ie the ratio of flexural to compressive strength changes with age.

Only two references were found on the effect of fly ash on the fatigue strength of concrete. Tse et al[141] found little significant difference between the fatigue strength of opc and fly ash concretes. A similar finding was reported by Taylor and Tait[154] for mixes having up to 25 % of fly ash replacement, although they noted that the fatigue strength of the fly ash mixes was lower than the control at very early ages.

Coole[127] noted that the tensile strain capacity of slag or fly ash concretes is lower than a comparable opc concrete and this may lead to an increased risk of cracking. Site experience of cracking of fly ash mixes in a concrete pavement in Australia was however ascribed to the fact that the fly ash mix was hand placed while the opc mix was placed through a paving machine.[155] Roper et al concluded after a survey that there was no evidence that fly ash concretes cracked more than ordinary portland cement concretes.[156]

The CSIR reported that the bond strength of fly ash mixes is poorer than the control.[58] Ionescu and Ispas[92] on the other hand reported that the use of fly ash results in little difference on the bond strength between opc and opc/fly ash mixes with up to 50 % fly ash content.

In summary, the use of most fly ashes appears to have the effect of reducing the early age strength relative to what an ordinary portland cement mix would have given, irrespective of the method of use applied. At 28 days the mix design method does have an effect as with partial replacement there should be comparable compressive strengths with the control. The strength beyond 28 days will generally be higher than the control under moist curing conditions and this appears to hold for relatively large pours of site concrete exposed to ambient conditions. Many researchers claim that the effect of poor curing on fly ash mixes is no greater than is the case for ordinary portland cement concrete. A more detailed look at the curing issue is however warranted.

3.5.3 Effect of curing conditions

Hobbs[157] suggested that as the rate of hydration of fly ash concretes is slower the quality of the critical concrete in the skin zone might be more sensitive to poor curing than ordinary portland cement concrete. Tikalski et al[90] showed mass-fly ash mixes (25 %, replacement method) to have higher strengths than the control when exposed to hot dry curing conditions while they seemed to be no more susceptible than the control mix to cold curing at both 7 and 28 days.

The CSIR[42] stated that fly ash mixes have difficulty in achieving strength equivalence under poor curing conditions and this could affect the economics of the use of fly ash. They reaffirmed this finding in a subsequent paper and state that the fly ash mixes are more sensitive to poor curing than the plain cement mixes.[122] In a further paper[136] they state that the sensitivity of the fly ash mixes to poor curing increases as the fly ash content increases. Kruger et al[43] presumably using data from the same source showed the permeability of fly ash mixes to be more affected by poor curing than the plain cement mixes.

Dewar[158] noted that although BS 8110 was expected to advise that the durability of concretes made using extenders could be regarded as being equal to ordinary portland cement concrete of the same grade, a requirement of more critical attention to curing was also expected. (The requirement in BS 8110 is that concretes containing fly ash or slag should be cured longer than opc mixes)[5]. Hughes[159] stated that blended cement pastes are more reliant on adequate curing than normal cements to achieve their potential properties.

Gopalan and Haque[160] showed that adequate curing is more important when using pozzolans at 20, 35 and 50 % replacement as the effect of dry curing is greater than on the plain cement mix. They do however qualify this effect as possibly not applying to massive structural pours but would apply to thin exposed members with high surface area to thickness ratios. Osborn had similar concern for the curing of slag mixes.[161]

Killoh et al[162] showed that neither hydration nor pozzolanic reactions can occur at a relative humidity (RH) less than [illegible] %, while the pozzolanic reaction is severely restricted below an RH of 80 %. They suggested that the blended cement mix is more sensitive to poor curing than OPC.

Thomas et al[82] used a partial replacement method with equal 28 day strength with varying percentages of fly ash. They noted a greater sensitivity for the fly ash mixes when exposed to poor curing with the sensitivity increasing with the fly ash content; moist curing for 7 days improved the situation but did not eliminate the problem altogether. Moisture loss from the fly ash mixes was greatest but this, too, reduced with longer moist curing. The long term strength of all the mixes decreased

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5 British Standards Institution, **Structural Design of Concrete; Code of Practice for Design and Construction**, London: British Standards Institution (1985)(BS 8110 Part I), p. 6/11, table 6.5.

dramatically with poor curing when compared against the standard curing; the difference between the fly ash and control mix compressive strength values was greatest for the shortest periods of moist curing. They noted that the ordinary portland cement mixes required two to three days of moist curing to ensure that the 90 day dry cured strength exceeded the 28 day level under standard curing, while the period was 3–6 days for the fly ash mixes.

Barrow et al[126] gave results for various periods of moist curing for several finenesses of fly ash for mixes based on the replacement method. The results show the fly ash mixes to be more affected by poor curing, with fine ash being less susceptible than the coarser ashes. Swamy and Mahmud[163] showed that the swelling strain for a high fly ash mix amounted to between 40–55 % of the shrinkage value and this they believed indicated the need for continued water curing for full realization of the pozzolanic potential of the fly ash.

Ryan[130] pointed out that there was significant market resistance to blended cements by the specifying authorities due to concern that contractors were not treating concrete with extenders in an appropriate manner. Subsequently the cement producers started manufacturing the blends to suit climatic conditions. Munn[91] noted, again for Australian conditions, that it might be necessary to increase the curing period for some lower strength grade fly ash concretes. Samarin[84] noted that it is generally accepted that in concretes continually exposed to air the inclusion of fly ash would most probably increase the rate of carbonation relative to ordinary portland cement concrete, although the difference in high strength well cured concrete is small.

Gebler and Klieger[110] showed ordinary portland cement concretes to be slightly less sensitive to air curing than the fly ash mixes using 25 % replacement. Even when the results are compared on a partial replacement basis the class F fly ash showed more sensitivity. They further showed the fly ash mixes to benefit more from higher temperatures during moist curing. Devalsto[142] showed a reduction of pozzolanic reaction for specimens cured outdoors for a partial replacement method and stated that the specimens need to be cured in water or under high relative humidity to allow pozzolanic activity.

Dhir et al[44] contradicted these findings by stating that the fly ash mixes are no more affected by poor curing than the control and that the fly ash mixes benefit more from extended moist curing. The fly ash mixes were proportioned using their own design method. Vom Berg[149] concluded that the fine filler effect at early ages overcomes to some extent the loss in strength due to dry curing so the results of fly ash mortar mixes are only slightly lower than those of the ordinary portland cement control.

Kasai et al[164] noted that for fly ash blended cements used on a replacement basis, the depth of carbonation is greater than the control and the situation deteriorates as the fly ash content increases. The compressive and flexural strength values given are lower than the control values for more than 6 months. Gopalan and Haque[66] noted that it is essential to provide adequate curing when the fly ash to cement ratio is high in order to allow proper strength development, irrespective of the method of mix design used.

Kruger et al[33] showed that fly ash mixes were more affected by high or low temperatures than the control mix was; the reduction was bigger in the case of cold conditions while the benefit was greater with warm conditions. Marsh et al[165] agreed with the effect of high temperatures, but pointed out that both ordinary portland cement and fly ash mixes will show drops in strength after prolonged exposure to elevated temperatures. Dhir et al[153] noted that exceeding 70 °C with steam curing of fly ash mixes is not economically feasible, irrespective of fly ash content, as there is little extra benefit for the additional heating. The quality of the ash does have a strong influence on the reactivity under accelerated curing.

Fraay et al[50] noted that the rate of the pozzolanic reaction of the fly ash was strongly temperature dependent as the solubility of the fly ash and the alkalinity of the pore water are temperature dependent.

Gebler and Klieger[166] noted that 25 % fly ash mixes designed for equal 28 day strength are more sensitive to low temperatures than the control. The CSIR[167] also noted a greater sensitivity of the fly ash mixes to low temperatures at early ages and point out that stripping times need to be increased under these conditions. Jensen and Pratt[168] noted a similar increased sensitivity for the fly ash mixes but reported that this enhances the paste quality and is thus beneficial in the long term.

Ehm and Diederichs[169] showed that curing a 22 % fly ash replacement mix at 95 °C and 95–100 % relative humidity resulted in all the fly ash being reacted in 3 months, and all the calcium hydroxide had also been consumed at that stage. The pH however did not drop below 9,5. Ionescu and Ispas[92] showed that heat treatment allows higher proportions of fly ash to be used and still achieve the same level of compressive strength as the control. Vasquez et al[170] found that the microstructure of high temperature cured fly ash mixes was different to that under normal curing.
Owens emphasised that because of the different way that fly ash mixes respond to high heat of hydration the use of temperature matched curing of test specimens is essential.[121] Harrison[171] stated that the selection of the point in the structure with which the temperature was to be matched needs to be done with care and understanding of the consequences.

Cannon[172] showed figures for the strength development of ordinary portland cement and fly ash mixes which were designed to give very similar strengths under standard curing. He showed that the fly ash mix gave about 65 % greater strengths under temperature matched curing conditions that matched the temperature at the centre of a 4,5 metre deep pour than the ordinary portland cement mix gave under its own temperature matched curing conditions.

In summary, there are grounds for expecting some additional sensitivity of fly ash mixes to poor curing due to the slower rate of hydration of these mixes. The fine filler effect is believed to overcome some of the losses incurred here and it seems that the choice of a suitable mix design method can eliminate the problem altogether although more work is needed on this aspect to confirm the findings. Temperature matched curing is opening up a new field of study and seems to show considerable benefits of

using cements with fly ash or slag in areas where the heat of hydration might become high.

3.5.4 Fine filler effect

Ravina and Mehta[78] referred to the action of the fly ash as a filler and how these fine particles formed nuclei for the formation of hydration products as being one of the factors which influence the compressive strength of fly ash mixes. Kelly[173] noted that fly ash provided additional surfaces on which hydration products could grow. The calcium hydroxide was reportedly adsorbed onto the fly ash surfaces thus allowing the hydration of the cement to be accelerated. The consumption of lime at 3 days is insignificant, while at 28 days it has become substantial as the pozzolanic reaction gets under way. Beedle et al[174] however showed that the effect is not simply one of providing nuclei for reaction products as fillers such as graphite and alpha–alumina have little effect on the initial rate of reaction of tricalcium silicate. The authors believed that the acceleration of the hydration by some fine materials might be due to the existence of two forms of C–S–H gel; a high calcium to silica ratio (C/S) form which has low permeability, and a low C/S form with high permeability. They postulated that the fine materials that do cause acceleration of hydration might be lowering the calcium concentration of the pore fluid thus generating the more soluble form of C/S, and this hastens the end of the induction period.

Tenoutasse and Marion[131] noted that the incorporation of fly ash speeds the formation of calcium hydroxide by somehow improving the water to cement contact. They believed that the fly ash had a physical action which promoted the dispersion of the cement particles. Idorn and Thaulow[62] stated that fly ash assists with cement dispersion and therefore gives increased density in hardened pastes. This allows retention of water in the smaller pores so that hydration can continue, unlike the situation with ordinary cement pastes. Devalsto[142] noted that the deflocculation of the cement is affected by the introduction of any fine powder.

Popovics[144] showed that fly ash and ground quartz powder gave similar strength results up to 7 days after which the pozzolanic reaction of the fly ash allowed greater compressive strength development. Vorn Berg[146] also referred to the fine filling effect which he said was also noted with fine inert materials.

Krell[175] stated that fly ash only acts as an inert filler at ages up to 28 days, and after this the pozzolanic reaction lets the fly ash mixes show significant improvement over the control mix. Gopalan and Haque[66] reported that the replacement of cement by fly ash on a volume basis minimizes the filler effect.

Detwiler and Mehta[176] found carbon black to give very similar compressive strength results to similar silica fume mixes; special techniques were used to disperse the carbon black. These results tend to disprove the statements by Beedle et al on the fine filler effect; they may simply not have achieved effective dispersion of the fine materials in their mixes. It is however possible that the phenomenon noted by Detwiler and Mehta could be caused by some difference in particle shape of the carbon black relative to the generally spherical silica fume particles.[177]

Some physical effect of fly ash on the hydration rate of, particularly, tricalcium silicate is generally agreed on. Some authors believe that the same effect could be achieved in the short term by other equally fine but otherwise inert materials.

Another means of evaluating the effect of fly ash incorporation in cementitious mixes is to look at the hydration process. This is covered in the following paragraphs.

3.5.3 The hydration process

Marsh and Day[178] pointed out that the calcium hydroxide content of a fly ash mix is not only dependent on the amount of reacted cement but also depends on the extent of the pozzolanic reaction; the cement hydration produces calcium hydroxide while the fly ash pozzolanic reaction consumes it. In another paper Marsh et al[165] reported that in an ordinary portland cement mix the calcium hydroxide content stabilizes at about 28 %. In a fly ash mix this is reduced initially by dilution, and the pozzolanic reaction only seems to occur after 28 days. For a fly ash paste to exceed the strength of the control cement pastes the fly ash must consume 30–50 % of the calcium hydroxide.

Fajun et al[123] noted that the fly ash particles act as calcium sinks by dropping the calcium ion concentration during the first 2 hours, which in turn retards the formation of a calcium rich surface on the clinker particles. Jun–yuan et al[56] pointed out that at later ages the calcium hydroxide content of fly ash mixes is reduced as the calcium hydroxide reacts with the alumina and silica of the fly ash to form additional C–S–H gel.

Saito and Kawamura[57] found that the addition of fly ash decreases the degree of orientation of the calcium hydroxide crystals at the aggregate interface and suppresses their precipitation there. Feldman[179] noted that the fly ash started reacting with the calcium hydroxide between 3 and 7 days in mixes with about 50 % fly ash. He further noted that there is still considerable calcium hydroxide and unreacted fly ash present even after 90 days of curing.

The CSIR[39] commented that it would require 99,9 % of the calcium hydroxide to react with the fly ash to drop the pH to 10,0. They found that with 80 % fly ash content the pH only dropped to between 12,5 and 13,0. Al–Amoudi et al[180] confirmed this by stating that the pH of fly ash mixes does not drop below the saturation pH of calcium hydroxide.

Dhir et al[41] noted that the following processes probably applied during the hydration of fly ash mixes: there was an initial retardation of the C_3A reaction thus allowing a potential acceleration of the C_3S hydration; there was a physical effect on the microstructure (fine filler effect) leading to a reduction in bleeding. These first two effects dominated the first 7 days. Then finally there was the pozzolanic reaction which resulted in about 50 % being reacted in 6 months and 60–80 % after 2 years.

Fajun et al[123] noted that the hydration of both C_3A and C_3S is retarded and that this is not merely the effect of dilution. The CSIR[39] stated that the rate of hydration of fly ash

mixes is very much slower than ordinary portland cement mixes. Tenoutasse and Marion[131] on the other hand, stated that use of 20 % fly ash has no great effect on the hydration of cement. There would seem to be some differences in the quality or composition of the fly ashes used in these different reports.

There seems to be some disagreement on the effect that fly ash has on the hydration processes of ordinary portland cement. There is agreement that the pozzolanic reaction consumes calcium hydroxide and the fact that this is not likely to lead to a severe drop in pH. There is however considerable variation in thinking on the time at which the pozzolanic reaction starts.

The pozzolanic reaction and the reactivity of fly ash have also received a lot of attention as will become evident in the following paragraphs.

3.5.6 Reactivity of fly ash

The fineness of fly ash, as measured by the retention on the 45 micrometre sieve, is reported to correlate well with the reactivity of the ash,[41,42,45,56] and the use of fine ash can be expected to overcome some of the influences that fly ashes normally have on early degree of reactivity.[28,38,59]

Mehta[89] stated that the reactivity of fly ash depends on the rate of dissolution of the glass and this is strongly dependent on the curing temperature. Sybertz[181] and Korac and Ukraincik[117] noted that the reactivity depends on the temperature of burning of the coal in different types of furnace. Several authors pointed out the relationship between reactivity and fly ash fineness or particle size distribution.[54,69,181] Fraay et al[122] found little influence of fly ash composition on its reactivity.

The CSIR showed that milling of a fly ash improved its pozzolanicity,[42] while it decreased on exposure of the raw fly ash to moisture.[122] The pozzolanicity does not correlate well with the water reduction however,[61] but there is a general tendency for pozzolanicity to increase with glass content of the fly ash.[44]

There is disagreement as to exactly when the pozzolanic reaction actually starts. Dhir et al[44] listed a range of views from 3 days to between 70 and 100 days. The consensus appears to lie around 7 to 14 days or more, with little reaction before 7 days.[85,131,178,183,184]

A test for pozzolanicity has been included in several national specifications for fly ash. The type of test is reported as being strongly influenced by the cement used in the test,[181] and the use of a standard cement has been suggested.[32] Dhir et al expressed some doubt as to what such pozzolanic activity tests measure.[44] Sybertz questioned whether advantage should be taken of the water reduction brought about by the fly ash in these tests.[181]

The commonly accepted quality measure of retention on the 45 micrometre sieve seems to be the most convenient means of assessing the suitability of a particular fly

ash for use in cementitious mixes. Once a fly ash source is proved acceptable this test can serve as the main quality control measure.

3.6 Dimensional and elastic properties

The influence that the incorporation of fly ash has on the dimensional stability of the mix is covered in the paragraphs that follow. These properties are influenced to a large extent by the quality of the microstructure of the paste and therefore by the effect that the fly ash has on the quality of the microstructure.

3.6.1 Elastic modulus

Several researchers have reported that incorporation of fly ash has little or no influence on the ratio between the modulus of elasticity and the compressive strength; the ratio is reported to be similar with or without the use of fly ash in the mix.[44,109,111,116,134,147,149,153,185] This does imply that when fly ash use reduces or increases the compressive strength at any given age, the elastic modulus will be affected accordingly.

Brooks and Ferrugia[150] showed a small drop in elastic modulus against compressive strength as the fly ash content increased. As these mixes were based on replacement, the compressive strength also dropped.

Rodway and Fedirko[113] stated that the elastic modulus of the high fly ash content mixes all exceeded that of the control at 91 days. This is a little surprising as the compressive strengths of the mixes provided showed the highest fly ash content mix to have a much lower compressive strength than the control. Sivasundaram et al[196] produced data showing that the ratio of elastic modulus to compressive strength of a high volume fly ash mix exceeded the ACI 318[6] and ACI 363[7] values. They ascribed the high modulus value to increased densification of the concrete resulting from the use of fly ash, and the possibility that unreacted fly ash particles were acting as aggregates.

Swamy and Mahmud[145] showed the loss in elastic modulus of about 20 % for 50 % fly ash concretes of strength between 30 and 60 MPa when exposed to dry curing conditions to be less than would normally be expected (about 25 to 45 %) for ordinary portland cement concrete under similar conditions.

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6 American Concrete Institute, Committee 318, Building code requirements for reinforced concrete, (ACI 318–83, revised 1986) **ACI Manual of Concrete Practice**, Detroit: American Concrete Institute, (1989) Part 3, p. 318–29, clause 8.5.

7 American Concrete Institute, Committee 363, State–of–the–art report on high–strength concrete, (ACI 363R–84), **ACI Manual of Concrete Practice**, Detroit: American Concrete Institute, 1989, Part 1, p. 363R–21, clause 5.3.

In summary therefore, the influence of fly ash on the elastic modulus of cementitious mixes seems to be consistent with the effect it has on the compressive strength.

3.6.2 Shrinkage

A net outflow of moisture from a cementitious mix to the atmosphere will result in a decrease in its volume; this process is known as drying shrinkage. If the incorporation of fly ash changes the potential amount of water that can be lost, or the rate at which it can be lost this will probably reflect in a change in the magnitude and rate of the drying shrinkage of that mix.

Several papers stated that the effect of fly ash on the shrinkage is negligible.[33,44,68,110,134,147,164,165,187] Other authors have reported that the effect of using fly ash is to decrease the shrinkage.[111,117,153,163,167,188,189]

However, in contrast, Ravindarajah and Tam[109] found increased shrinkage in mixes with 20 or 40 % replacement of fly ash at age 90 days where the compressive strengths of the fly ash mixes were close to or exceeded those of the control mixes. Extended curing tended to reduce the difference in these tests.

Ravina[63] looked at the very early dimensional changes of mortars and found that the use of fly ash at various replacement values increased the initial expansion. His results generally show a decrease in the shrinkage of the mortars after the end of expansion when the fly ash is used.

Dhir et al[44,185] noted that the use of fly ash could be expected to lower the thermal coefficient of expansion of concrete, although there was no obvious trend in their results.

The general effect of fly ash incorporation in cementitious mixes seems to be either negligible or a slight decrease in the magnitude of the shrinkage strains measured. As the generally agreed trend when fly ash is used is to find a reduction in the water requirement of the mix, it is likely that the fly ash mixes have less water to lose. The reduction in shrinkage is therefore not surprising.

3.6.3 Creep

Creep is defined as the time-dependent increase in strain of a solid body under constant or controlled stress.[190] Various hypotheses have been proposed for the mechanisms involved; a common factor is that mobile water needs to be present at different bonding levels within the structure of the cement gel. Creep movements are believed to be associated with a change in the state of this water leading to a change in the gel structure.

If the use of fly ash brings about any change to the characteristics of the hardened cementitious paste or the ease with which the water can change state it is likely that this will be reflected by a change in the creep behaviour of the mix.

A large proportion of the published information on the effect of fly ash on the creep behaviour of cementitious mixes is that the magnitude of the creep strain measured is reduced.[33,44,69,90,109,111,116,153,157,185,187,188,191]

Two papers showed an increase in creep strain when fly ash was used. Nasser and Al–Manaseer[192,193] found that the creep of fly ash + admixtures concrete was some 72 % higher than the control. The fly ash mix had a higher slump than the control mix but it contained 3 chemical admixtures in addition to the fly ash as opposed to the single air entraining admixture of the control mix. It is therefore difficult to blame the fly ash for the increase in creep strain as either the admixtures or the higher slump could also have played a role.

Brooks and Farrugia[160] found the early age specific creep of fly ash mixes to be greater than the control; the difference was relatively small at 30 % fly ash but at 70 % fly ash the difference was large. As these mixes were proportioned on a replacement basis the compressive strengths achieved by the fly ash mixes were well below those of the control mix. The degree of hydration of the fly ash mixes was presumably far lower than that of the control, particularly in the case of 70 % fly ash and it is possible that the rate of moisture movement in these mixes was greater. It should be noted that no adjustment was made in the water content of the fly ash mixes and therefore the workability was far greater than that of the control mix.

Carette and Malhotra[111] postulated that, as with shrinkage, at early ages in the fly ash a large proportion of the fly ash particles remain unreacted and contribute increased restraint as fine aggregate particles instead. Dhir et al[153] noted that fly ash inclusion must reduce the creep by altering the nature of the gel in which the creep takes place.

Nasser and Al–Manaseer[187] noted that the fly ash mix had creep that was about 15 % below that of the control even when the heat of hydration raises the temperature slightly. The CSIR showed that at low temperatures the creep of fly ash mixes is still lower than the opc control, but that it was increased relative to the figure for the fly ash mix at normal temperatures.

The effect that the inclusion of fly ash has on the hardened cementitious paste therefore appears to reduce the creep of the mix. Where increases have been shown in the creep with the use of fly ash the evidence against the fly ash is not absolutely clear.

The dimensional stability of cementitious mixes seems to be little affected by the incorporation of fly ash.

3.7 Durability

One of the major concerns for owners and designers of concrete structures is that the structure should provide as long as possible a life without the need for major maintenance or reconstruction. It is also true today, with the level of industrial activity as it is, that the environmental conditions that concrete has to face are becoming more and more aggressive as time goes by. Concrete is expected to be durable, but stories

such as those on concrete "cancer" and the major maintenance bills for the repair of concrete now facing the developed world indicate that there is a gap between expectation and performance.[194]

Part of the problem is due to changes in the quality of the ordinary portland cements available today that are different from those made in the past. In some countries modern cements are more reactive than they were about 35 years ago.[121] This has led the Concrete Society of the UK to identify a need for cements to be less, rather than more, reactive.

The properties of concrete that determine how resistant it is likely to be against the attack of aggressive elements are as follows; impermeability and low porosity, abrasion resistance, resistance against attack by soft water, carbon dioxide and sulphates, resistance against the diffusion of chloride ions, and low sensitivity to alkali silica reactivity.

The influence that fly ash has on the ability of a cementitious mix to resist these forms of aggression are covered in the following paragraphs.

3.7.1 Impermeability and low porosity

Permeability is defined as the property that characterizes the ease with which a fluid flows within a material due to a pressure differential[195] and is measured by the volume of liquid or gas transmitted per unit area per unit time per unit of pressure. It is commonly expressed in units of metre (or millimetre) per second.

In concrete the aggregate fraction can be regarded as effectively impermeable. Concrete owes its permeability to the paste fraction. Fresh paste consists of solid particles dispersed in water. The volume of the space between the particles depends originally on the ratio of cement to water. As the cement hydrates, so this space becomes occupied by gel – the unfilled space represents capillaries, and it is these capillaries that allow the transport of fluids through the concrete. A survey of the literature on the subject of the effect of the use of fly ash on permeability follows.

Many papers have reported on the reduction in permeability when fly ash is used.[33,45,50,54,69,82,102,121,196] Fraay et al[50] reported that the decrease in permeability in fly ash mixes is due to the fact that the hydration products are deposited relatively far from the fly ash particles compared with deposition close to the cement particles in an ordinary portland cement mix.

Kasai et al[197] showed the permeability of fly ash mixes, with the same w/c ratio as the control, to be greater than the control under each of three different curing regimes. It is notable that the fly ash mixes had compressive strengths well below the control at all ages of test and also that the use of the fly ash made no improvement to the water requirement of the mixes; there is a possibility that this was a poor quality ash.

Marsh et al[198] showed how the fly ash pozzolanic reaction brought about a dramatic reduction in permeability. The permeability of the 30 % replacement fly ash mixes (no

reduction in water content) was initially higher than the control but after slightly more than 28 days curing at 20 °C the pozzolanic reaction commences and the permeability reduces sharply to be lower than the ordinary portland cement mix at about 100 days.

Rasheeduzzafar et al[141] and Al-Amoudi et al[180] reported that while the permeability of fly ash mixes exceeded that of the plain cement mixes at 28 days, at 90 days the fly ash mixes had lower permeability than the control mixes. This is not entirely surprising as the fly ash mixes were designed on a replacement basis and the level of compressive strength of the fly ash mixes only overtakes the control near 28 days.

The CSIR reported that the water permeability of fly ash mixes was similar to that of opc mixes when cured at low temperatures. They found however that these values are increased relative to those found under standard curing conditions.[167]

Cabrera and Wooley[199] and Baweja and Roper[155] reported that the proportion of pores larger than 0,5 micrometres is higher in an ordinary portland cement mix than in a fly ash mix. Marsh et al[198] noted that the permeability of a material is proportional to the proportion of large voids. Li and Roy[200] noted that a finer pore structure results from using a fly ash blended cement in a paste. They further showed that increasing the fly ash content or decreasing the water to cementitious ratio dramatically reduces the permeability of the paste to water or chlorides, even though the porosity increases. Kumar et al[201] showed that the porosity of both opc and fly ash mixes increases as the curing temperature increases, although the pores in the fly ash mix are smaller.

Lin and Hwang[117] noted that the cumulative pore volume of fly ash pastes decreases with time and that fly ash pastes have finer porosity at later ages. Feldman[202] reported that the low permeability of blended cement mixes results from a discontinuous pore structure.

The porosity of concrete mixes when measured by mercury porosimetry is reported to increase above the levels recorded in control mixes when fly ash is used.[79,151,203] This is possibly due to the collapse of some hollow fly ash particles under the extremely high pressures to which the mercury porosimetry exposes the concrete.

A number of authors[155,164,202] have warned that the high pressures exerted in some of the permeability tests may cause some breakdown of the pore walls and give misleading results particularly for the fly ash mixes.

Dhir et al[204] reported on a variety of apparatus designed to evaluate the permeability of the outer skin of concrete structures and made recommendations on which apparatus to use. The quality of the skin concrete is fundamental to the durability of reinforced concrete as it is this zone that has to provide the protective layer for the steel. Such apparatus will be useful to determining the sensitivity of fly ash concretes to poor curing.

Gebler and Klieger[110] reported that the water absorption of fly ash concrete is lower than the plain cement control. The CSIR came to a similar conclusion[147] although in another paper they noted that while age appeared to have little effect on the absorption

of opc or fly ash mixes exposure to carbon dioxide reduced the absorption of the fly ash mix.[205] Aimin[206] noted an increase in the moisture loss from fly ash mixes at high relative humidity values and suggested that an excess of fly ash coarsens the pore structure. Hobbs[157] found the moisture loss from fly ash mixes to be controlled by the water/cement ratio ignoring the fly ash.

Killoh et al[162] noted that the gel porosity of opc/fly ash pastes is about 50 % higher than for opc pastes indicating a lower bulk density of the paste. They suggested a need for curing at high relative humidity to ensure that the proportion of large diameter pores is small thus ensuring low permeability.

Fly ash does seem to contribute to reducing the permeability of mixes although the porosity might increase as the fly ash content increases. As there is some effect of exposure to low temperatures attention to the skin concrete is warranted where this is exposed to poor curing conditions.

3.7.2 Abrasion resistance

Concrete and mortars are exposed to abrasive forces in pavements and some structural environments where wind, water or gravity borne solids impact on the exposed surfaces. The aggregates play an extremely important role in abrasion resistance, but in the following paragraphs this factor is ignored in the study of published work on the effect of the incorporation of fly ash in mixes on the abrasion resistance.

All the papers consulted on this topic indicated that when a fly ash mix has the same level of compressive strength as the control mix the degree of abrasion resistance offered is similar in both mixes.[39,90,110,116,129,207] Barrow et al[129] stated that the abrasion resistance is proportional to the compressive strength at the time of test, and is independent of the fly ash content. They added that as fly ash mixes are more sensitive to poor curing, site-exposed fly ash mixes might abrade faster.

Samarin et al[116] noted that while laboratory tests showed the levels of abrasion of fly ash and control mixes to be similar, in a field trial a fly ash concrete showed greater wear than the control. When effective curing was carried out the degree of wear was similar.

Butler and Ashby[207] found that under wet curing conditions there was little difference in abrasion resistance between control and blended cement mixes. Air curing gave reduced resistance for all mixes, while a good curing membrane was found to improve the resistance of all mixes but not to the same level as when wet cured. The curing compound seemed less effective with the fly ash mixes.

Abrasion resistance seems to be related to compressive strength and is not affected by the use of fly ash in well cured specimens. As abrasion usually occurs on the surfaces exposed to the worst of site curing the abrasion resistance can be expected to be one of the most sensitive properties of concrete to any factor that increases the

susceptibility of the concrete to poor curing; a site trial has indicated a negative effect of fly ash on this property.

3.7.3 Soft water attack

Soft water is water with the concentration of dissolved calcium salts close to zero. The concentration gradient between concrete with its high concentration of calcium compounds, and a soft water to which it is exposed is very steep, and the dissolution rate of calcium from the concrete is likely to be high.[208]

There appears to be confusion about the effect that fly ash has on the resistance of cementitious mixes when exposed to soft water. The resistance seems to have generally been determined on exposure to carbon dioxide dissolved in water. The CSIR has shown an improvement in resistance,[122] although in another paper they are unsure about the long term effect.[57] In a further paper they have shown the resistance to be poorer.[209]

Ballim[210] indicated better resistance from fly ash mixes than an opc control but poorer than a mix containing slag.

It is clear that more work is required on this subject, and possibly the first step should be to define proper test conditions.

3.7.4 Carbon dioxide and carbonation

Carbonation is the process of conversion of the calcium hydroxide in the cementitious paste to calcium carbonate by combination with carbon dioxide from the atmosphere. This process causes shrinkage of the reacted material and may result in crazing of the surface.[211] It is accompanied by a drop in the pH of the pore solution from about 12,5+ to about 8,0.[157] The extent of carbonation depends on the permeability of the mix, the concentration of carbon dioxide in the air, and the ambient temperature and humidity.

Carbonation is not particularly deleterious to concrete; the drop in the pH does however reduce the protective environment around any reinforcing steel in concrete and corrosion may result. Owens[121] noted that corrosion of embedded steel is inevitable and can not be avoided without special treatment unless the concrete has cement content of at least 380 kg/m^3. There has been fierce debate recently[130] in Australia on the impact that fly ash and slag have had on the durability of concrete.

The effect of the use of fly ash on permeability has already been studied, and some mention has been made of the effect that fly ash has on the calcium hydroxide content of cementitious mixes. The effect that the use of fly ash has on carbonation will be covered now.

The most commonly used test for carbonation is the use of the indicator phenolphthalein which is colourless at a pH of 8,0, but has an intense pink at a pH of

9,8. Although Rahman and Glasser[212] pointed out that this test does not detect the intermediate zone of carbonation it is a quick and simple test.

Kruger et al[33] showed the wide range of published opinion on this effect, but reported little difference between the rates of carbonation between the fly ash and control mixes in their research work. Subsequent work by the CSIR showed that at low temperatures the depth of carbonation for fly ash mixes was found to exceed the control and was also greater than at standard temperatures.[167]

The use of fly ash has widely been reported as increasing the carbonation.[92,158,167,164,175,213,214,215,216,217] Many others have shown little impact[39,134,155,213,218,219] or have found little difference at later ages after an initial faster rate.[117,147,181,205,220,221] Some authors have expressed the view that the rate of carbonation is proportional to the w/c ratio ignoring the fly ash content,[39,214] but others[167,216] have shown that the fly ash does have the impact of being about half as effective as its weight in cement in controlling the carbonation. The use of curing compounds is reported to slightly improve the resistance to carbonation of fly ash mixes.[207]

There has even been some evidence of very low rates of carbonation for fly ash concrete when exposed to site conditions.[198]

The data presented seem to indicate that before any appreciable pozzolanic reaction has occurred there is less resistance to carbonation of fly ash mixes, but once the pozzolanic reaction has played its role the rate of carbonation of the fly ash mixes decreases. Consideration should again be given to the impact that the heat of hydration has on the quality of the microstructure[121] as this too could play a part in determining the resistance of fly ash mixes to carbonation. There seem to be two factors that have an effect here, ie the fact that the fly ash will tend to reduce the calcium hydroxide content of the mix and thereby reduce the resistance to carbonation, but on the other hand through pore refinement the permeability will tend to be reduced slowing the rate of gas penetration.

3.7.5 Sulphate attack

Cementitious mixes are susceptible to deterioration by attack by sulphates in the following ways;

- conversion of calcium hydroxide to calcium sulphate with subsequent crystallization, expansion and disruption,
- conversion of hydrated calcium aluminates and ferrites to hydrated calcium sulpho-aluminates and sulpho-ferrites again followed by expansion and disruption,
- decomposition of hydrated calcium silicates.[222]

Good quality dense concrete with a low permeability will be more resistant to attack by sulphates than more permeable concretes. If the use of fly ash can contribute to

the impermeability of a mix then it should reduce the susceptibility to sulphate attack. The use of fly ash will also contribute by reducing the calcium hydroxide content by pozzolanic reaction, and so the first of the above mechanisms can be reduced in severity. The following paragraphs detail some published reports on the effect of fly ash on sulphate resistance.

Most of the reports show significant improvements in the resistance to sulphates[67,69,116,122,141,223,224,225,226,227] when fly ash is incorporated in the mixes. Hughes[159] reported that the sulphate resistance of a mix is proportional to the entry pore diameter and as the fly ash mix had smaller pores it was less affected.

Marsh and Joshi[228] stated that the sulphate resistance of fly ash mixes is dependent on the degree of pozzolanic reaction of the fly ash. Joshi[225] found improved sulphate resistance for fly ash inclusion but noted that fly ash with high calcium oxide contents reduce the resistance. Yuan et al[226] confirmed that class F fly ash is more effective than class C fly ash in reducing sulphate attack.

Some of the authors noted that the chemical composition of the cement used in the tests remains an important factor in the results.[224,225] Hughes[159] noted that a well cured 70/30 fly ash cement mix did not provide the same degree of resistance to sulphate attack as a sulphate resisting cement even though the fly ash mix was well cured; he hesitated to extrapolate these findings to recommendations for site practice.

The general impression is that fly ash improves the resistance of cementitious mixes to sulphate attack. The mechanism is possibly through dilution or consumption of susceptible compounds in the mix as well as by improvement of the pore structure and reduction of the permeability of the mix. From one result it would seem that more than 30 % fly ash is needed to provide equivalent sulphate resistance to sulphate resisting cement.

3.7.6 Chloride diffusion and corrosion of steel

Basson[209] notes that the chloride ion can readily penetrate even slightly porous concrete to reach the reinforcement, and once there forms ferrous chloride which oxidizes to ferric chloride and under the alkaline conditions present in the concrete is then precipitated as ferric hydroxide thus freeing the chlorides for further attack. He points out that the corrosion products occupy more than twice the volume of the original metal and the process will thus lead to expansion and disruption of the cover concrete.

The majority of published information on the rate of chloride diffusion through cementitious mixes has reported that the use of fly ash brings about a reduction in the rate of diffusion.[26,70,141,200,201,219,229,230]

Plante and Bilodeau[229] noted that a 25 % replacement fly ash mix with lower 28 day strength than the control had a lower chloride diffusion rate. Tuutti and Fagerlund[219] reported that the chloride diffusion rate reduced by a factor of 50 when a 40 % fly ash replacement mix is used.

Plante and Bilodeau[229] noted that the rate of chloride ion diffusion decreased in all mixes as the period of moist curing increased. Kumar et al[201] found that an increase in curing temperature makes a significant improvement in the chloride diffusion rate of fly ash mixes while this improvement is not evident in ordinary portland cement mixes. Gebler and Klieger[166] found that when cured in air fly ash concretes are as resistant as ordinary portland cement concretes to chloride penetration.

It seems evident that the rate with which the chloride ions can penetrate a fly ash mix is in no way inferior to plain cement mixes. The following paragraphs give the findings of researchers into the aspect of resistance offered by fly ash mixes to the corrosion of the embedded reinforcing steel.

As noted before the steel will rust under alkaline conditions if chlorine and oxygen are present.[39] Kokubu and Nagataki[214] noted in 20–year old concrete that in some places corrosion had occurred before the carbonation front had reached the steel.

Some authors have indicated that fly ash mixes offer no poorer protection against steel corrosion than is the case for plain concretes.[27,82,106,163] Other researchers have reported that the protection improves with fly ash use.[180,231,232] Hansen et al[233] reported that fly ash seems to be more effective in controlling the ingress of chlorides than in contributing to compressive strength.

The CSIR noted that although the use of fly ash helped control chloride ingress in high strength mixes, in some lower grade mixes the use of fly ash resulted in a severer form of corrosion than was the case for the control.[234]

The use of fly ash seems to assist in reducing the rate of chloride ingress and with dense concrete the protection offered by fly ash concretes is, in most cases, at least the equal of the ordinary portland cement concretes.

3.7.7 Alkali–aggregate reactivity

The phenomenon of the expansive reaction of some susceptible aggregate types in concrete was first identified in the USA in 1938, but has, in recent years, been recognized in most countries in the world. In South Africa the first reports were of the deterioration of Steenbras dam, followed by reports of other structures in the Western Cape showing similar signs of deterioration. In 1974 the problem in the Cape was identified by the NBRI of the CSIR as alkali–aggregate reaction with the Malmesbury hornfels coarse aggregate in the structures.

The factors influencing the reaction are the total available alkali content of the concrete, the degree of compaction and density of the concrete, the presence of a reactive aggregate and the necessary environmental conditions. The total available alkali content will typically be made up from contributions from the cement, the cement extender (if present), admixtures, the aggregates and the mixing water. The main source will generally be the cement.

A great deal of pioneering research was done by the NBRI and they have published widely on the control measures to be taken where deemed necessary.[235] Included amongst these recommendations is one of incorporating at least 20 % fly ash in the mix where problems are anticipated. Other published information is summarized in the following paragraphs.

Many authors have reported on the reductions that occur in the destructive expansion from alkali silica reaction with the inclusion of fly ash.[45,54,119,135,147,236,237,238,239,240,241] Others have noted that some alkalis are contributed by the fly ash, the proportion of available alkalis being estimated as about 17–35 % of the total alkalis, but generally this does not rule out the high alkali fly ashes for use.[25,79,242,243]

Al–Asali[244] reported on tests where the fly ash contributed to higher expansions at later ages even though the initial expansion of the fly ash mix was less. The alkali content of the fly ash was not unusually high at 2,1 % sodium equivalent, and fused silica was used as the aggregate. Ravina and Mehta[79] noted that when fly ash is used expansions occur at lower alkali contents (ignoring contributions from the fly ash) than would be the case with plain cement. Carrasquillo and Snow[243] also found that a high alkali content in the fly ash reduced its effectiveness in reducing the expansion, and found some increase in expansion with a 15 % fly ash mix.

Some authors noted that the problem can be exacerbated by alkalis penetrating from outside the concrete from sources such as sea water or de–icing salts.[245,246,247] Roper warned against the use of reactive aggregates in prestressed concrete as the control of expansion using pozzolans has not been proved over a period of longer than 10 years.[246] Farbiarz[248] reported that the process of intergrinding the fly ash with the cement improved its performance in controlling the expansion relative to blended cements using the same materials, although this did not work for all the fly ashes used.

The role that fly ash can play in reducing the deleterious expansions caused by alkali silica reaction is well documented although it would seem appropriate to carry out tests if the fly ash to be used has a high total alkali content. The appropriate minimum level of fly ash to be used to bring about a suitable reduction in expansion seems to be 20–25 %.

3.7.8 Acid attack

Ordinary portland cement concrete is inherently susceptible to attack by practically all mineral acids and some organic acids too. The rate of attack is determined by the cement content of the concrete, the amount and solubility of the aggregate and the permeability of the concrete and the amount and concentration of the acid.[249]

Marsh and Joshi[249] reported that the weight loss from pastes immersed in sulphuric acid increased with a 30 % partial replacement of fly ash. Backes[250] found that it was only possible to use 20 % fly ash in mixes exposed to carbonic acid before the improvement that the fly ash brought about was negated. Fidjestol[251] noted that fly ash and fly ash+silica fume mixes are less susceptible to attack by organic acids, with rich mixes showing more resistance than lean mixes.

This is an aspect which has had relatively little attention, with presumably the philosophy being not to expose concrete of any composition to acids if this is avoidable.

3.7.9 General durability aspects

The following paragraphs contain reported effects of fly ash on some other aspects of durability not previously covered.

Some papers have reported on general durability improvements due to pore refinement (ie a discontinuous structure), a lower permeability and a reduction in the calcium hydroxide content.[34,69,121,202] Reports have been published of satisfactory durability in exposed fly ash concretes.[155,252]

There are several reports stating that the use of fly ash has little impact on the freeze/thaw resistance of concrete provided that the air content and compressive strength are equal to the control,[30,152,219,239,253] although Yuan and Cook[152] felt that there might be an upper limit to the fly ash content as they noted higher scaling damage in a high fly ash content mix. Other authors have reported a deterioration in the resistance to freeze/thaw attack with the use of fly ash.[166,176,203,254] It is not clear from the literature whether the differences of opinion are due to the fly ash used or differences in the methods of proportioning, curing or testing.[74]

Baweja and Roper[155] reported that fly ash concretes have a high degree of salt exudation; this is likely to be of cosmetic importance only.

It is likely that a fly ash concrete can be proportioned to provide adequate durability under most circumstances, even if this means that the cementitious content of the mix is higher than without the fly ash.

3.8 Miscellaneous

Some other aspects of the effect that the use of fly ash has on concrete remain to be considered.

3.8.1 Ternary blends

With the relatively free availability of supplementary cementitious materials some users have used combinations of ordinary portland cement and two of the range of other materials. Some information has been published on the combination of fly ash and slag or silica fume and this is covered in the following paragraphs.

Potter[70] noted that 3 component blends have been used since slag became commercially available in Australia in 1966 but little information on this has been published. Munn[91] reported that ternary blends had been used with great success and that there is a unique interaction between the slag and fly ash that leads to superior concrete properties.

Austin et al[255] reported that a combination of 25,5 % coarse fly ash with 4,5 % silica fume performed similarly to a 30 % fly ash (fine) mix and proved more cost effective. Mantegazza et al[256] noted that the setting time decreased as the ratio of silica fume to fly ash is increased. The compressive strength of the ternary blend is reported to be superior to the opc fly ash mix, and carbonation is reported to be decreased with the use of fly ash or silica fume.

Little published information could be located on this topic. While there appears to be a potential for such mixes, it would seem that more research is needed to provide a better understanding of the interaction between all the cementitious components of the mix.

3.8.2 Use of admixtures

Use of chemical admixtures has become commonplace in most countries, although they have not yet made a very big impact in South Africa. The following paragraphs cover the reported effects that the use of fly ash has on the effectiveness of such admixtures.

Dahl and Meland[83] reported that the effect that fly ash has on the performance of a chemical admixture depends on the rate of adsorption of the admixture onto the fly ash particles. Several authors[31,37,40,90,189,253,257] have reported that the dosage rate of air entraining admixtures needs to be increased in fly ash mixes, particularly class F fly ashes. This has been ascribed to the carbon content of the fly ash as it apparently absorbs air.[40] This phenomenon has also been reported to occur with water reducing admixtures[37] as well as with superplasticisers.[113] Superplasticisers have been used to make it possible to get a sufficiently low water to cement ratio with high-volume fly ash mixes to provide the compressive strength performance desired.[105,258]

Alasali[244] reported that some high range water reducing admixtures have been found to aggravate alkali aggregate reactions in concrete.

Although it is possible that some adjustment may be necessary to the dosage rate of chemical admixtures in order to achieve the desired effect there are no reports of any incompatibilities with fly ash.

3.9 Summary

After consideration of all the published data on the effects of the use of fly ash in cementitious mixes the following factors appear:

i) There is much conflicting information on the effect of the use of fly ash.

ii) Some of the differences can be ascribed to the wide differences in the quality and chemical composition of the various fly ashes used in the tests reported on.

iii) Another, possibly more significant, factor is the different ways with which the mixes have been proportioned to prepare the test specimens, ie replacement, addition, partial replacement etc.

iv) A third factor is that there are differences that occur when different test methods are used to produce similar results.

Fortunately in South Africa the user is not faced with a wide range of different sources for fly ash and is only likely to be able to get fly ash from either the Matla or Lethabo sources supplied by Ash Resources for the foreseeable future. The literature survey however serves to set the scene for the experimental work covered in subsequent chapters.

CHAPTER 4

4. RESEARCH METHODOLOGY

4.1 Problem definition

The users, specifiers and owners of products or structures containing portland cement in South Africa are accustomed to a level of performance defined by their experience with the behaviour of ordinary portland cement under site conditions in the various parts of South Africa. The fact that the performance of ordinary portland cements tends to vary with time and source of supply is taken into account to some extent by these experienced users or specifiers. Any cement producing company that wishes to introduce a new product into this market needs to be aware of the impact such an introduction could have on the user body if the performance of the new product is different from that of the ordinary portland cement used in the past. This is especially so if the difference in performance is substantial and greater than the normal variability of ordinary portland cement.

The objective of this study is to evaluate the order of magnitude of difference, if any, between the performance of:

i) the early-age characteristics of ordinary portland cement against the performance of the new product containing fly ash; these differences are of prime concern to the contractor involved with the everyday use of materials on the construction site.

ii) the medium- and long-term characteristics of ordinary portland cement concrete against the new product containing fly ash; these differences are of prime concern to the specifier and owner with their desire for long term durability of the structure.

In both cases cognizance must be taken of the inherent variability of ordinary portland cement. The above differences in performance must be considered in the light of the ability the experienced user generally develops to accommodate the variability of ordinary portland cement performance.

Once these factors have been considered, guidelines can be proposed for the practical use of the new portland cement on sites and in yards in South Africa.

4.2 Research methodology

In most cases use has been made of common laboratory techniques covered by South African Bureau of Standards (SABS), British Standards (BS), American Concrete Institute (ACI) or American Society for Testing and Materials (ASTM) test methods to determine laboratory values for commonly measured characteristics in concrete or mortar. Due consideration has however been given to site conditions and their possible impact on these characteristics. In each case full method descriptions have been given where deviations have been made from standard test methods or where a new test

where deviations have been made from standard test methods or where a new test method has been developed.

The characteristics which have been evaluated are as follows:

4.2.1 Characteristics of fresh mixes

Laboratory measurements have been made of the changes that the incorporation of fly ash brings about in a fresh mix of concrete or mortar to the following parameters:

- rheology and workability
- setting time
- bleeding
- heat of hydration

4.2.2 Characteristics of hardened mixes

Measurements have been made under laboratory and simulated site conditions of the influence that the incorporation of fly ash has on the properties of hardened mixes. The following parameters have been studied:

- compressive strength
- elastic modulus
- shrinkage
- creep
- durability

4.2.3 Other studies

Some work has been done to evaluate the influence that the use of fly ash has on the effect of chemical admixtures in fresh and hardened mixes. A study has also been made into some aspects of ternary blends i.e. blends of ordinary portland cement, fly ash and another pozzolanic or latent hydraulic material such as silica fume or ggbs, in an attempt to develop an understanding of performance in anticipation of what might become construction practice in the future.

4.3 Selection of materials to be used

4.3.1 Cementitious materials

In the introductory chapter details were given of the declared intentions of the three

South Africa Cement Producers as regards fly ash cements. These companies were asked to submit suitable samples of the cements that would be used for blending purposes.

D & H Ash Resources were asked to supply PCI with sufficient fly ash from the Matla power station, at that time the only source of commercially available fly ash. Some of this ash was subsequently supplied to PPC to manufacture the interground products for this test programme. PPC was asked to submit interground fly ash cements at 5 %, 15 % and 30 % fly ash content in addition to the cement to be used for blending purposes.

At the time that the test programme was initiated the fly ash from Matla power station was being taken from the material retained in fields 2 and 3 of the electrostatic precipitator. Subsequently, due to a change in the operating procedure by Escom, it became necessary to install air classification equipment at Matla. Initially little of the classified material was used in testing. However it was subsequently found that there were differences in the behaviour of fly ash collected by selection or classification and further tests were done using the classified ash too.

The construction of the Lethabo power station commenced during the test programme and samples of fly ash became available. The classifier for selecting fly ash for cementitious use was only commissioned in mid 1990 and test samples were made available for some indicator tests shortly after that. However, the majority of the testing has been done on the Matla ash.

The physical characteristics of the cements and fly ash samples supplied are given in table 4.1 while their chemical characteristics are given in table 4.2. All these data were obtained from analyses carried out by the Technical Services Department of the Pretoria Portland Cement Company. It should be noted that the data presented in table 4.2 are for analyses on the fly ash samples used in this investigation; in contrast to this, the data in table 2.2 are for total ash produced at the two power stations in a raw unclassified or unselected form.

For the investigation into the effect of the use of Lethabo there were slightly different objectives. In this case the fly ash was obtained from Lethabo, and the cement came from three sources close to the PWV.

The cements used in this work are identified by code as the information is derived from a confidential testing programme that was incomplete at time of writing. The client preferred the information on the sources to remain confidential. The physical and chemical properties of these cements and fly ash samples are shown in table 4.3.

The data in tables 4.1, 4.2 and 4.3 show that both the Matla and Lethabo fly ash samples comply with the chemical requirements of SABS 1491: Part II–1989[260], and also meet the fineness requirement of the same specification. Other requirements not evaluated for their compliance with SABS 1491 are the degree of water reduction, the reactivity and the soundness. None of these requirements existed when the original testing of the cementitious materials was done. Both ashes also comply with the

equivalent requirements in ASTM C 618–89[261] for both classes F and C fly ash, and those of BS 3892 : Part 1 : 1982.[262]

All the cements comply with the relevant requirements of SABS 471.[263]

4.3.2 Aggregates

A wide selection of aggregates is available in the PWV area. In choosing the coarse aggregate the following aspects were considered:

- Reef quartzite was rejected on the basis of possible alkali–silica reactivity.
- Granite was rejected on the basis of the effect lenses of relatively soft weathered material might have on the elastic properties of mixes.
- Dolomite and andesite were rejected as they both appear, to a greater or lesser extent, to enhance the compressive strength of mixes by mechanisms which are not fully understood. In the case of dolomite this effect is confined to the sand fraction.
- Dolerite aggregate was eventually selected as there were no known potential "side effects" associated with its use. A 13,2 mm road stone material was selected as it would permit the manufacture of small specimens where necessary. The road stone material was used because of its superior particle shape. The physical characteristics of this material are given in table 4.4.

In considering the selection of the fine aggregate the above list of materials was rejected on the same grounds as for the stone. In the case of the dolerite the particle shape of the sand proved to be too poor to permit reasonable plastic characteristics to be achieved in fresh mixes. The commonly used decomposed granite (river) sands were considered too friable for use where prolonged mixing cycles might be necessary. The sand eventually selected for use was a processed weathered Ecca grit from the Kendal–Balmoral area of the eastern Transvaal. This sand produces "friendly" mixes over a wide range of strengths and has a sound history of use as a standard sand by PCI.

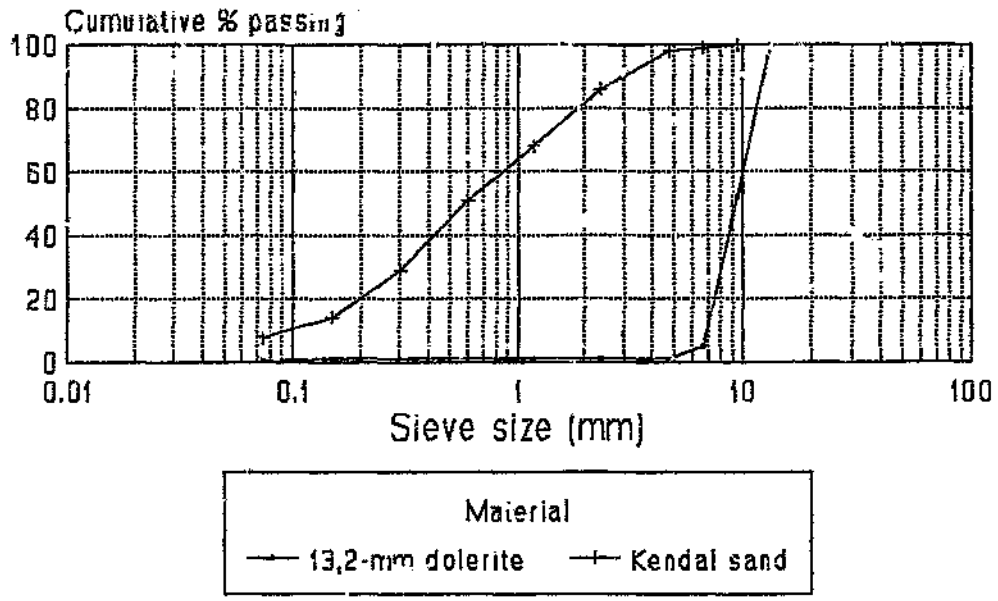
The sand was identified by Professor McIver of the Department of Geology at the University of the Witwatersrand as a medium grained sand strongly dominated by angular to subangular quartz grains accompanied by minor feldspar and characterised by reddish iron oxide staining.

The physical characteristics of this sand are given in table 4.4. The gradings of both aggregates are portrayed in figure 4.1.

Although the sand has a dust content exceeding the upper limit set by SABS 1083: 1976[264] several years of experience of using this sand in laboratory tests has shown this factor not to be deleterious, and in fact the sand allows the production of concretes with very good plastic characteristics.

The grading of the dolerite stone sample complies with the requirements of SABS 1083: 1976.[264] This stone was identified by Professor McIver as an unweathered fine grained dolerite dominated mineralogically by a crystalline assemblage of calcic plagioclase and augitic pyroxene. The grading of this sample is also shown in table 4.3 and in the graph in figure 4.1.

Figure 4.1
Particle size analysis for aggregates in mixes with Matla fly ash



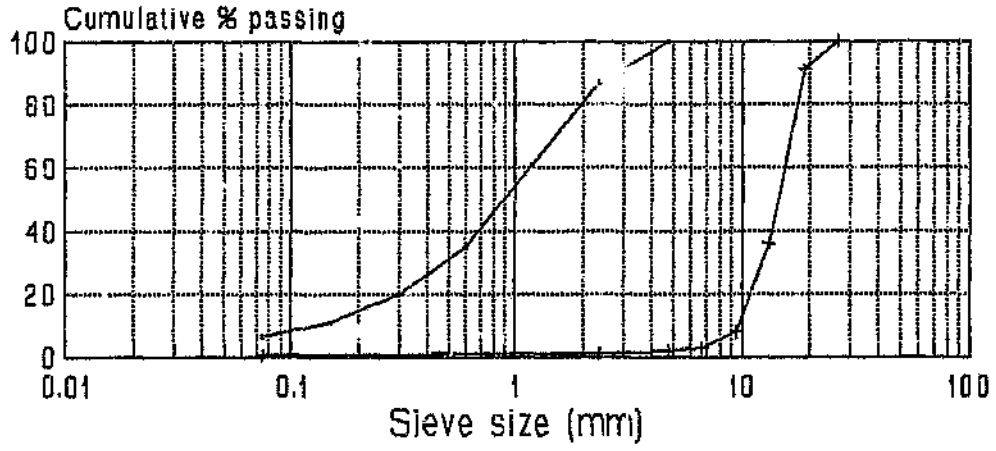
When it came to the selection of the materials for the investigation into the influence that Lethabo fly ash has on the properties of concrete, different objectives were set for the investigation. In this case the aggregates selection was based on the most commonly used combination of aggregates in the Pretoria/Witwatersrand/Vereeniging (PWV) area.

The sand selected for this investigation was a "river" sand from the Jukskei quarry of Messrs. Hippo Quarries. The physical characteristics of this sample are given in table 4.5 and shown graphically in figure 4.2. The grading of the sand, apart from a slightly high dust content, complies with the requirements of SABS 1083: 1976[264] for concrete sand. Professor McIver identified this sample as a decomposed granite sand composed of grains of quartz and granular aggregates of quartz and feldspar showing various degrees of alteration to sericite and kaolin. Biotite is present as a minor phase. Fines include the foregoing together with sericite and kaolin.

The stone used in this case was a sample of 19–mm reef quartzite stone derived from

Cooke Shaft crushers of Blue Circle Materials. The grading of the sample complies with the grading requirements of SABS 1083: 1976[264] for 19–mm stone. The physical properties are detailed in table 4.5 and shown graphically in figure 4.2. Professor McIver identified this sample as a medium grained orthoquartzite dominated by recrystallised detrital quartz grains accompanied by variable lesser quantities of white mica, chlorite, chloritoid and pyrite.

Figure 4.2
Particle size analysis for aggregates in mixes with Lethabo fly ash



4.4 Principles of mix proportioning

The mix proportions used differed depending on the purpose of each test. All mixes used for sample preparation have been summarised at the end of this chapter. For convenience in most cases the details of the actual mixes used have been placed in each chapter where the technical aspects are discussed.

The need, when mixes are proportioned with fly ash as a cement extender, for some modification to be made to the conventional procedures is discussed in section 4.4.1.

The particle size distribution of Matla fly ash is shown in table 4.6 against the same analysis for an ordinary portland cement from PPC Jupiter.[265] It can be seen that the mean particle size for this sample of Matla fly ash is less than half of that of the sample of Jupiter ordinary portland cement.

Figure 4.3 shows the particle size distributions for the two samples graphically.

The particle shape of the two materials is evident in the photomicrographs given in figures 4.4 and 4.8. Figures 4.5, 4.6, 4.7, 4.9, 4.10, 4.11 and 4.12 give similar photomicrographs of other cementitious materials used in this work.

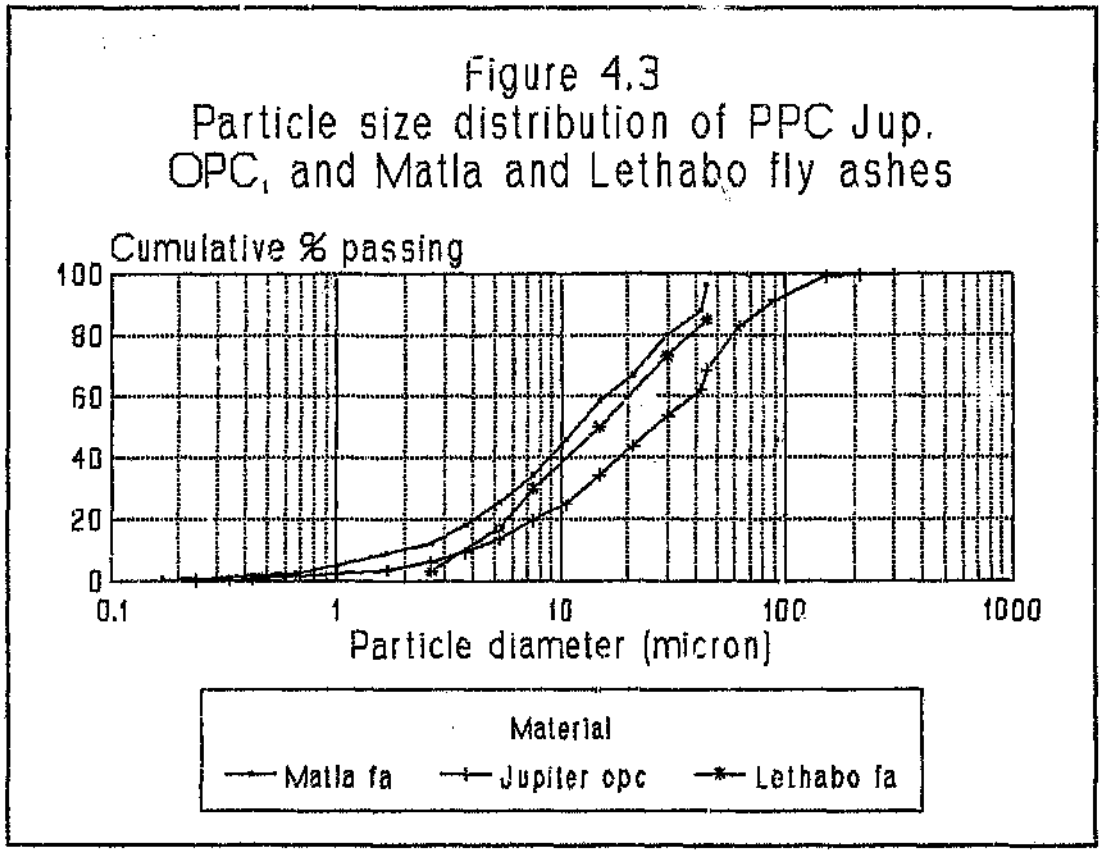


Figure 4.4 shows particles of Matla fly ash while figure 4.5 gives an idea of the shape of fly ash from Duvha power station for comparison. Figures 4.6 to 4.8 respectively show views for the samples of Roodepoort, Lichtenberg and Jupiter ordinary portland cements used in this project. Figure 4.9 shows particles of ggbs from VanderBijlpark and figure 4.10 particles of silica fume from Silicon Smelters in Pietersburg. Figures 4.11 and 4.12 give views of the 15 % interblend and interground cements respectively.

Figure 4.4
Photomicrograph of Matla fly ash

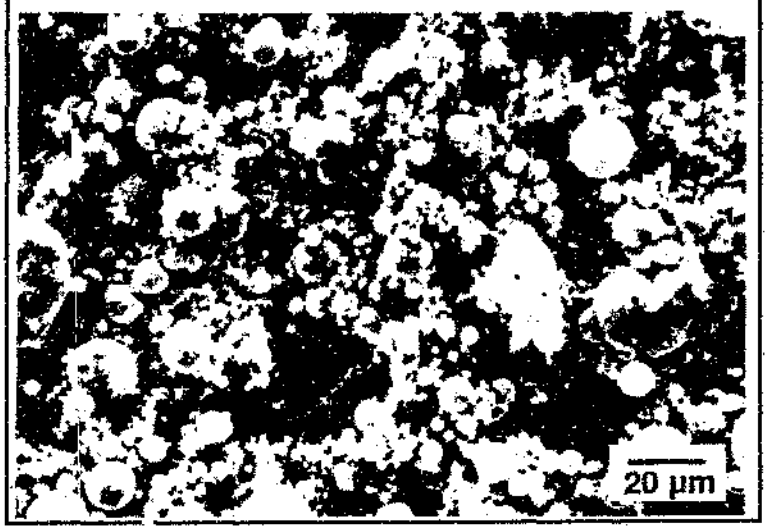


Figure 4.5
Photomicrograph of Duvha fly ash

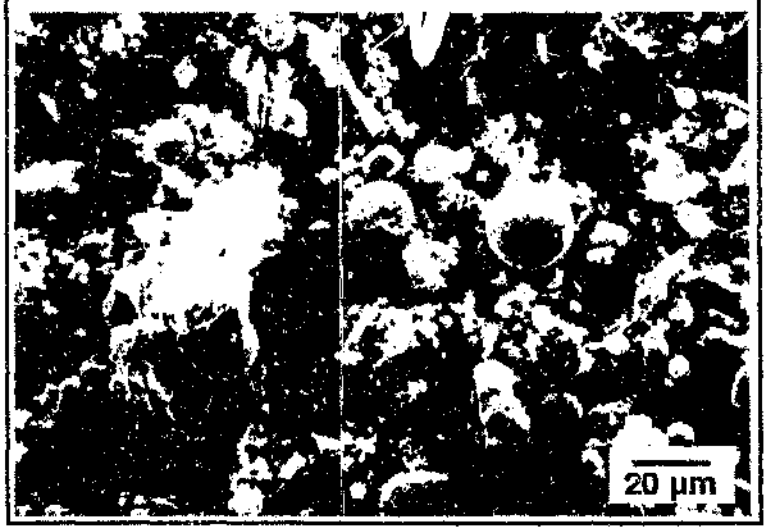


Figure 4.6
Photomicrograph of A–A CPC

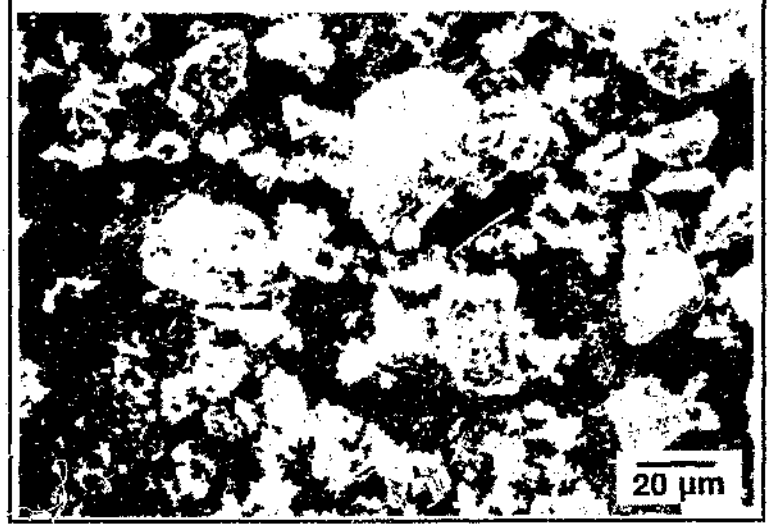


Figure 4.7
Photomicrograph of BC OPC



Figure 4.8
Photomicrograph of PPC OPC



Figure 4.9
Photomicrograph of V d Bijl slag



Figure 4.10
Photomicrograph of silica fume

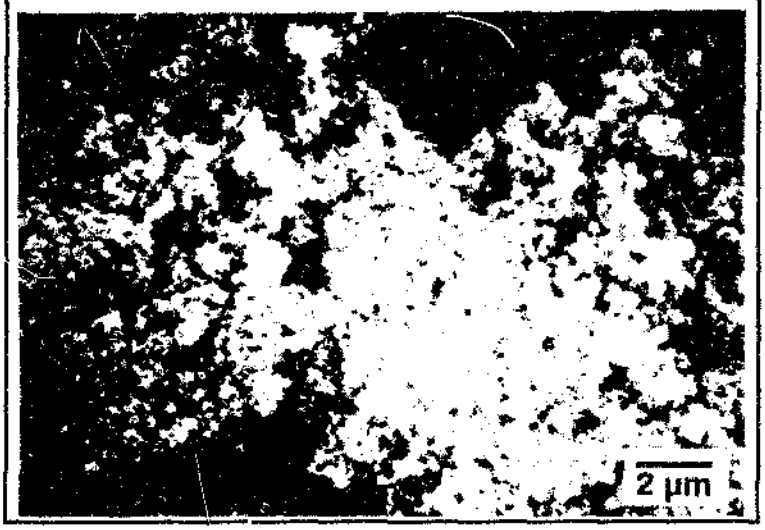


Figure 4.11
Photomicrograph of PPC 15 % blend



Figure 4.12
Photomicrograph of PPC 15 % grind



These photomicrographs were produced on the Scanning Electron Microscope equipment at the University of the Witwatersrand.

It is obvious that most of the fly ash particles are spherical while those of the ordinary portland cement and slag are much more angular. There is also a fairly obvious difference in the degree of sphericity of the fly ash particles from the two sources Matla and Duvha – the fly ash from Duvha shows far more non-spherical debris (possibly mullite) particles than is the case for the fly ash from Matla.

The differences are referred to again when the rheology of fly ash mixes is discussed in chapter 5.

4.4.1 Stone content determination when fly ash is used

One of the properties used in South Africa for the first estimate of the stone content of a concrete mix is the fineness modulus of the fine aggregate. The fineness modulus of the sand is determined as the sum of the cumulative percentages passing sieves from 150 micrometers up to 4,75 mm. (Sieves above this size are also included where relevant but only those in a series of doubling the aperture above 4,75 mm are taken into account in the calculation of the fineness modulus.)

Experienced concrete technologists will however be aware that while the conventional theory is generally applicable it is also true that as the cement content of the mix

increases it becomes possible to increase the stone content without prejudicing the placeability and compactibility of the mix. Much of this extra mix plasticity can probably be ascribed to the increase in total mortar fineness as a result of the fine material introduced by the cement; i.e. the theory used to determine the stone content for trial mix purposes is probably a little simplistic although the errors are small enough not to require revision of current practice.

Because the fly ash is finer than the cement that is being replaced by it, the overall grading of the paste and mortar becomes finer. This can be regarded as being equivalent to an increase in the cementitious content of the mix, irrespective of whether the cementitious/water ratio is increased or not; i.e. the mortar fineness increases and therefore it becomes possible to increase stone content as described above.

D & H Ash Resources have published a bulletin giving details of a proposed mix design method.[266] The proposals made in that paper regarding the modifications that can be made in the stone content of the mix have been shown in this study to be appropriate for the combinations of materials used in the experimental work.

It should be noted that a moderate increase in the stone content of a mix will result in a reduction in the water demand of the mix. This fact has not gone unnoticed by some less scrupulous technologists who have "saved" their clients money by increasing the stone content and therefore reducing the water, and proportionately the cement content of the mix. While this practice may be justified in some cases it can result in a mix being under-sanded and difficult to place and compact.

The increases in stone content of a concrete mix that have been found possible with the introduction of fly ash have been shown generally to be justified. No proof of this statement can be provided as the assessment of the quality of a fresh concrete mix is rather subjective. It is so subjective in fact that on one occasion when each of the technical staff of PCI and some construction industry concrete technologists were asked to design a concrete mix using the same materials and same mix design procedure a range of stone contents was obtained that exceeded 10 % of the mean.[267]

As the proposed magnitude of the increase in stone content of a mix is equal to 3 % for every 15 % of fly ash added it can be seen that the lack of sensitivity of the mix design procedure could mask the apparent validity of the change.

Several very experienced concrete technologists at PCI have however agreed that the principle of modification of the stone content of the mix when fly ash is incorporated is acceptable and justified.

This modification has been applied in some of the work in this study.

4.4.2 Other changes to standard procedure

Aspects of adjustment of cement/water ratio to ensure equivalent 28 day compressive strength that may be necessitated by the introduction of the fly ash will be discussed

in more detail in the chapter on compressive strength.

The use of fly ash also has an impact on the rheology of the mix; this allows other changes to the normal proportioning practices. This is covered in chapter 5.

4.5 Details of mix proportions used from which test specimens have been produced in these investigations

A large number of test specimens was produced during the process of these investigations. The following paragraphs give some details of the mix proportions used for manufacturing the various test specimens used.

4.5.1 Mixes for workability assessment

Chapter 5 deals with the properties of fresh concrete. In the measurement of the effect of fly ash on the workability of concrete (as measured by the slump test) many mixes were made. Table 4.7 gives the details of the mixes made with the materials for the Matla fly ash investigation. Table 4.8 gives information for the Matla fly ash mixes determined for a commercial client of PCI. Table 4.9 gives the mixes used for the Lethabo investigation.

4.5.2 Mixes for measurement of rheology

Chapter 5 also contains a section covering the measurement of the rheology of pastes made with ordinary portland cement and with opc/fly ash blends. The proportions used in these mixes are given in table 4.10.

4.5.3 Mixes for setting time determinations

A number of mortar mixes were made using Matla fly ash and Kendal sand to provide the test specimens for setting time determination covered in chapter 5. Initial work was done to evaluate the influence of making the specimens from a screened concrete specimen or making a mortar with the same mix proportions excluding the stone. Table 4.11 gives the mix proportions used in the OPC and 30 % fly ash mixes. Once the principle of using mortar mixes instead of screened concrete specimens had been established a full series of setting time determinations was carried out using PPC Jupiter opc and selected Matla fly ash. These mixes are detailed in table 4.12. Additional information on the effect of Matla fly ash on setting time was generated from the mixes in table 4.8. Another set of information was available from an investigation done in the PCI laboratories for another client. These mixes, again using Matla fly ash, are detailed in table 4.13.

The mixes made to evaluate the effect of the addition of various anions and cations were made using the mortar proportions given in table 4.11.

Setting time determinations were done at different temperatures with mixes from tables 4.12 and 4.13 and the results are discussed in chapter 5.

Setting time determinations with Lethabo fly ash were done using mixes in table 4.14; these tests were done over a similar range of temperatures.

4.5.4 Tests for bleeding

Mortar mixes were made with Matla fly ash, PPC Jupiter OPC and Kendal sand for bleed determination. The mix details are those given in table 4.12. Additional tests were done on concrete. The mix proportions for these mixes are given in table 4.13.

4.5.5 Mixes for heat of hydration measurement

Chapter 6 covers the work done to time of document preparation on the measurement of the adiabatic heat of hydration in a calorimeter built at the University of the Witwatersrand to an initial concept obtained from Blue Circle in the UK.

The mixes used in two sets of tests are detailed in tables 4.15 and 4.16

4.5.6 Mixes for compressive and flexural strength determination

Substantial numbers of specimens were made for the determination of compressive strength at ages up to 120 days and flexural strengths at age 28 days. The mixes used for the Matla fly ash are detailed in table 4.7 and those for the Lethabo fly ash in table 4.9.

Large blocks were cast to allow an evaluation of the impact "site" curing has on extended mixes. The proportions used for these mixes are given in table 4.17.

The compressive strength under temperature matched curing was determined using specimens made with the proportions in table 4.16.

4.5.7 Determination of elastic modulus

Concrete prisms were made for the determination of the elastic modulus using mix proportions given in table 4.18. These tests were only done with Matla fly ash.

4.5.8 Shrinkage testing

Mortar mixes were made using Matla fly ash to the proportions given in table 4.12 for the preparation of shrinkage specimens. No tests were done on the Lethabo fly ash.

4.5.9 Creep testing

Two series of tests were done at the University of the Witwatersrand to evaluate the effect of fly ash on creep in both exposed and sealed specimens. Both series were made using proportions detailed in table 4.19.

4.5.10 Assessment of permeability

Permeability and the effect that the use of fly ash has on this property was assessed using the mixes detailed in table 4.20 for Matla fly ash. Additional tests were done on cores extracted from the large blocks made with the Matla fly ash mix proportions in table 4.17. The mixes from which water penetration specimens were made for Lethabo fly ash evaluation are detailed in table 4.9.

4.5.11 Abrasion resistance testing

Testing for this property was done using a test method developed by the PCI. The large "site" cured blocks with Matla fly ash were the specimens tested, although cubes made from the same mixes were also cured after standard laboratory curing. The mix proportions used are those in table 4.17. In the case of the Lethabo fly ash mixes these were proportioned to the details in table 4.9

4.5.12 Carbonation testing

The depth of carbonation was assessed on the large blocks made to the proportions given in table 4.17. Additional tests were done on specimens made with Lethabo fly ash to the mix proportions given in table 4.21.

4.5.13 Alkali reactivity testing

The effect that the use of Matla fly ash has on the expansion of mortar prisms due to alkali reactivity was assessed using a rhyolite crusher sand in the standard mix proportions for the test used.

4.5.14 Ternary blends

Mixes with three cementitious materials or ternary blends were assessed in mixes made with Matla fly ash and slag from VanderBijl Park. The mix proportions used are those given in table 4.22.

4.5.15 Effect on admixtures

A single series of mixes was made to evaluate the effect of both Matla and Lethabo fly ash on the efficiency of an admixture. The mix proportions used are given in table 4.23.

4.6 Summary

Details of all the mixes used in the tests described in later chapters of this work have been set out at the end of this chapter. For convenience, some of these tables have been repeated in the relevant chapter. For proportions which are not provided in the different chapters reference should be made to chapter 4.

Table 4.1

Physical properties of cementitious materials used in laboratory investigations.
Results of standard SABS tests.

Sample source	OPC ex Anglo-Alpha	OPC ex Blue Circle	OPC ex PPC	PC5FA ex PPC (mixed)	PC15FA ex PPC (mixed)	PC5FA ex PPC (ground)	PC15FA ex PPC(ground)	MATLA Fly ash	LETHABO Fly ash
Parameter									
Specific Surface (m^2/kg)	2880	3270	2910	3080	3100	3080	3090		
Standard Consistency (%)	26,25	26,25	25,50	24,75	23,75	24,00	23,75		
Initial Set (min)	190	210	250	255	300	220	325		
Final Set (min)	215	250	295	305	350	285	385		
Residue (%) on 45 micron								6,4	6,1
90 micron	1,2	1,9	2,0	2,6	2,4	1,5	1,0	1,5	0,6
210 micron	0,0	0,0	0,2	0,1	0,2	0,1	0,0		
Le Chatelier exp. (mm)	0	1	1	2	2	1	1		
VMC cubes(MPa) 1 day	13,8	14,2	13,6	13,0	10,8	14,4	10,8		
3 day	28,8	31,1	31,0	29,6	27,4	30,9	28,1		
7 day	37,9	43,3	37,9	36,8	34,8	39,1	36,1		
28 day	52,6	58,3	47,9	45,9	44,8	46,8	44,8		

Acknowledgements to TSO of PPC for all this information
Acknowledgement to Blue Circle Limited for the information on Lethabo week 13/91 sample representing typical Lethabo values

Table 4.2

Chemical characteristics of cementitious materials used in this investigation

Sample source	OPC ex Anglo-Alpha	OPC ex Blue Circle	OPC ex PPC	PC5FA ex PPC (mixed)	PC15FA ex PPC (mixed)	PC5FA ex PPC (ground)	PC15FA ex PPC (ground)	MATLA Fly ash	LETHABO Fly ash
Parameter (%)									
SiO_2	22,50	22,50	21,40	22,46	24,90	22,50	25,10	38,20	53,2
Al_2O_3	4,18	3,54	3,90	4,98	7,06	4,81	6,60	28,30	32,4
Fe_2O_3	3,00	3,40	3,33	3,39	3,52	3,71	3,81	5,24	3,6
Mn_2O_3	0,14	0,22	0,93	0,90	0,89	0,91	0,82	0,08	–
TiO_2	0,24	0,46	0,43	0,47	0,60	0,46	0,59	1,70	1,95
CaO	64,30	63,85	62,50	60,40	55,60	60,50	55,60	14,40	4,98
MgO	1,80	2,10	4,14	4,11	4,10	4,00	3,86	3,95	1,20
P_2O_5	–	–	–	0,06	0,22	0,06	0,20	1,70	0,60
SO_3	1,61	1,75	1,80	1,76	1,72	1,79	1,72	1,30	0,17
K_2O	0,47	0,16	0,65	0,64	0,59	0,68	0,70	0,78	0,55
Na_2O	0,06	0,07	0,06	0,08	0,09	0,10	0,13	0,50	0,30
Eq. Na_2O	0,37	0,18	0,49	0,50	0,48	0,55	0,59	1,01	0,66
LOI	1,90	1,90	0,74	0,77	0,89	0,82	0,92	2,90	0,23
C_3S (%) *	53,7	55,2	55,6	31,8		32,5			
C_2S (%) *	24,1	22,9	19,5	40,5		40,1			
C_3A (%) *	6,0	3,6	4,7	7,5		6,5			
C_4AF (%) *	9,1	10,3	10,1	10,3		11,3			

* VALUES FROM BOGUE FORMULAE[258]

Table 4.3

Physical and chemical properties of cements used in the investigation into the influence of Lethabo fly ash

Property	Cement source			
	OPC A	OPC B	OPC C	Lethabo fly ash
Chemical (%)				
SiO_2	21,6	22,2	22,1	52,8
Al_2O_3	4,1	4,16	3,9	31,3
Fe_2O_3	2,0	2,81	2,8	3,22
CaO	64,3	64,2	64,8	4,41
MgO	4,3	2,41	1,8	1,2
K_2O	0,67	0,16	0,3	0,45
Na_2O	0,12	–	0,1	0,30
SO_3	2,1	1,74	1,3	0,18
Mn_2O_3	1,1	0,22	–	–
LOI	–	1,44	1,2	0,39
Free CaO	1,8	0,4	0,6	–
Bogue[250] values (%)				
C_3S	61,1	55,8	61,9	–
C_2S	15,9	21,6	16,8	–
C_3A	7,5	6,3	5,6	–
C_4AF	6,1	8,5	6,5	–
Physical				
Surface area Blaine (m^2/kg)	301	329	298	–
VMC strength (MPa)				
1d	14,7	–	11,0	–
3d	25,2	28,7	26,5	–
7d	38,5	40,2	42,0	–
28d	51,9	59,3	–	–

Table 4.4

Physical characteristics of aggregates used in the Matla fly ash mixes

Sample description	13,2 mm dolerite	Kendal sand
Relative Density	3,00	2,65
Loose Bulk Density (kg/m^3)	1550	1510
Compacted Bulk Density (kg/m^3)	1760	1715
Sieve size (mm)	Cumulative % passing	
19,000		
13,200	100	
9,500	52	100
6,700	5	99
4,750	1	98
2,360	1	88
1,160	1	69
0,600	1	51
0,300	1	29
0,150	1	14
0,075	0,5	7,9
Fineness Modulus	6,44	2,54

Table 4.5

Physical characteristics of aggregates used in the evaluation of the effect of Lethabo fly ash

Sample description	"River" sand	19–mm quartzite
Relative Density	2,60	2,69
Loose Bulk Density (kg/m^3)	1390	1480
Compacted Bulk Density (kg/m^3)	1570	1570
Sieve size (mm)	Cumulative % passing	
26,500		100
19,000		91
13,200		36
9,500		8
6,700		3
4,750	100	2
2,360	87	1
1,180	61	
0,600	35	
0,300	20	
0,150	11	
0,075	6,5	0,7
Fineness Modulus	2,86	

Table 4.6
Particle size distributions of Matla fly ash and Jupiter OPC

Sample description	Matla fly ash	Lethabo fly ash*	Jupiter opc
Particle size (micron)	Cumulative % passing		
300,00			99,52
212,00			99,45
150,00			99,05
90,00			91,51
63,00			83,06
45,00	96,10	85	68,57
42,21	87,60		62,19
29,85	79,98	73	53,61
21,10	67,10		43,47
14,92	58,52	50	34,33
10,55	46,08		24,94
7,46	34,34	30	19,40
5,27	25,40	17	13,81
3,73	17,87		9,14
2,63	11,91	3	6,16
1,69	8,85		3,30
1,01	4,99		2,18
0,66	2,37		1,24
0,43	1,84		0,50
0,34	1,14		0,19
0,24	0,61		0,06
0,17	0,35		-
Median size (microns)	12,5	13,5	27,4
Mean size (microns)	16,5	23,7	38,30

Note: The tests on the opc and the Matla fly ash were conducted on a Leeds and Northrop Small Particle Analyser by the Technical Services Division of PPC, The tests on the Lethabo fly ash were performed on a Galai Laser Particle Size Analyser also by the Technical Services Division of PPC

* Indicates an interpolated value as the method of reporting differed for the two different apparatus,

Table 4.7
Mix proportions of concrete mixes (kg/m^3) using Matla fly ash

% Fly ash	Materials	c/w 1,0	c/w 1,5	c/w 2,0	c/w 2,5
0	Water	209	205	203	207
	Cement	209	308	406	518
	Fly ash	–	–	–	–
	Stone	1065	1090	1110	1129
	Sand	979	884	789	675
5	Water	206	201	199	203
	Cement	196	286	378	482
	Fly ash	10	15	20	25
	Stone	1070	1095	1115	1125
	Sand	982	892	797	684
10	Water	203	198	196	199
	Cement	183	267	353	448
	Fly ash	20	30	39	50
	Stone	1075	1100	1120	1130
	Sand	986	895	800	691
15	Water	200	194	193	194
	Cement	170	247	328	412
	Fly ash	30	44	58	73
	Stone	1085	1110	1130	1140
	Sand	985	898	800	701
30	Water	193	188	185	183
	Cement	135	197	259	329
	Fly ash	58	85	111	141
	Stone	1110	1130	1150	1160
	Sand	980	894	803	694
50	Water	186	179	176	179
	Cement	93	134	176	224
	Fly ash	93	134	176	224
	Stone	1135	1160	1180	1190
	Sand	973	890	798	688

Note: Fly ash ex Matla; Sand, grit ex Kendal; Stone, dolerite ex Rooikraal

Note: c/w above refers to total cementitious material to water ratio.

Table 4.8

Mix proportions used in mortar mixes (kg/m^3) using Matla fly ash
Additional data from commercial work at PCI

% fly ash	Cement source	c/w ratio	water	cement	fly ash	Kendal sand
0	PPC Slurry	1,90	290	551	–	1416
	BC Licht	1,82	290	528	–	1436
	A–A Ulco	1,82	295	537	–	1415
15	PPC Slurry	2,00	279,5	475	84	1414
	BC Licht	1,80	278	425	75	1470
	A–A Ulco	1,80	284	435	77	1444
30	PPC Slurry	2,13	266,5	397	170	1416
	BC Licht	1,93	267	361	155	1464
	A–A Ulco	1,93	280	378	162	1406

Table 4.9

Mix proportions (kg/m^3) used in the assessment of workability with Lethabo fly ash using 19–mm quartzite stone and "river" sand with 3 different OPCs.

Material	OPC A			OPC B			OPC C		
0 % fa	C/W 1,7	C/W 1,9	C/W 2,1	C/W 1,7	C/W 1,9	C/W 2,1	C/W 1,7	C/W 1,9	C/W 2,1
water	205	204	205	204	203	204	209	209	212
OPC	349	388	431	347	386	428	355	397	445
fa	–	–	–	–	–	–	–	–	–
stone	1121	1121	1121	1121	1121	1121	1121	1121	1121
sand	695	665	627	699	669	631	679	644	597
15 % fa	C/W 1,8	C/W 2,0	C/W 2,2	C/W 1,8	C/W 2,0	C/W 2,2	C/W 1,8	C/W 2,0	C/W 2,2
water	200	200	200	196	193	195	205	200	202
OPC	306	340	374	300	328	365	314	340	378
fa	54	60	66	53	58	64	55	60	67
stone	1121	1121	1121	1121	1121	1121	1121	1121	1121
sand	697	661	626	714	692	649	675	661	616
22,5 % fa	C/W 1,9	C/W 2,1	C/W 2,3	C/W 1,9	C/W 2,1	C/W 2,3	C/W 1,9	C/W 2,1	C/W 2,3
water	197	197	200	192	195	192	197	197	197
OPC	290	321	356	283	317	342	290	321	351
fa	84	93	104	82	92	99	84	93	102
stone	1121	1121	1121	1121	1121	1121	1121	1121	1121
sand	684	648	598	706	657	636	684	648	612
30 % fa	C/W 2,0	C/W 2,2	C/W 2,4	C/W 2,0	C/W 2,2	C/W 2,4	C/W 2,0	C/W 2,2	C/W 2,4
water	195	195	195	194	190	187	190	188	188
OPC	273	300	328	272	293	314	266	290	316
fa	117	129	140	116	125	135	114	124	135
stone	1121	1121	1121	1121	1121	1121	1121	1121	1121
sand	667	630	594	671	654	633	689	663	628

Table 4.10

Quantities of materials used for paste mixes (gram) for viscometer tests.

Material	c/w	OPC	Fly ash	Slag	CSF	Water
Pure cement	1,30	505,6	–	–	–	389,0
	1,67	599,6	–	–	–	359,0
PC 5 FA	1,30	477,8	25,1	–	–	386,9
	1,67	566,0	29,8	–	–	356,8
PC 15 FA	1,30	423,0	74,6	–	–	382,8
	1,67	500,1	88,3	–	–	352,3
PC 50 FA	1,30	240,0	240,0	–	–	369,2
	1,67	281,9	281,9	–	–	337,6
PC 50 SL	1,30	250,9	–	250,9	–	385,9
	1,67	297,0	–	297,0	–	355,7
PC 5 CSF	1,30	477,4	–	–	25,1	386,5
	1,67	565,4	–	–	29,8	356,4
Fly ash	1,30	–	456,8	–	–	351,4
	1,67	–	532,2	–	–	318,6
Slag	1,30	–	–	497,8	–	382,9
	1,67	–	–	588,6	–	352,5

Note: Fly ash used in these mixes was selected fly ash ex Matla. Various ordinary portland cements were used; details of the sources of all materials used are given in table 5,3a, Mixes were identical for all ordinary portland cements used.

Table 4.11

Mix proportions (kg/m^3) used to evaluate the difference between setting times of mortar samples screened from concrete or mortar mixes. (Matla classified fly ash and PPC Jupiter opc)

Material	OPC concrete	OPC mortar	PC 30 FA concrete	PC 30 FA mortar
water	205	205	189	189
OPC	390	390	251	251
fly ash	–	–	108	108
19–mm quartzite	1100	–	1145	–
Kendal sand	694	694	688	688

Table 4.12
Mortar mix proportions for preparation of specimens for setting time determinations (PPC Jupiter opc, Matla selected fly ash)(kg/m^3)

% fly ash	Materials	c/w 1.0	c/w 1,5	c/w 2,0	c/w 2,5
0	Water	310	305	308	320
	opc	310	458	616	800
	fly ash	0	0	0	0
	sand	1567	1455	1314	1127
5	Water	305	302	303	314
	opc	290	430	576	746
	fly ash	15	23	30	39
	sand	1581	1462	1328	1146
10	Water	301	298	299	308
	opc	271	402	538	693
	fly ash	30	45	60	77
	sand	1501	1472	1338	1164
15	Water	296	293	294	302
	opc	252	374	500	642
	fly ash	44	66	88	113
	sand	1604	1485	1352	1183
30	Water	291	286	285	296
	opc	204	300	399	518
	fly ash	87	129	171	222
	sand	1611	1497	1369	1184
50	Water	284	276	275	286
	opc	142	207	275	358
	fly ash	142	207	275	358
	sand	1621	1515	1386	1196

Table 4.14

Mortar mix proportions (kg/m^3) for setting time determinations using Lethabo fly ash

MIX	A	B	C	D	E	F	G	O
CEMENT	A	A	A	A	A	A	A	A
TYPE	OPC	PC15FA	PC22.5FA	PC30FA	PC15FA	PC22.5FA	PC30FA	OPC
DESIGN		EQ 28	EQ 28	EQ 28	DR	DR	DR	
C:W RATIO	1,75	1,87	1,99	2,1	1,75	1,75	1,75	1,9
WATER CONTENT	289	284	278	269	286	245	269	283
CEMENT CONTENT	505	532	554	565	500	429	471	538
SAND CONTENT	1432	1399	1383	1385	1423	1579	1470	1419
SLUMP (mm)	70	80	90	80	70	70	65	70
MIX	H	I	J	K	L	M	N	P
CEMENT	B	B	B	B	B	B	B	B
TYPE	OPC	PC15FA	PC22.5FA	PC30FA	PC15FA	PC22.5FA	PC30FA	OPC
DESIGN		EQ 28	EQ 28	EQ 28	DR	DR	DR	
C:W RATIO	1,67	1,82	1,93	2,06	1,67	1,67	1,67	1,9
WATER CONTENT	287	275	274	280	277	276	272	267
CEMENT CONTENT	479	501	529	576	462	461	455	508
SAND CONTENT	1457	1443	1416	1347	1479	1472	1477	1485
SLUMP (mm)	60	55	55	65	60	70	65	70
MIX	R	S	T		V	W	X	Q
CEMENT	C	C	C	C	C	C	C	C
TYPE	OPC	PC15FA	PC22.5FA	PC30FA	PC15FA	PC22.5FA	PC30FA	OPC
DESIGN		EQ 28	EQ 28	EQ 28	DR	DR	DR	
C:W RATIO	1,7	1,88	2,04	2,21	1,7	1,7	1,7	1,9
WATER CONTENT	285	281	265	274	290	285	281	297
CEMENT CONTENT	485	529	541	606	493	484	478	565
SAND CONTENT	1457	1409	1429	1334	1417	1428	1434	1360
SLUMP (mm)	40	70	50	70	60	75	75	50

Table 4.15
Mix proportions for OPC and PC30FA mixes per m^3 of concrete used in test method trials for adiabatic calorimeter (Matla fly ash)

Material		Mix No. A	Mix No. B
OPC	(kg)	308	197
Fly ash	(kg)	–	85
Sand	(kg)	884	894
Stone	(kg)	1090	1130
Water	(l)	205	188
c/w ratio		1,5	1,5
f/(c+f)	(%)	0.0	30,1
Starting temperature	(°C)	23,5	24,0

Table 4.16

Mix proportions for OPC and PC30FA mixes per m^3 of concrete used for measurement of adiabatic heat of hydration (Matla fly ash)

Material		Mix No. 1	Mix No. 2	Mix No. 3
OPC	(kg)	308	220	226
Fly ash	(kg)	–	94	97
Sand	(kg)	885	865	963
Stone	(kg)	1090	1136	1000
Water	(l)	205	185	190
c/w ratio		1,5	1,7	1,7
f/(c+f)	(%)	0,0	29,9	30,0
Starting temperature	(°C)	25,9	23,0	27,1

Note: Materials used in the manufacture of these concretes are as follows:

OPC ex PPC Jupiter,
fly ash ex Matla,
Kendal sand,
13,2 mm dolerite stone.

Table 4.17

Mix proportions for concrete used in large blocks for evaluation of curing effects with extenders (quantities in kg/m^3)

Material	OPC mix	PC15FA mix	PC30FA mix	PC50SL mix
Cement	350	296	250	175
Fly ash	–	54	111	–
Slag	–	–	–	175
Granite Crusher sand	422	422	413	419
Kendal sand	422	422	413	419
19 mm Granite Stone	1050	1063	1072	1050
Water	210	201	194	208
C/W ratio	1,67	1,77	1,88	1,77
Slump (mm)	150	160	140	150

Table 4.18

Mix proportions of concrete mixes (kg/m³) for elastic modulus tests (Matla fly ash)

Materials	% Fly ash	c/w 1,0	c/w 1,5	c/w 2,0	c/w 2,5	% Fly ash	c/w 1,0	c/w 1,5	c/w 2,0	c/w 2,5
Water	0	209	205	203	207	15	200	194	193	194
Cement		209	308	406	518		170	247	328	412
Fly ash		–	–	–	–		30	44	58	73
Stone		1065	1090	1110	1120		1085	1110	1130	1140
Sand		979	884	789	675		985	898	800	701
Water	5	206	201	199	203	30	193	188	185	188
Cement		196	286	378	482		135	197	259	329
Fly ash		10	15	20	25		58	85	111	141
Stone		1070	1095	1115	1125		1110	1130	1150	1160
Sand		982	892	797	684		980	894	803	694
Water	10	203	198	196	199	50	186	179	176	179
Cement		183	267	353	448		93	134	176	224
Fly ash		20	30	39	50		93	134	176	224
Stone		1075	1100	1120	1130		1135	1160	1180	1190
Sand		986	895	800	691		973	890	798	688

Table 4.19

Concrete mix proportions used in creep specimens (kg/m^3) (Matla fly ash)

Mix No.	Cement source	Stone size (mm)	Fly ash (%)	c/w ratio	Water (l)	OPC (kg)	Fly ash (kg)	13 mm stone (kg)	19 mm stone (kg)	Sand (kg)
1	PPC Jup	13,2	0	1,5	205	308	0	1090	0	884
2	PPC Jup	19	0	1,5	195	294	0	236	944	843
3	BC Licht	13,2	0	1,3	207	269	0	1080	0	921
4	PPC Jup	13,2	15	1,6	197	268	47	1100	0	878
5	BC Licht	13,2	15	1,4	198	236	42	1090	0	868
6	PPC Jup	13,2	30	1,7	189	225	96	1115	0	917

Table 4.20

Mix proportions for concrete mixes used for DIN water penetration tests. PPC Jupiter OPC and Matla fly ash used. Quantities given in kg/m^3.

OPC mixes				
Materials	cement/water ratio			
	1,40	1,60	1,80	2,00
water	212	210	208	210
OPC	297	336	375	420
fly ash	–	–	–	–
13,2–mm stone	970	980	990	1000
granite sand	982	945	908	856
PC 15 FA mixes				
Materials	cement/water ratio			
	1,49	1,70	1,90	2,11
water	204	201	199	200
OPC	258	290	321	359
fly ash	46	51	57	63
13,2–mm stone	981	993	1005	1017
granite sand	973	938	900	848
PC 30 FA mixes				
Materials	cement/water ratio			
	1,58	1,81	2,04	2,26
water	197	194	192	193
OPC	218	246	274	305
fly ash	93	105	118	131
13,2–mm stone	993	1007	1020	1035
granite sand	962	920	876	819

Table 4.21

Mix proportions (kg/m^3) for mixes for carbonation investigation

Mix details	OPC Mix 1 (kg/m^3)	PC30FA Mix 2 (kg/m^3)
C/W ratio	1,7	1,95
OPC (PPC Jup)	340	259
FA (Lethabo)	–	111
19 mm granite	971	971
Crusher sand	874	843
Water	200	190
Slump (mm)	65	110

Table 4.22

Mix proportions (in kg/m^3) used to evaluate the effect of using a ternary blend of OPC, slag and fly ash on compressive strength development of concrete.

Material	Units	Mix no. 1	Mix no. 2	Mix no. 3	Mix no. 4	Mix no. 5
c/w ratio		1,7	1,8	1,8	1,9	1,9
Cement	(kg)	366	194	161	136	273
Slag	(kg)	–	194	161	136	–
Fly ash	(kg)	–	–	57	117	117
Sand	(kg)	765	733	740	729	739
Stone	(kg)	1007	1007	1007	1007	1007
Water	(l)	215	215	210	205	205
100xs/c+s+f	(%)	0	50	43	35	0
100xf/c+s+f	(%)	0	0	15	30	30
Slump (mm)		55	60	60	65	70

Note: Matla fly ash and slag ex Slagment VanderBijl Park were used together with PPC Jupiter opc.

Table 4.23

Mix proportions (in kg/m^3) used to evaluate the influence of two sources of fly ash on the effectiveness of an admixture regarding the compressive strength development of concrete

Material	Mix No.1	Mix No.2	Mix No.3	Mix No.4	Mix No.5	Mix No.6
(c+f)/w	1,70	1,70	1,85	1,85	1,85	1,85
Cement	374,0	349,0	259,0	252,5	259,0	252,5
Fly ash M	–	–	111,0	108,2	–	–
Fly ash L	–	–	–	–	111,0	108,2
Sand	744,9	806,0	740,7	762,5	740,7	762,5
Stone	1007,4	1007,4	1036,6	1036,6	1036,6	1036,6
Water	220,0	205,0	200,0	195,0	200,0	195,0	
Admixture (l/m^3)	–	1047,0	–	1082,1	–	1082,1
100x	0,0	0,0	30,0	30,0	30,0	30,0
Slump (mm)	65	65	60	65	60	70

Note: Fly ash M sourced from Matla; L was sourced from Lethabo.
MCC Multiflow 606N admixture dosed at 300 ml/100 kg cementitious material content of mix.

CHAPTER 5

5. PLASTIC PROPERTIES: RHEOLOGY, SETTING TIME, BLEEDING

5.1 Introduction

The characteristics of concrete or mortar in the plastic or mouldable state are very important for the placing and compaction of the material on site. This is one of the places where the element of experience is relied on in producing the final product and changes in the behaviour of the material may result in the need for some modification of work practices. Frequently, as a result of the relatively poor training that many workers receive and the fact that the problems are probably initially ascribed to worker errors, these modifications may only be made after the occurrence of one or more "failures" of the material. There is a perceived need for a better understanding of these plastic properties and the influence that fly ash might have.

The following paragraphs should help to throw some light on the effects that South African fly ash has on the plastic properties of concrete or mortar.

5.2 Rheology

As stated before in chapter 3 rheology is the science of the flow of materials.[74]

In this study work has been done on two methods of assessing this characteristic, namely the measurement of workability using the rather crude but widely used slump test, and the measure of fluid viscosity by means of a coaxial cylinders viscometer.

5.2.1 Workability assessment by slump test

The improvement of the level of workability in a concrete mix, as shown by the change in the values recorded by the slump test, is noted (see paragraph 3.3.1) as being one of the major indicators of fly ash quality and suitability for use in concrete. As mentioned before the slump test is a rather crude and insensitive test. When fly ash is used in a mix the slump value is often found to have increased relative to the slump of the mix without the ash. However there are other, more subtle, changes in the degree of compactibility and placeability of a mix that the slump test does not reveal; these changes can be observed, when a fly ash mix is placed and compacted, in the ease of compaction, but they are not easy to measure. These other changes do contribute to the quality of the finish but again the changes tend to be subjective due to a lack of suitable methods of measurement.

5.2.1.1 Matla fly ash; effect on workability

Table 5.1a gives the concrete mix proportions used in this test programme. The mixes given in this table are all intended to give the same slump of 75 mm. In the mixes made in the laboratory however the actual slump recorded was not always as intended. Table 5.1b gives the slump recorded in the laboratory work. Note that, in

accordance with normal PCI practice using skilled personnel under supervision, only one slump measurement was made per test.

The water reduction has been determined as the change in the amount of water required for a similar slump from the fly ash mixes when compared against the water content of the control ordinary portland cement mix. The slump values of table 5.1b therefore needed to be "corrected" to the same level; this level was selected as 75mm slump. This was done by taking slump values between 60 mm and 90 mm as being 75 mm slump. Slumps from 45 mm to 60 mm were adjusted up by 5 litres/m^3 and between 30 mm and 45 mm by 10 litres/m^3.

This adjustment is based on the rule of thumb found by experience at PCI that an increase of 10 litres/m^3 will generally double the slump of concrete.

The differences between the water contents of the control mixes and the various fly ash mixes are given in table 5.1c in litres per cubic meter of concrete. Much of the published information on the extent of the water reduction achieved on using fly ash expresses the water reduction in percentage; as the materials used in this study represent only a small proportion of the full spectrum available it is felt that it would be inappropriate to use percentages as the results obtained cannot be claimed to cover the full range of water demands. Nevertheless some indication will be given of the order of magnitude of the percentage water reduction in later paragraphs.

Data obtained from commercial studies done in the laboratories of the Portland Cement Institute have been included to give a wider scope of materials. These additional data are given in table 5.1d.

The data from table 5.1c is presented graphically in figures 5.1a to 5.1c for the cement from Blue Circle Limited, Anglo–Alpha Limited and PPC Limited respectively. The curves shown on these graphs are best fit straight lines. Figure 5.1d gives curves taking all the data from both tables 5.1c and 5.1d into account and provides a best fit line for all combinations.

There are differences between the best fit straight lines for the different cement/water ratios of the mixes tested and the different cements used in this work as can be seen in figures 5.1a, 5.1b and 5.1c. However there does not seem to be a definite trend of water reduction against a change in cement water ratio, as the position and slope of the different cement/water ratio lines is different for the cements from different sources. It is possible that the relatively poor accuracy of the slump test is partially responsible for the lack of a definite trend here.

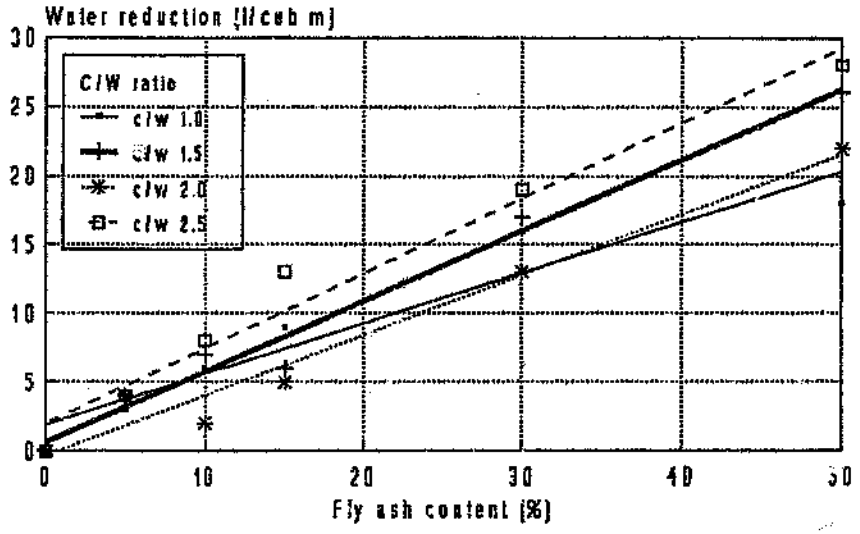
From a linear regression calculation for a on all the data given in tables 5.1c and 5.1d it would appear that the water reduction that can be expected will be of the order of:

Water reduction (l/m^3) = 0,55 x fly ash content(%)

Bearing in mind the previously expressed reservation about percentage reduction in water this equation could also be expressed as:

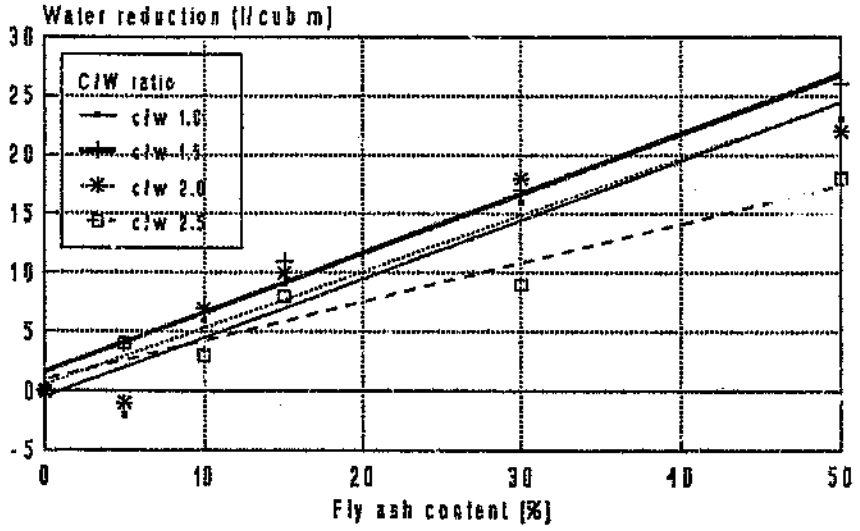
Water reduction (%) ≈ 0,27 x fly ash content (%)

Figure 5.1a
Water Reduction vs FA content
Blue Circle cement



1

Figure 5.1b
Water Reduction vs FA content
Anglo Alpha cement



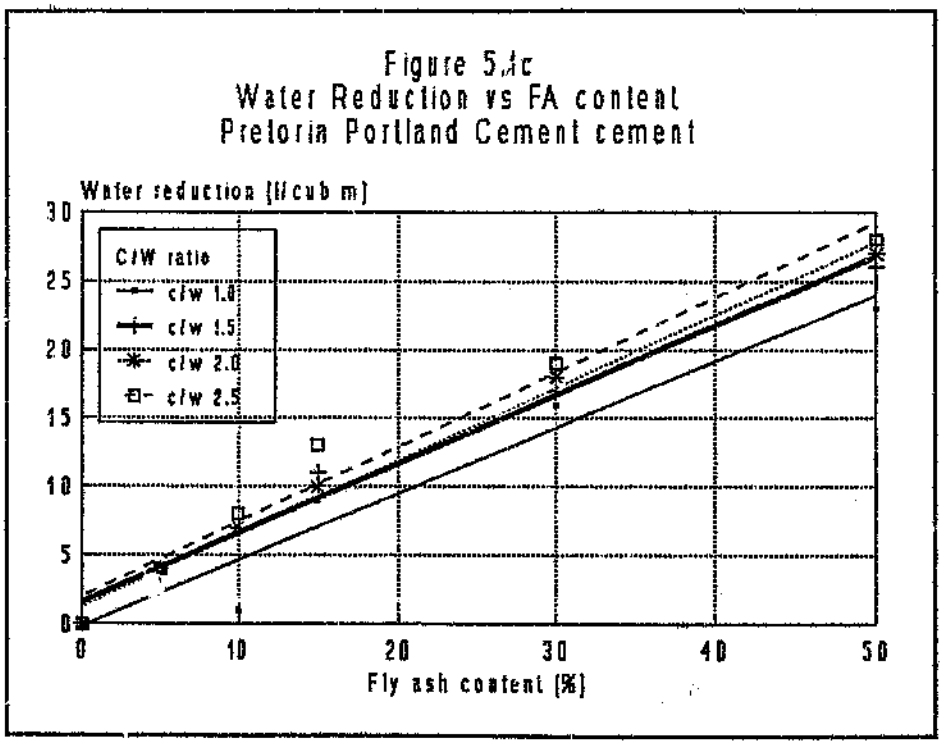
For this particular set of combinations of materials and conditions the correlation coefficient for the linear regression for the water reduction against fly ash content is 0.89. Other correlations (power, logarithmic and exponential) were evaluated but the linear regression proved to give the best fit. This straight line is shown as the best fit line on figure 5.1d.

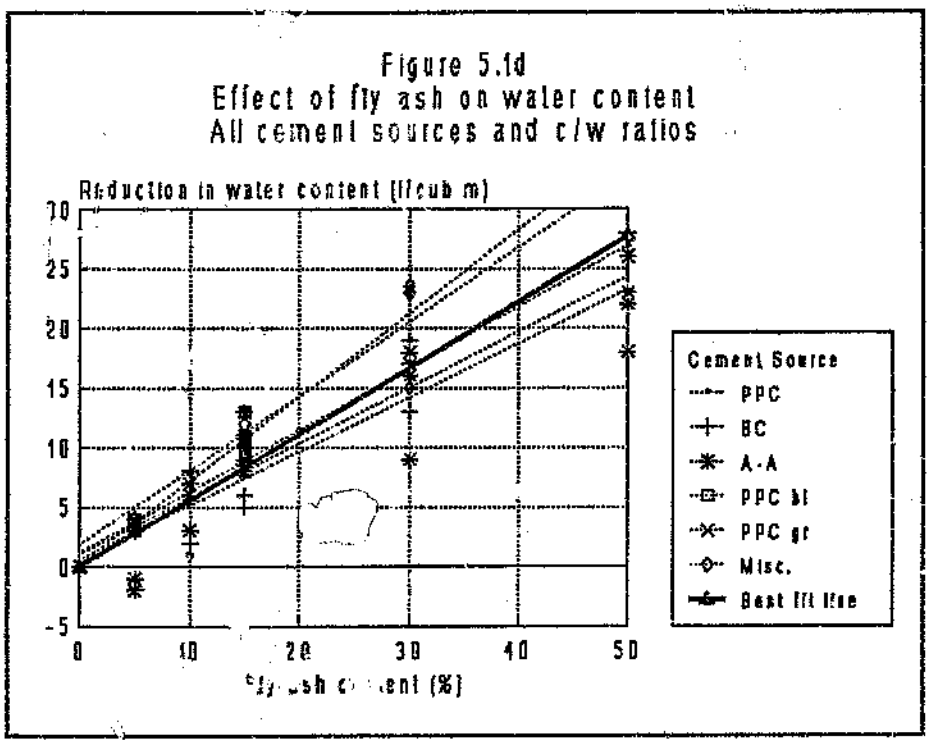
This will however only serve as a first approximation as it can be seen from figure 5.1d that there are differences in the water reductions that occur on using Matla fly ash with the cements from different sources.

In these results it can be seen that the best reductions are offered by the interground or blended cements produced by PPC for this test programme. Both of these cements gave the same values for water reduction in each case and the lines are therefore identical. Next best is the cement from PPC with those from Anglo–Alpha and Blue Circle giving rather lower but similar water reductions.

There is no obvious link between the original "water demand" of the cement used and the magnitude of the water reduction as can be seen from the slump values in table 5.1b, where it is evident that the PPC cement generally has a higher "water demand" than the Blue Circle cement, but lower than the Anglo–Alpha cement.

This is likely to mean that unless the technologist who is designing the fly ash mix knows what particular combination of cement and fly ash is to be used he will be required to do a trial mix to evaluate the actual water reduction that occurs.





5.2.1.2 Lethabo fly ash; effect on workability

Similar studies were subsequently done when Lethabo classified ash became available for testing purposes. Tables 5.1e and 5.1f give the results of water content tests done with samples of ordinary portland cement from 3 sources identified as A, B and C as the client for whom the commercial work was done preferred the information regarding the sources to remain confidential. A linear regression analysis done with the data from table 5.1f gives a slightly different coefficient for the slope of the water reduction line. In this case the water reduction can be expressed as follows:

Water reduction (l/m^3) = 0,59 x fly ash content(%)

This indicates that the Lethabo fly ash has marginally superior water reducing properties to those of the Matla fly ash. However, far fewer data are available for this regression calculation than was the case with Matla fly ash; for this reason no graphs have been drawn for these data. The reliability of this constant is therefore not as good as that for the Matla fly ash even though the correlation coefficient is better at 0,95. It is therefore safer to assume the same value of 0.55 until further data confirms that the Lethabo fly ash is in fact a more effective water reducing material than is the case with Matla fly ash.

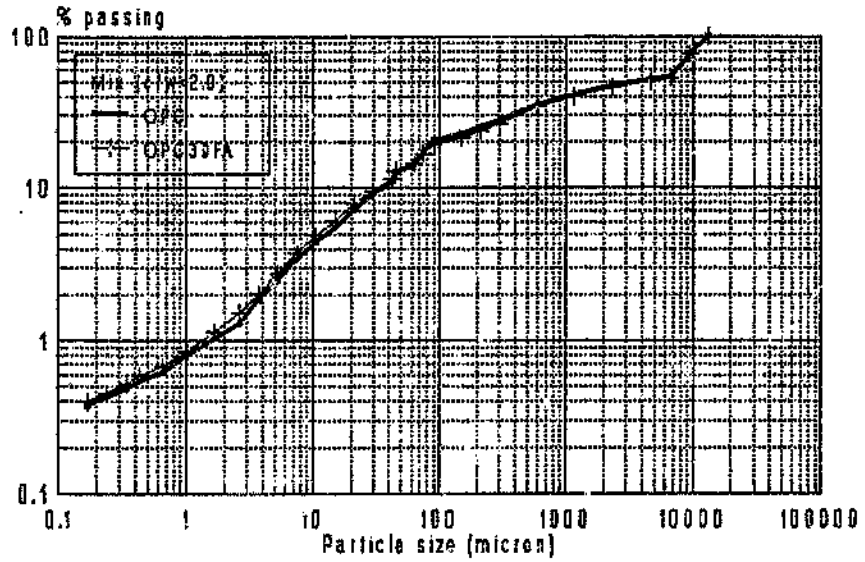
These data also indicate some differences between the magnitude of the water reduction that occurs with different cements. In this case the biggest reduction was found with the ordinary portland cement C which also had the highest water requirement on its own. Cement B was the cement with the next most significant effect and cement A was the cement least affected. This is in contrast to the effects noted with the Matla fly ash where the cement similar to cement A was that most affected. It would therefore seem that a lot more data will be required to provide a better understanding of the water reduction interaction between ordinary portland cement and fly ash.

5.2.1.3 Effect of grading

Theissing[37] argued that the effect that the fly ash addition has on the shape of the overall grading curve of the concrete influences the magnitude of the water reduction that occurs. This factor has been taken into consideration with the fact that all the materials used in the tests which provided the additional data in table 5.1c were very different to those in the initial investigation. The use of these different materials does not appear to have made a significant difference to the water reductions observed in this case.

The effect that the introduction of fly ash had on the overall grading of the concrete is shown in figure 5.1e. This graph shows the effect of using 30 % fly ash in a mix having a cementitious/water ratio of 2,0 when compared against an ordinary portland cement mix of the same cement/water ratio. It can be seen that there appears to be little difference in the shape of the curves even when plotted, as this graph is, on a log–log scale to emphasise differences. It is difficult to reconcile the 18 litres/m^3 water reduction achieved with the introduction of the fly ash with the insignificant changes in the shape of the overall grading curve. While this graph probably does not entirely disprove Theissing's contention that the water reduction is influenced by the improvement in the overall grading it is likely that other factors play a (perhaps more significant) role too.

Figure 5.1e
Grading curves of opc and pc30fa mixes



The obviously better particle shape of the fly ash (see figures 4.4 to 4.8) must contribute considerably to improved mobility, while the dispersive effect referred to by Dhir et al[41], Helmuth[85] and Roy[86] would tend to free water which would otherwise be caught up in the flocs of cement, thereby adding to the fluidity of the mix. Swamy[268] on the other hand discounted the physical effects of the fly ash and stated that the water reduction resulting from the use of fly ash came about purely as result of the dispersive effect. The view that the dispersive effect is significant is supported by evidence provided in later paragraphs of this thesis.

5.2.1.4 Summary

In conclusion the following statements can be made:

- The inclusion of Matla or Lethabo fly ash in a cementitious mix improves the flow characteristics of the mix when compared with a similar mix without the fly ash.

- This effect can be expressed as the volume of water that can be removed from the mix while still giving the same slump, i.e. the water reduction.

- The magnitude of the water reduction depends on the source of the ordinary portland cement used, some sources allowing more improvement than others. More data is required for a better understanding of the interaction between cement and fly ash.

- There is no apparent link between the "water demand" of the cement and the magnitude of the water reduction that occurs with the use of fly ash.

- Introduction of fly ash makes only an insignificant difference to the overall concrete grading, and the fly ash particle shape and its dispersive effect are probably more significant mechanisms in the water reduction process.

- A first approximation for the magnitude of the water reduction which will occur on using Matla fly ash is:

  Water reduction (l/m^3) = 0,55 x fly ash content (%)

  In the case of Lethabo fly ash the available data suggests that this fly ash is a slightly more effective water reducer giving a constant in the above formula of 0,59.

5.2.1.5 Comparison of these findings with other work

The magnitude of the change in water demand of concrete mixes measured in this work is greater than that reported by Ravina and Mehta[79] who found only 15 to 20 litres/m^3 water reduction for a 75 % fly ash content by mass. It is also greater than that noted by ENCI[134] with a maximum of 11 litres/m^3 in the case of their 25 % fly ash blend cement.

This would probably lead to the conclusion that the water reducing ability of Matla fly ash is better than those tested in the two references above; as these fly ashes have not been tested under identical conditions this statement could be challenged. Suffice it to say that it appears that the water reducing ability of Matla or Lethabo fly ash is at least as good as other ashes tested elsewhere.

Butler[61] stated that most fly ashes will reduce the water demand of concrete but that the cement used plays a significant role. The findings of this study agree with this statement. There is however no support in these findings for his contention that the greatest water reductions occur in the case of the cements with the highest water demand. It would therefore appear that there is a greater number of factors that play a role in the mechanism of water reduction than Butler realized.

5.2.2 Viscosity measurement

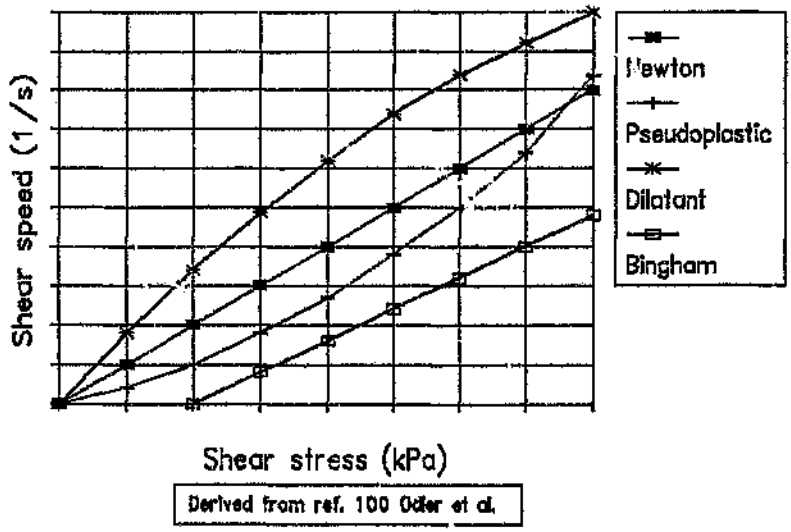
Early South African work on the use of ggbs by Fulton[269] used viscosity tests on pastes of ordinary portland cement with and without mgbs (convention now dictates that the product is called ggbs) to try to explain the effect of the extender on the workability of concrete made using ggbs. Similar work was done in this study to evaluate the effect of fly ash on the viscosity of cementitious pastes to see if the additional information would help to explain the effect that the fly ash has on the workability and placeability of concrete. The information gathered in this study was

presented in a paper to an international conference on fly ash in 1987[270], but is given in more detail in paragraphs below.

As mentioned in 3.3.1.2 Atzeni et al[93] reported on the importance of the experimental conditions when carrying out viscosity testing with coaxial cylinders viscometers and noted that variations in conditions had sometimes lead to discrepancies in the results obtained. This factor was considered when assembling the apparatus for viscosity testing of the materials used in this study.

Odler et al[100] gave the shape of four basic types of flow curves as shown below. The shape of the curves obtained in this study indicate that the behaviour is either pseudoplastic, to judge from the upward shape of the curve, or Binghamian, as the curve, if it were projected back to the horizontal axis, might not go through the origin. Figure 5.2a below shows the different types of flow (from Odler[100]).

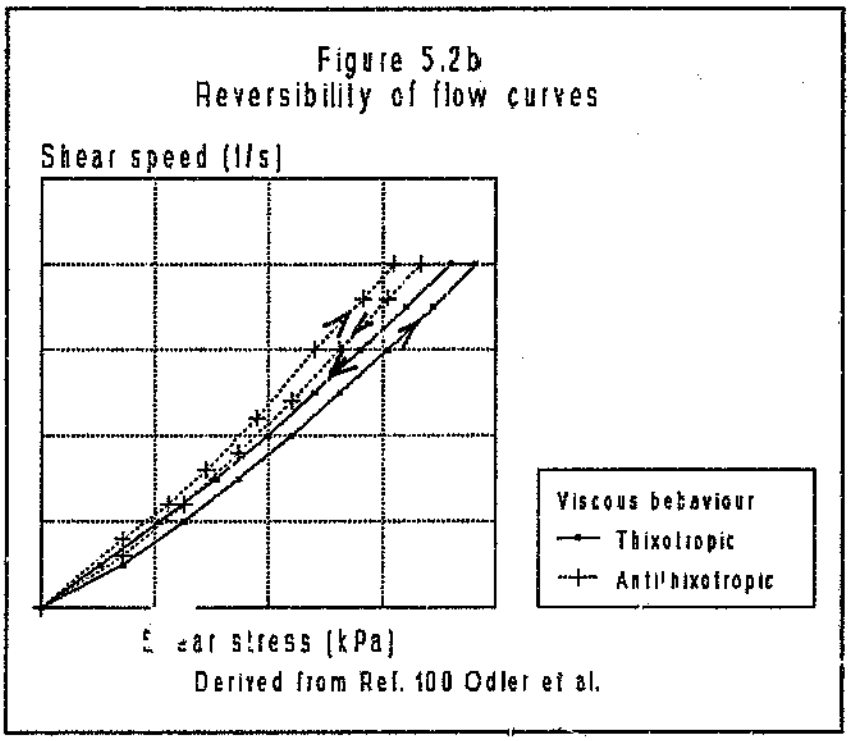
Figure 5.2a
BASIC TYPES OF FLOW CURVES



Derived from ref. 100 Odler et al.

Many authors[96,99,100,101,102,103,104] have reported that cement pastes exhibit the Bingham type of flow pattern; this is probably true for this study too.

Figure 5.2b, also derived from Odler,[100] shows the two basic modes of reversibility of the flow curves, namely thixotropic and antithixotropic.



5.2.2.1 Apparatus used in this work

The apparatus used in this work was that available from the Civil Engineering Department at the University of the Witwatersrand. The apparatus used was as follows:

- A Klaxon mixer with a mixing speed of 6000–9000 rpm.
- A Feranti VL portable coaxial cylinders viscometer using cylinders with diameters of 47,6 mm (outer) and 42,9 mm (inner). This viscometer has a range of rotational speeds of 109,7 to 327,7 (s^{-1}).

5.2.2.2 Method of test

Initial tests were done to evaluate the difference between hand mixing with a spatula, and machine mixing using the above equipment. The hand mixing cycle was 30 seconds of mixing, a 30 second period of rest followed by a further 270 seconds of mixing. This mixing cycle produced thixotropic behaviour (typical hand mixed paste viscosity curve shown in figure 5.2c) with highly variable results.

The machine mixing cycle described in the following paragraphs gave shear stress values of about 50 % of those produced from the hand mixing cycle on the up curve

and anti–thixotropic behaviour i.e. the down curve was to the right of the up curve as shown in figure 5.2d which shows a typical curve for a machine mixed paste.

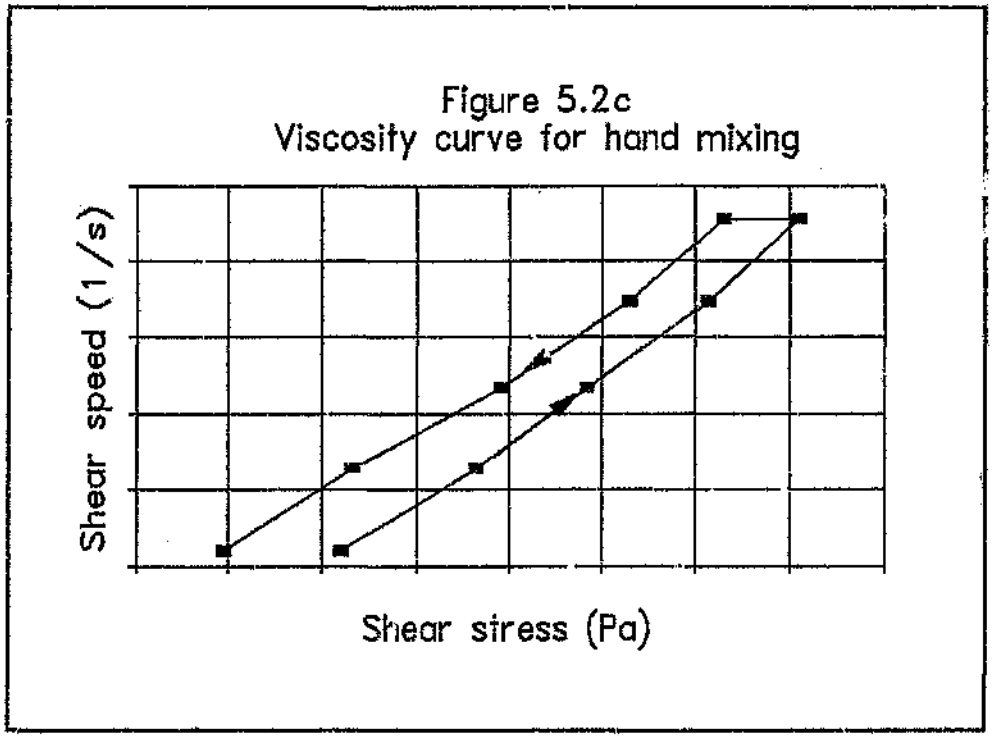


Figure 5.2d shows a typical curve for a machine mixed paste. The readings obtained from the machine mixed pastes showed far better repeatability than the hand mixed pastes.

The machine mixing cycle was subsequently chosen on the basis of the better repeatability of this method. A further reason for selecting machine mixing in prefference to hand mixing was that it was believed that the amount of shear imparted to the paste with machine mixing approached that to which the paste in a concrete mix would be exposed in a concrete mixer more closely than did hand mixing.

It was believed that the machine mixing cycle was therefore more likely to produce the sort of behaviour that the paste in a concrete mix might exhibit.

The method used for the tests described in subsequent paragraphs was largely developed on the equipment available in the PCI laboratories.

All materials were initially conditioned to a temperature of 22 to 25 degrees Celsius and quantities were weighed out on a Sartorius balance to the nearest 0,1 gram.

The quantity of paste produced in each case was 550 ml as this ensured that the cylinders of the viscometer were always immersed to the same depth. First the desired quantity of water was measured into the bowl of the high speed mixer.

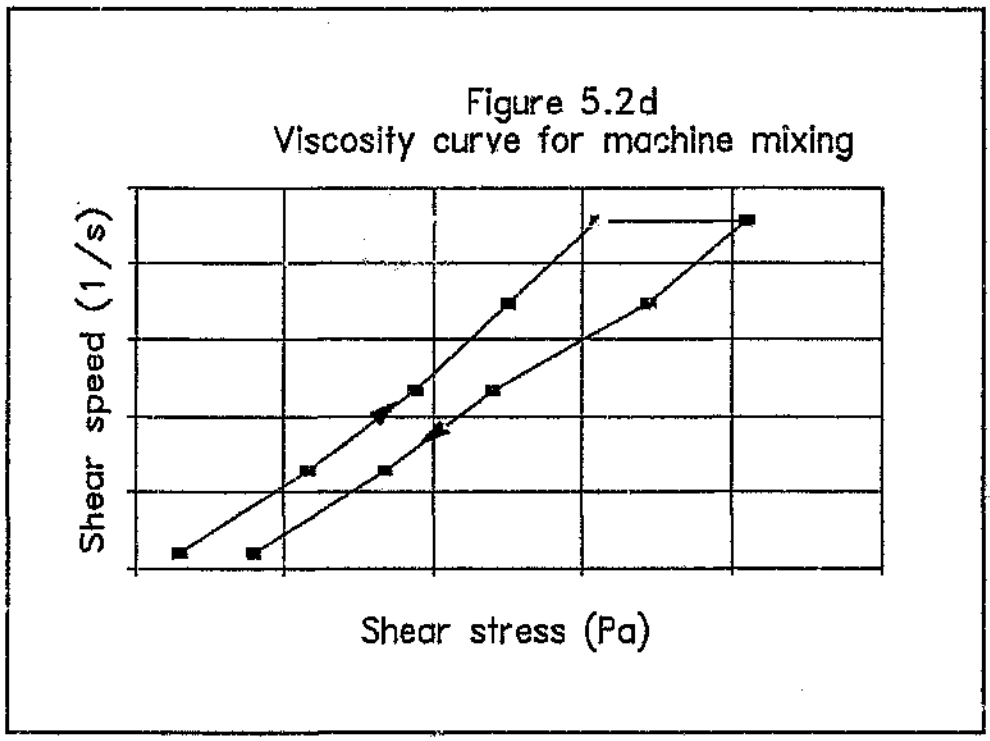


Figure 5.2d
Viscosity curve for machine mixing

The desired quantity of cementitious materials was added and mixed by hand for 15 seconds using a spatula. The bowl was then attached to the mixer and the paste was mixed in the Klaxon mixer for 3 minutes. A temperature reading was taken just before the end of the mixing cycle.

The bowl was then immediately placed under the viscometer, immersing the cylinders to the set depth, and the test was started. The viscometer was started at its lowest speed and a viscosity reading was taken as soon as it stabilized. The speed was then increased to the next step and the process repeated until the maximum speed was reached. The viscometer was left running at the maximum speed for 3 minutes and then a second reading was taken. The speed was then reduced in steps, reversing the earlier process.

Each mix was repeated in its entirety at least once to confirm the results obtained.

The mix proportions used were at fixed cement/water ratios irrespective of whether fly ash or other extenders were used or not. The original intention was to use c/w ratios of 1,3, 1,67, and 2,0. This range was found to be too wide for the apparatus used as

the viscosity of the high c/w ratio was too high to be measured, and the c/w ratio had to be limited to values of 1,3 and 1,67.

Tests were also done with cement/water ratio 1,67 to assess the change in viscosity with time for different binder combinations.

5.2.2.3 Tests done and materials used

When testing with fly ash, proportions of 15 and 50 % were used. Fly ash was used from two different sources for this testing as it was believed that this would provide additional information to look at the difference between a "good" and a "poor" ash. The Matla fly ash previously detailed in tables 4.1 and 4.2 was used in comparative tests against a sample of fly ash obtained from the Duvha power station.

Tests were done with each of the ordinary portland cements or the blended or interground cements detailed in tables 4.1 and 4.2. To provide further perspective similar tests were done using a sample of milled granulated blastfurnace slag from the Pretoria works of Slagment Pty. Ltd. and a sample of condensed silica fume from Messrs. Silicon Smelters in Pietersburg. No viscosity testing was done with the Lethabo fly ash.

Table 5.2 gives the details of the quantities of material used to produce the paste mixes tested in the viscometer. The source of the materials and the mix coding is given in table 5.3.

5.2.2.4 Discussion of test results

Tables 5.4a to 5.4e give the results of the viscosity tests done on mixes no 1 to 21.

The results of the viscosity tests on the three samples of ordinary portland cement are shown in figures 5.3a and 5.3b.

The following can be seen from these figures:

- The apparatus used was not capable of operating at orbital speeds of less than 109,7(1/s). It is therefore not possible to determine the shape of the viscosity curve below this speed.

- The type of behaviour exhibited by all the cements is antithixotropic at a cement/water ratio of 1,67. The trend is not so evident at the cement/water ratio of 1,3 although the Blue Circle cement still shows this tendency. In both cases the Blue Circle cement is more viscous than the other two cements, and it is these cements that display a rather poorly defined behaviour at cement/water ratio of 1,3.

Figure 5.3a
Viscous behaviour of OPC's
Cement/water ratio = 1.3

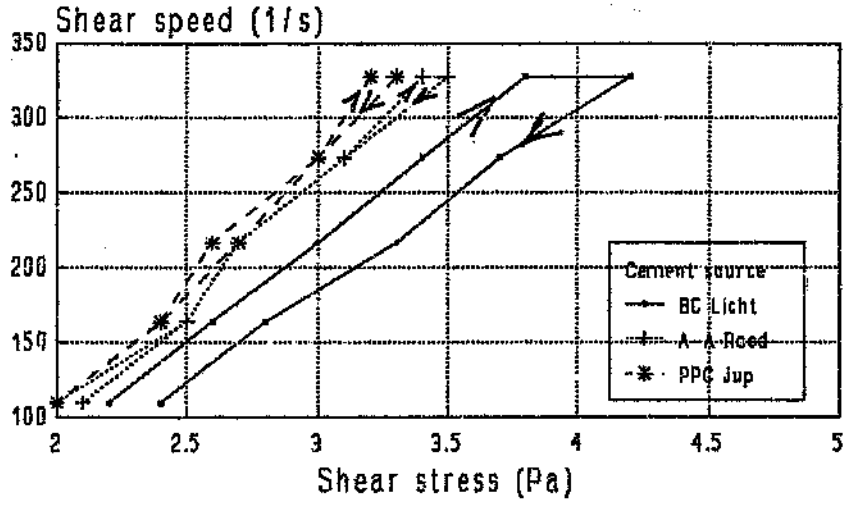
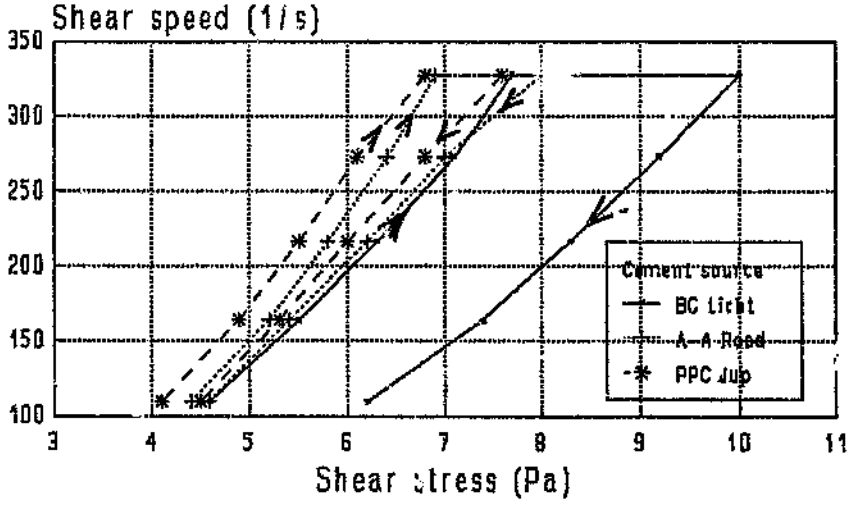


Figure 5.3b
Viscous behaviour of OPC's
Cement/water ratio = 1.67



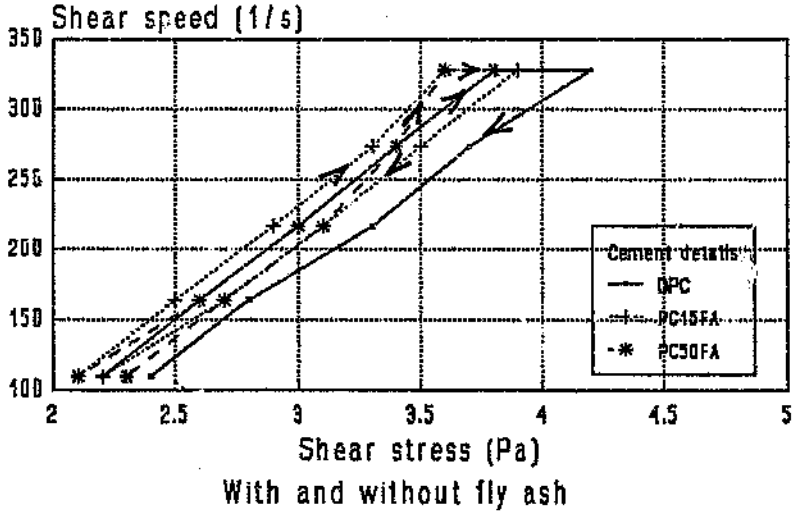
- It is evident that the viscc of all the cements increases with increased cement/water ratio, and tendency to antithixotropic behaviour is accentuated with the increase in cement/water ratio.

- There is no apparent link between the "water demand" of the cement shown in table 5.1b and the viscous behaviour of the different cements shown in figures 5.3a and 5.3b. In the case of the water demand of the concrete mixes the ranking was Anglo–Alpha, PPC and Blue Circle in order of decreasing water demand. In the viscosity tests the order of the results at both cement/water ratios appears to be decreasing from Blue Circle to Anglo–Alpha to PPC.

- The order of magnitude of difference in shear stress values shown between the cements from different sources must be remembered when considering the impact that fly ash has on the viscous behaviour of blended pastes.

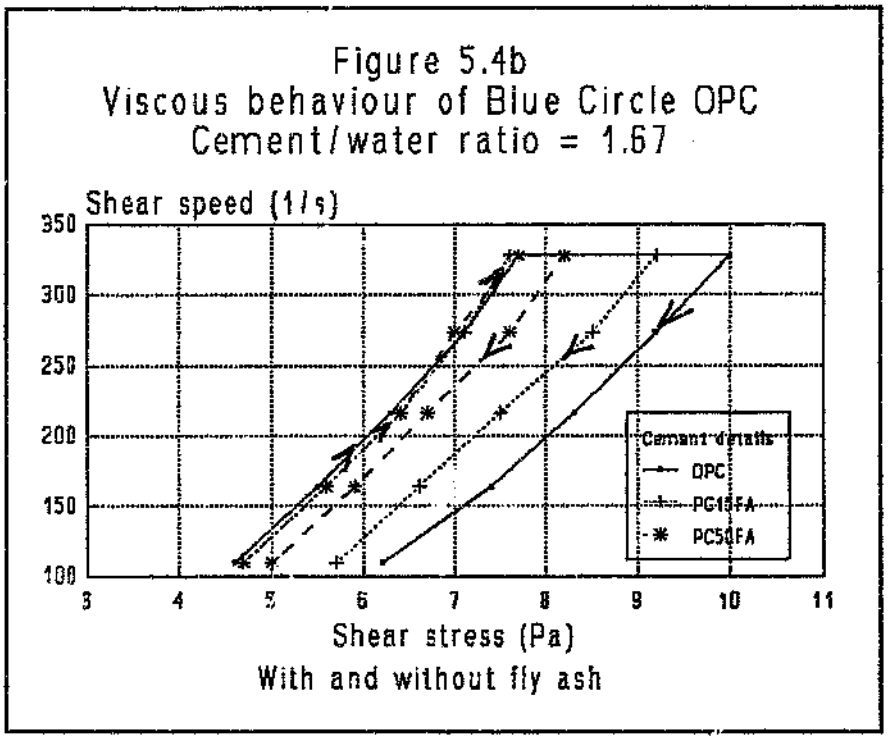
  The order of magnitude of the shear stress values found in these tests is roughly double the magnitude reported in similar tests by Odier et al,[100] while being lower by about half of the values reported by Rudzinski.[90] As both authors used similar methods of mechanical mixing for their pastes it is difficult to explain the differences other than by the fact that the results of several of Odier's initial runs during his testing were discarded as being too erratic. It therefore appears that his paste was allowed to undergo some relaxation before the test was carried out.

Figure 5.4a
Viscous behaviour of Blue Circle OPC
Cement/water ratio = 1.3



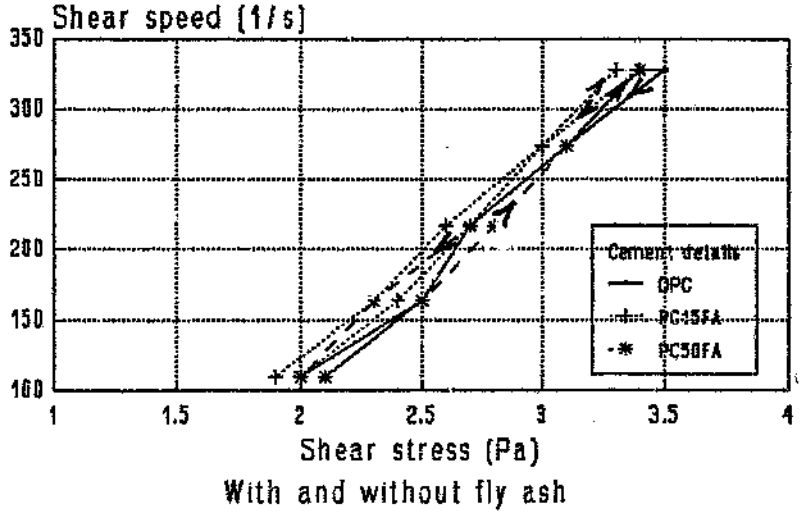
With and without fly ash

Figures 5.4a and 5.4b show how the incorporation of Matla fly ash influences the viscous behaviour of the Blue Circle cement pastes. It is clear that at both cement/water ratios the use of fly ash tends to reduce the shear stress values at any shear speed, with the shear stress decreasing further as the fly ash content increases. At cement water/ratio 1,3 there is a reduction in the shear stress values relative to the ordinary portland cement curve; at cement/water ratio 1,67 the peak values decrease although the "up" lines of all the curves coincide. The magnitude of the change in viscosity caused by the incorporation of the fly ash in the paste mix is smaller than the differences between the curves of Blue Circle cement and the other two cement sources.



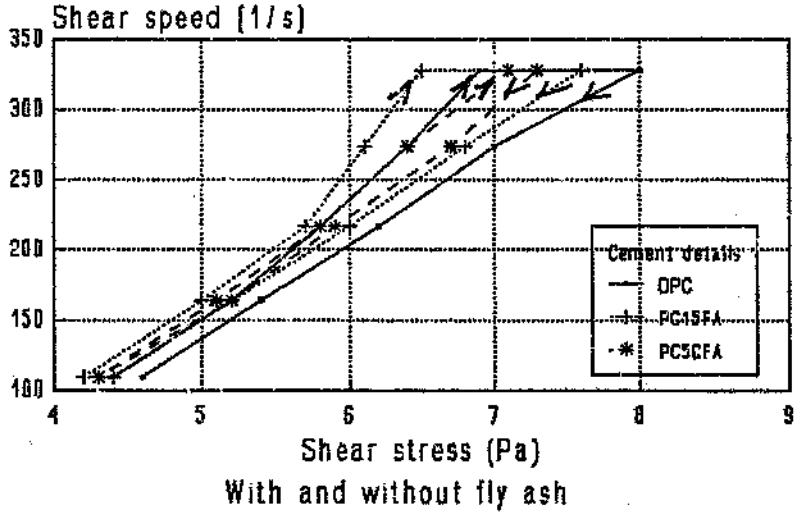
Figures 5.5a and 5.5b show how the incorporation of Matla fly ash influences the viscous behaviour of the Anglo–Alpha cement pastes. A similar trend can be seen in this case to that which occurred with the Blue Circle cement although the changes are less well defined, particularly at cement/water ratio 1,3. In this case, the antithixotropic behaviour of the pure cement was less obvious. Again reductions in shear stress are apparent, with the size of the change again smaller than the difference in results for the different cements.

Figure 5.5a
Viscous behaviour of Anglo-Alpha OPC
Cement/water ratio = 1.3

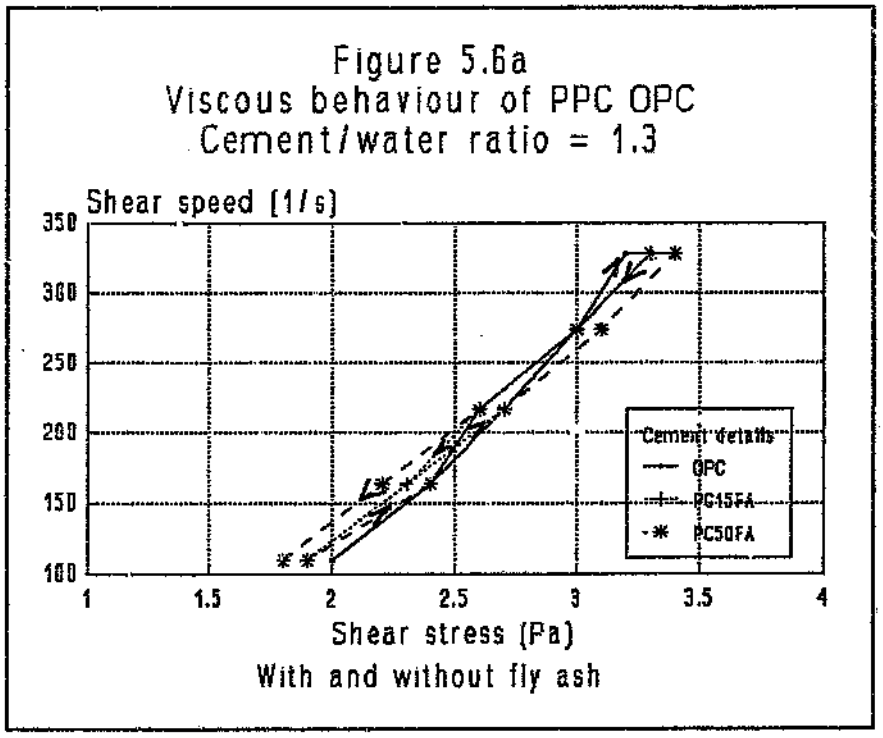


With and without fly ash

Figure 5.5b
Viscous behaviour of Anglo-Alpha OPC
Cement/water ratio = 1.67



With and without fly ash

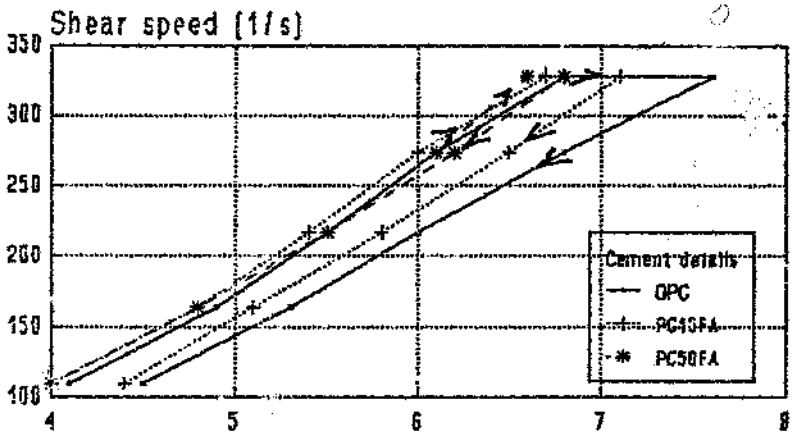


Figures 5.6a and 5.6b show how the incorporation of Matla fly ash influences the viscous behaviour of the PPC cement pastes. The effect that the fly ash has is again similar to the previous two cements except that the cement/water ratio 1,67 the effect is less marked.

Figures 5.7a and 5.7b show what happens with factory blending or intergrinding of PC 15 FA cements. In this case the fly ash seems to have the effect of slightly increasing the shear stress of the pastes with this trend being more evident in the case of the interground product. In each case the effect that the fly ash has is smaller than the differences between cements. In concrete there was little noticeable difference in the level of workability of mixes made with these cements as measured with the slump test.

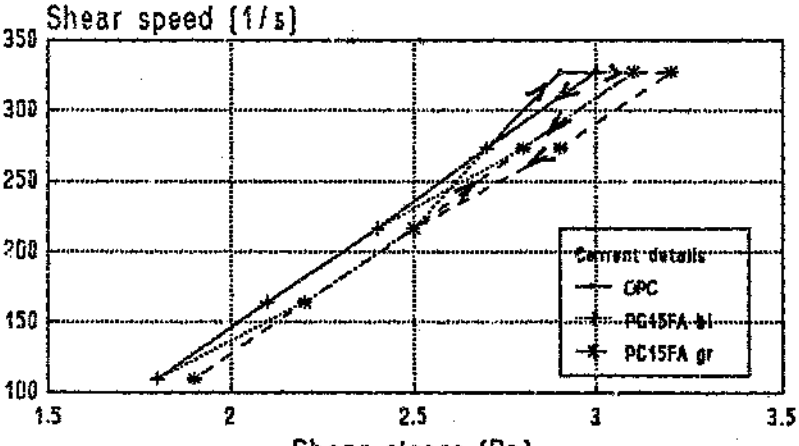
Figures 5.8a and 5.8b show the impact of using Duvha fly ash compared with the fly ash from Matla. The Duvha fly ash seems to have a far greater influence on the viscosity of the paste than the Matla ash. In this case the effect of the Duvha ash is to greatly increase the shear stress at any shear speed. The increase at cement/water ratio 1,67 was so dramatic that the viscosity of the 50 % Duvha mix exceeded the maximum range of the viscometer used. When this ash is used in concrete it results in a much smaller decrease in the water demand of the concrete relative to the control ordinary portland cement concrete than that produced by the Matla ash. The order of water demand decrease measured using the same materials as for all the other work in this study was 4 litres/m^3 compared with the 10 litres/m^3 for the Matla ash when used at the level of 15 % replacement.

Figure 5.6b
Viscous behaviour of PPC OPC
Cement/water ratio = 1.67



Shear stress (Pa)
With and without fly ash

Figure 5.7a
Viscous behaviour of PPC blends
Cement/water ratio = 1.3

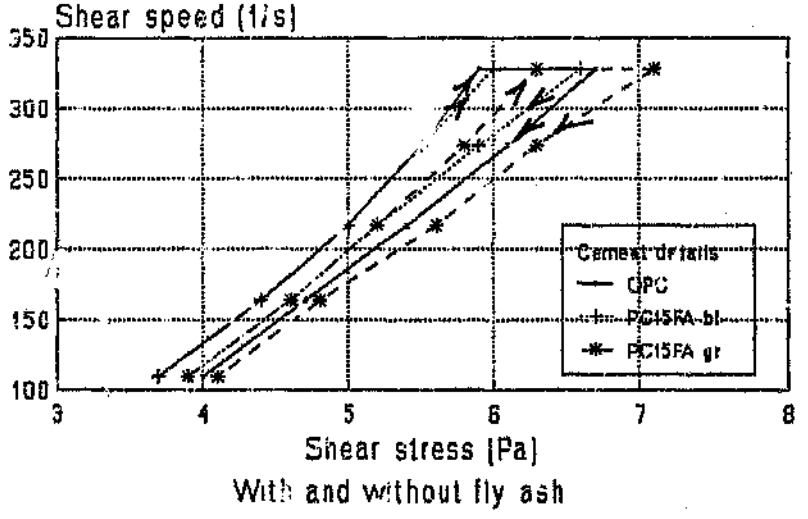


Shear stress (Pa)
With and without fly ash

Looking at the photomicrographs of Duvha fly ash in figure 4.5 it is obvious that the Duvha ash contains far more non-spherical debris particles which must detract from the overall sphericity of this ash. The poorer shape of this ash is a possible cause of the fact that it is not as effective a water reducer as the Matla fly ash in either the concrete slump tests or the paste viscosity tests.

Rudzinski[89] showed that the viscosity of a cement paste increased as the fly ash content was increased. It is possible that the quality of the fly ash used in his study was similar in terms of the degree of sphericity to that of the Duvha ash. A further possible contributory cause of the increase in viscosity on adding the fly ash is the fact that the Varna fly ash he used had a high loss on ignition. Rudzinski's curves only show antithixotropic behaviour at a fly ash content of greater than 40 % while this type of behaviour is evident without fly ash in the tests of this study.

Figure 5.7b
Viscous behaviour of PPC Blends
Cement/water ratio = 1.67



With and without fly ash

Figure 5.8a
Viscous behaviour of Duvha blends
Cement/water ratio = 1.3

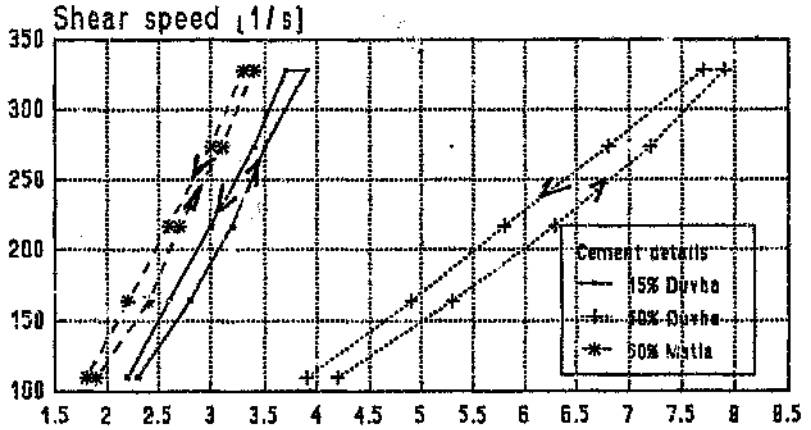
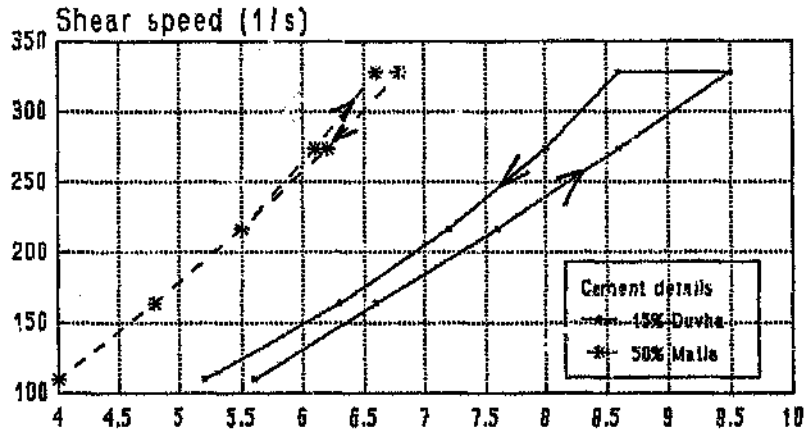


Figure 5.8b
Viscous behaviour of Duvha blends
Cement/water ratio = 1.67



5.2.2.5 Viscosity tests with other cementitious materials

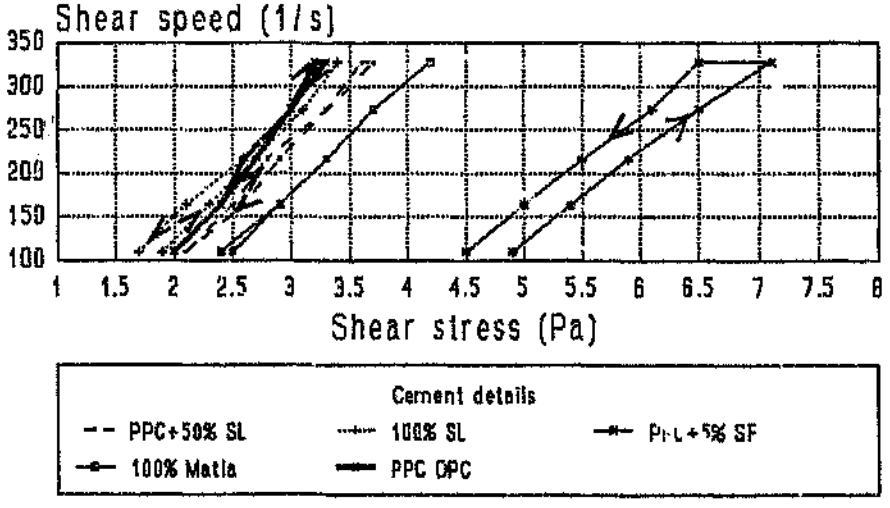
Figures 5.9a and 5.9b show the viscosity curves for other cementitious materials. The mix made with pure slag differs only slightly from the curve for the ordinary portland cement, while when the same slag is mixed 50/50 with the ordinary portland cement the mix becomes more viscous. Matla ash, as shown in figures 5.6a and 5.6b, gives only a slightly more viscous mix than the ordinary portland cement.

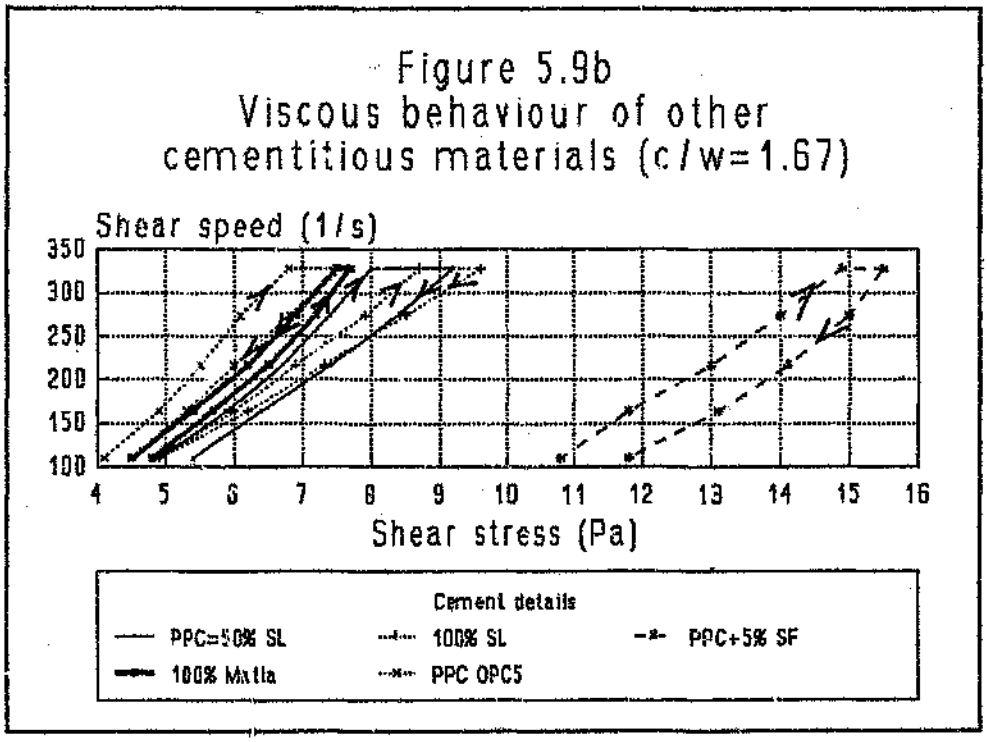
In contrast to this the use of only 5 % silica fume gives a dramatic increase in viscosity. The effect of the silica fume is so marked that a mix with 15 % silica fume became too viscous to be measured in this apparatus.

In the mixes with cement/water of 1,67 it can be seen that the antithixotropic stiffening of the mixes with extender is generally of smaller magnitude than is the case when the ordinary portland cement is tested on its own. Again the mix with 5 % silica fume is much more viscous than the other mixes. This sample of silica fume had the effect of increasing the water demand of concrete by about 5 litres per cubic metre at the level of 5 % replacement. It is evident therefore that the effect of this extender on the water demand of a concrete mix is matched by an increase in the viscosity of the paste, although the relative increase in the paste viscosity is more marked than the change in water demand.

No viscosity testing of the Lethabo fly ash was done.

Figure 5.9a
Viscous behaviour of other cementitious materials (c/w=1.3)





5.2.2.6 Effect of time on viscous behaviour

Figures 5.10a, b and c show the effect of the use of Matla fly ash on the change in paste viscosity with time. When ordinary portland cement ages it shows a strong tendency to become more viscous with time, particularly as the mix approaches its initial setting time.

When 15 % Matla fly ash was used the stiffening that occurred with the onset of setting was less marked and this phenomenon was almost totally absent in the 50 % fly ash mix. This gives an indication that the fly ash was having some effect on the setting behaviour of the pastes.

Setting time effects will be discussed more fully in later paragraphs.

Figure 5.10a
Change of viscosity with time
for PPC OPC at c/w = 1.67

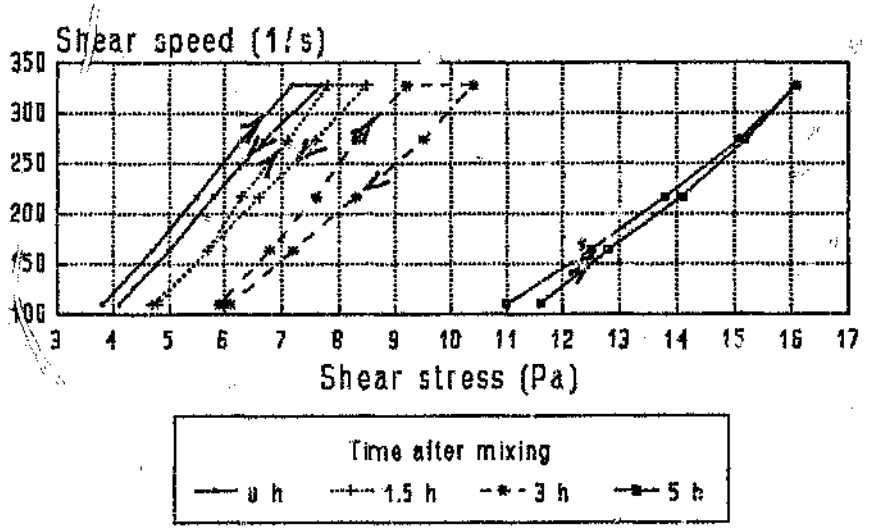
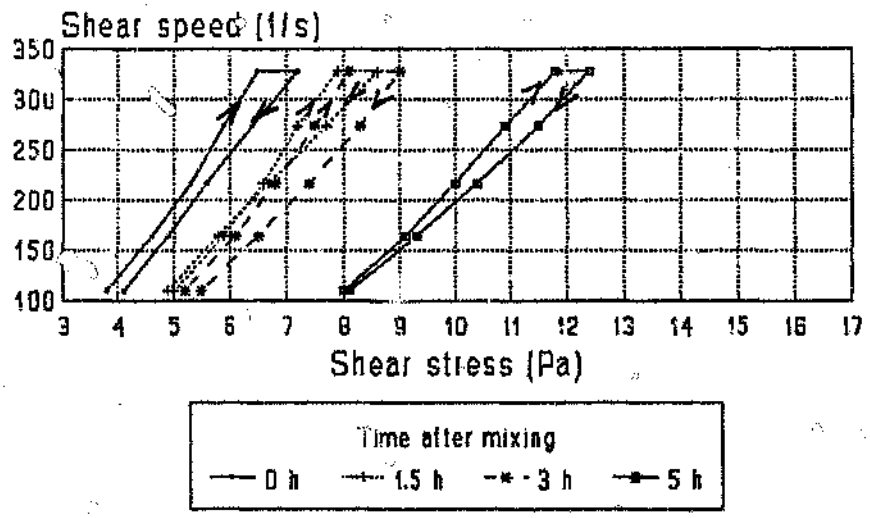
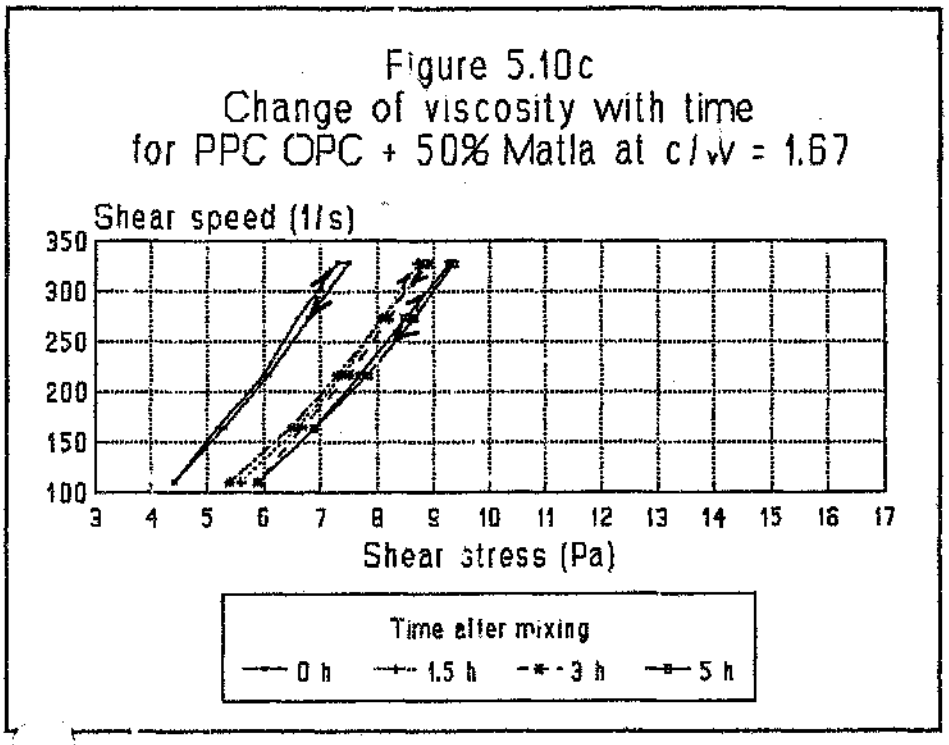


Figure 5.10b
Change of viscosity with time
for PPC OPC + 15% Matla at c/w = 1.67





5.2.2.7 Significance of viscosity test results

As Wolter[97] has shown there is much information of use to the producer of Ready Mixed Concrete in such curves. The curves show what stiffening is likely to occur when such a cement or cement blend is used in a mix that is to be hauled over a medium to long distance. It makes it possible for such a ready mixed concrete producer to select the type of cement or cement blend most suited to his particular operation. In this case the producer would be well advised to use the blend of cement and fly ash for long haul operations.

The information obtained from the viscosity tests is of some use to the users of cement. However it is difficult to interpret what the implications of a moderate increase in viscosity is to the user, as it is not clear whether this means a reduction in the water requirement of the concrete mix or not. As this test requires relatively sophisticated equipment and careful execution it cannot be regarded as a serious substitute for the site slump test on concrete. Moreover the slump test gives direct information about the degree of workability afforded by the concrete mix at any particular water content.

5.2.2.8 Recommendation for further work

It is believed that until more is understood about the interpretation of the results of such viscosity tests, this type of test is not likely to be widely used.

A better understanding about the relationship between paste viscosity and concrete slump might follow with experimental work on the viscosity of concrete. Equipment capable of measuring the viscosity of concrete has been made available to the Eastern Cape regional office of the PCI. This is a line of investigation that might be pursued profitably once the equipment is operating. It is probably desirable to include Lethabo fly ash mixes in the scope of the additional testing, although there is likely to be less difference between the effect of Lethabo and Matla fly ashes than was the case recorded between Matla and Duvha fly ashes as both Lethabo and Matla are high class fly ashes with beneficial water reducing effects. The same was not true for Duvha fly ash.

5.3 Setting time

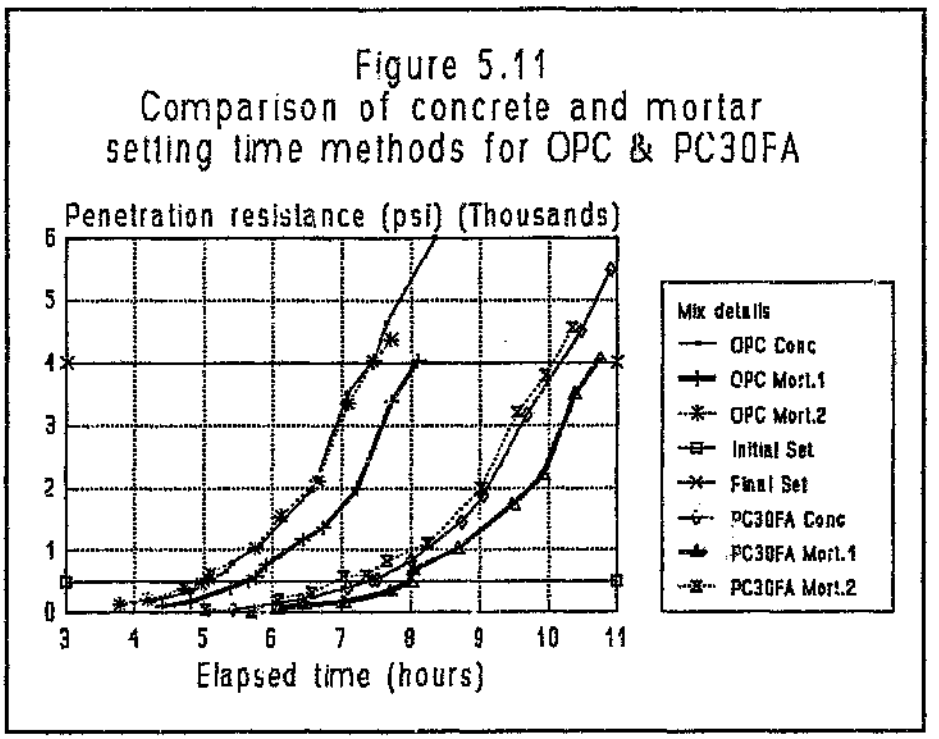
The initial and final setting times of a concrete or mortar have been arbitrarily defined as a particular level of resistance to penetration of the plastic material by a needle or probe of a specific size.

The setting time of a cement is determined as part of the standard set of tests for cement using the Vicat test. The results are often reported as part of the characterisation of a cement consignment delivered to a site. This value is irrelevant to the end user of cement however as the test is done on a rather rich pure cement paste.

Other tests have been developed for use on concrete or mortar and the method used here is described in the following paragraphs.

5.3.1 Test method used

In this investigation the setting time of concrete or mortar has been measured using ASTM method C403–88[271]. This method deduces the setting time as being the time taken for the mix to reach a particular resistance to penetration of a probe of a specific size. In the case of concrete the mix has first to be prepared by the removal of all particles larger than 4,75 mm so that there are no big particles to offer unusual resistance to the penetration of the probe.[271]



In this work it was found that it took rather a long time to screen sufficient of the minus 4,75 mm sample from concrete, and there was concern that the mix could be undergoing some form of setting which was disturbed or delayed during the screening process. As the test would be easier to perform on a mortar using the same sand as for the concrete mix, but screened prior to mixing to remove all +4,75 mm particles some trials were done to evaluate the difference between the setting times recorded using the screened concrete or a mortar.

The results of these trials are shown in tables 5.5a and 5.5b and figure 5.11. The results for the concrete tests refer to the penetration resistance/time relationship obtained for a mortar screened from a concrete mix. The values for mortar 1 refer to a mortar made using the concrete mix proportions, but leaving out the stone; the slump of this mix is greater than that for the mortar screened from the concrete. Mortar 2 is made in a similar way, but the sand to cement ratio is changed so that the slump is the same as for the mortar obtained from the concrete mix.

It can be seen that the mortar mixes, if made to the same mix proportions as the concrete but without the stone, show an increase in the setting time relative to the concrete although the magnitude of the increase is similar for both OPC and PC 30 FA mixes. These mixes are denoted as mortar 1. The difference between the setting times of the OPC and PC 30 FA mixes is therefore not changed by adopting this procedure. There is a great advantage in doing so as the screening operation for obtaining the mortar from the concrete is extremely time consuming.

If the sand/cement ratio of the mortar is adjusted to give a similar level of slump of the mortar to that displayed by the mortar screened from the concrete, then the absolute level of setting time is very similar to that of the screened mortar for both OPC and PC 30 FA mixes. These mixes are designated mortar 2. However as this is changing other characteristics of the mix it was thought that the simple mortar mix without the adjustment to the sand/cement ratio was the better method of the two to follow. In view of the time savings offered by using a mortar mix this modification was chosen for the rest of this part of the experimental program.

The order of magnitude of the retardation resulting from the introduction of 30 % of classified Matla fly ash is about 2,5 hours in the case of the results in figure 5.11.

5.3.2 Discussion of test results on Matla fly ash

In the first series of tests only one cement was used for setting time determinations and only the initial setting time was determined. The tests were done for mixes with ordinary portland cement and also various combinations of cement and fly ash. Table 5.6 gives the values for the initial setting times determined using the ordinary portland cement from PPC Jupiter with and without selected Matla fly ash. These data are for work done at a controlled temperature of 22 to 25 °C.

This information is depicted graphically in figure 5.12. It should be noted that these values are for mixes made to constant cement/water ratios and no adjustment has been made to ensure equivalent strength at any particular age.

Figure 5.12
Setting time of mortars
with and without fly ash

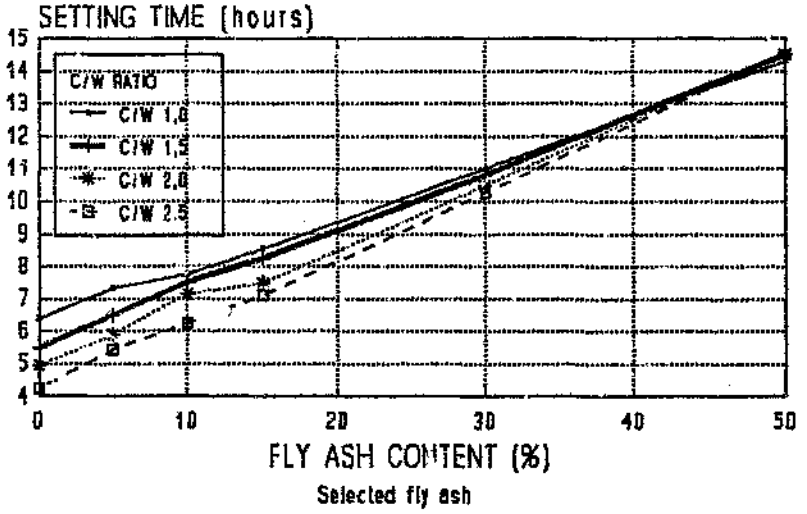


Figure 5.12 shows that the cement/water ratio of the mix has an important effect on the initial setting time of the mortar mixes where there is little or no fly ash present. For an ordinary portland cement mix the initial setting time of a low strength mix (c/w = 1,0) is 6,4 hours but this reduces to 4,2 hours for a high strength mix (c/w = 2,5). Consideration must be given to the fact that the absolute value of setting time with the mortar method is higher than would be the case if a screened concrete sample was tested.

The effect of an increase of, say, 10 % in the fly ash content on the setting time appears to be more significant than a change of 10 % in the cement/water ratio. This contradicts the findings of Samarin et al[116], modification of the cement/water ratio of the fly ash mixes to give strength equivalence at 28 days is unlikely to affect the validity of this statement.

As the fly ash content increases however the significance of the cement/water ratio becomes smaller and beyond 30 % fly ash there is little difference between the initial setting times of the different cement/water ratio mixes.

The introduction of the fly ash has the other obvious result that the initial setting times of all the mortar mixes increase significantly. The initial setting time of the mortar with 30 % fly ash is roughly double that of the ordinary portland cement mortar.

It appears that the setting time of a 30 % selected fly ash mix can be expected to be about 5 hours longer than the equivalent ordinary portland cement mix at standard temperature. Similarly the increase in initial setting time can be expected to be about 2 hours for 15 % selected fly ash and about 8 hours for 50 % selected fly ash.

However these results need to be put into perspective. Setting time tests were done with some other cement samples and using a different sand in the mortar mixes. These results are given in table 5.7a and the setting times of the mortars made from the 3 ordinary portland cement samples used are shown in figure 5.13a. It is evident that the setting times of the three cements differ quite considerably from one another. The order of magnitude of the difference between two of these cements is as much as the increase resulting from the introduction of 15 % fly ash as shown in figure 5.12. Therefore, although there is little doubt that the use of fly ash does increase the setting time of a mix, at the 15 % fly ash level, the increase may be no greater than might be experienced by a contractor who switches sources of cement during the course of a construction job.

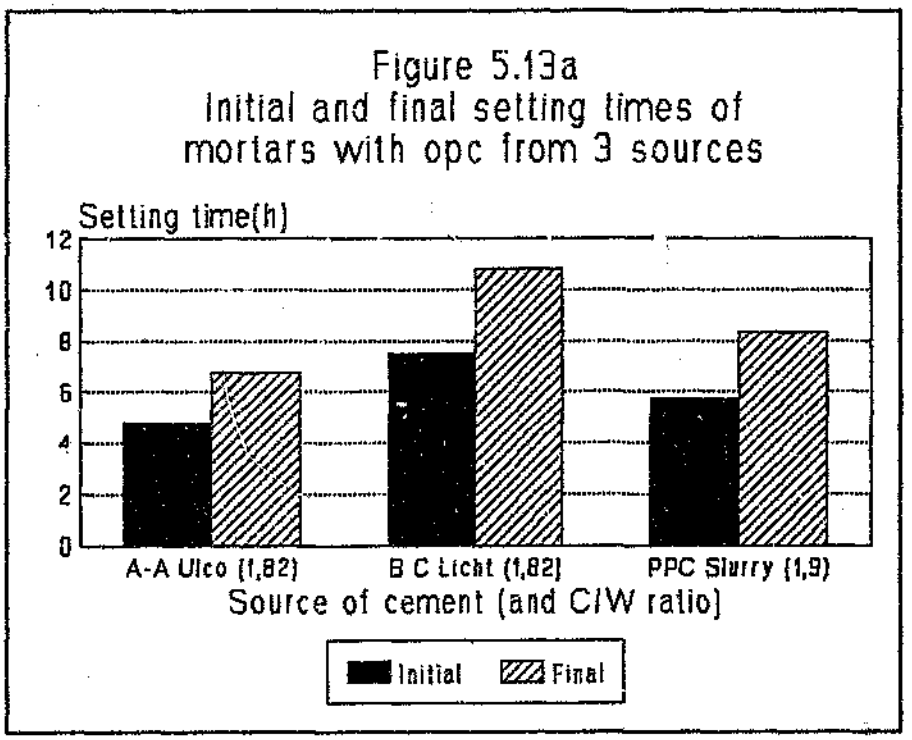


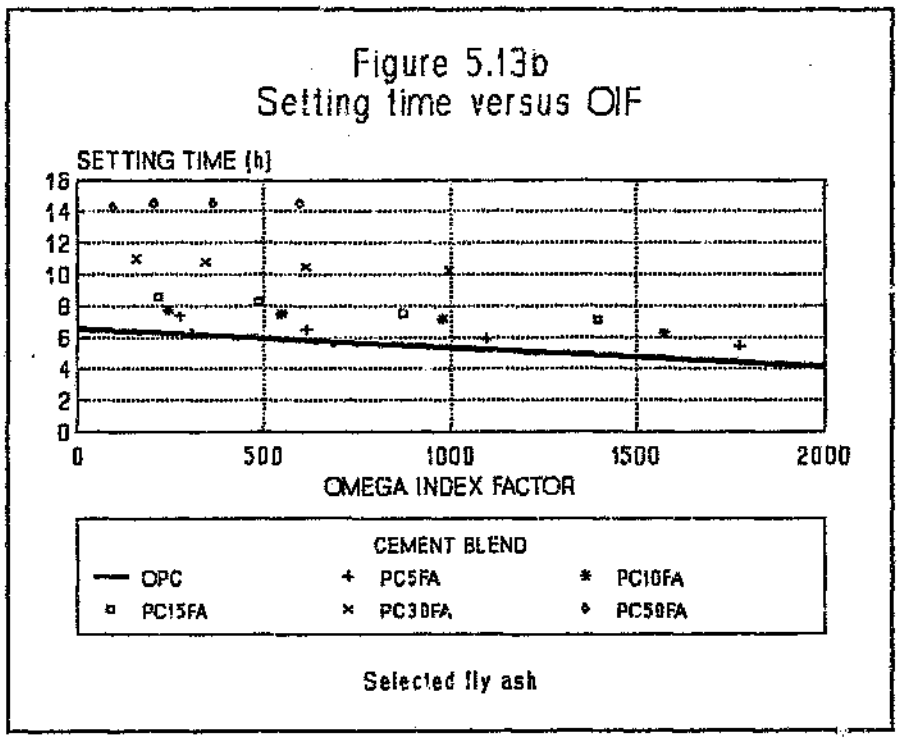
Figure 5.13a
Initial and final setting times of mortars with opc from 3 sources

5.3.3 Comparison with other reports

Dodson[107] reported that by plotting the setting time against an index he called the Omega Index Factor (OIF) the cause of retardation resulting from the addition of the fly ash could be determined. The OIF is determined by taking the ordinary portland cement content of the mix (kg/m^3) and multiplying it by the cement/water ratio. The index was calculated for the data in table 5.6 and a graph of setting time against OIF was plotted as shown in figure 5.13b.

All the fly ash mix values plot above the straight line for the ordinary portland cement mix. This, according to Dodson[107] indicates that a chemical reaction is taking place that further aggravates the set retardation resulting from the lower cement content and decreased cement/water ratio.

It should however be noted that this analysis has been done for mixes designed on the basis of similar cement/water ratios; adjustments to the cement/water ratio to ensure equivalent strength at 28 days would probably reduce the difference between the reference line and the fly ash mix values.



The magnitude of the retardation in initial setting time was strongly disputed by D & H Ash Resources and a joint testing programme was undertaken to re-evaluate this parameter. Although these tests indicated some differences in the actual method followed by the two laboratories it appeared that the order of magnitude of the results given in table 5.6 was correct to the satisfaction of the PCI technologists involved.

What was also apparent was that the sample of fly ash used to give the results in table 5.6 was one which was supplied prior to the Matla classifier being installed; some changes in fly ash quality and performance were thus possible. There was support for this hypothesis in the results shown in table 5.7a derived from tests done on Matla fly ash supplied after the classifier was installed.

Figure 5.13c shows the effect that this sample of classified fly ash had on the setting time relative to the original sample. The first three sets of bars are for tests done with classified ash, while the tests with the PPC Jupiter cement are those shown in table 5.6 for selected Matla fly ash. Ignoring for the time being the fact that for all cements except the PPC Jupiter cement the fly ash mixes were made at higher cement/water ratios, it seems that the original fly ash sample represented particularly by the bars for the PPC Jupiter PC 30 FA on figure 5.13c had a greater impact on the setting time relative to the opc than did the classified sample illustrated by the other three sets of PC 30 FA bars.

Figure 5.13c also shows that the change in setting time on the incorporation of fly ash depends on the ordinary portland cement used in the mix. In this graph the cements from Anglo–Alpha and Blue Circle show similar degrees of change in setting time with 15 % fly ash but differ at the 30 % fly ash level. The two PPC sources also show differences at both fly ash contents. This confirms the observation of Giaccio and Malhotra.[105]

The finenesses (Blaine) of the cements used for the results in table 5.7a are, Anglo–Alpha 358 m^2/kg, Blue Circle 324 m^2/kg and PPC 337 m^2/kg. The results in table 5.7a do not appear to support the relationship between cement fineness and the retarding effect suggested by Costa and Massazza[65] very strongly although the tendency for finer cements to retard less is evident. However it is possible that if any one of these cements was ground finer this might tend to reduce the impact of the fly ash on the setting time as the ordinary portland cement would then probably set sooner.

To return to the point of the cement/water ratios used, it is evident from figure 5.12 that an increase in the cement/water ratio will, for low fly ash contents, have the effect of decreasing the magnitude of the retardation. The mixes in table 5.7a had revised cement/water ratios in order to provide a compressive strength level in the fly ash mix which would match that of the ordinary portland cement mix at 28 days. This modification and its impact on setting time, will be discussed in more detail in the chapter on compressive strength.

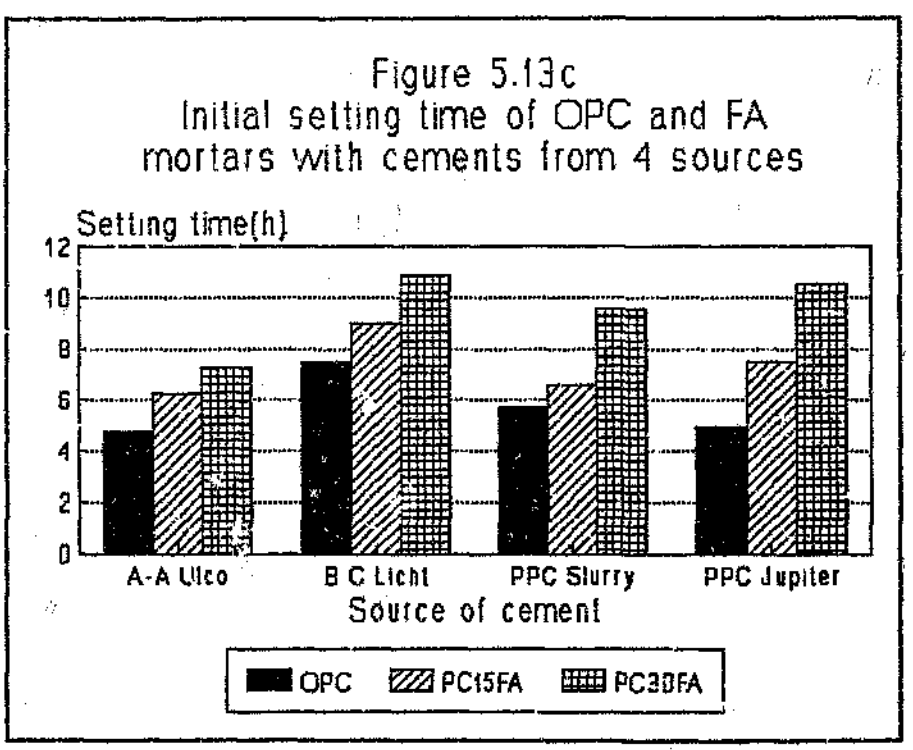


Figure 5.13c
Initial setting time of OPC and FA mortars with cements from 4 sources

Table 5.7b gives further results on setting times of mortars for an ordinary portland cement, a 50/50 blend of that opc and ggbs, a Blue Circle Industria factory produced 15 % fly ash blend cement and a laboratory 30 % blend of Blue Circle opc and Matla fly ash. It can be seen that the retardation of the initial set of the 15 % fly ash mix is less than that resulting from the slag mix or the 30 % fly ash mix. In the case of the final set the 15 % fly ash mix appears to be accelerated relative to the other opc, and is much less affected than the slag or 30 % fly ash mixes.

5.3.4 Investigation into cause of fly ash retardation effect

While PCI had reports of unusual delays in setting times for some fly ash mixes on site[272] D & H Ash Resources maintained that generally there was no problem with setting time on sites. Some further work was therefore needed to investigate what changes might have occurred and how these changes might influence the setting time results. Detailed analyses were obtained for the Matla fly ash samples before and after installation of the classifier[273] and these data are given in table 5.8. The ash extracted before the installation of the classifier is called selected ash and the other classified fly ash.

It can be seen from table 5.8 that there are some fairly major changes in both the oxide and the trace element analysis values between the two samples. It would be impractical to attempt to isolate all the variables that changed significantly in the analyses and therefore an attempt was made to evaluate the effect of introduction of some additional trace elements to the fly ash mixes.

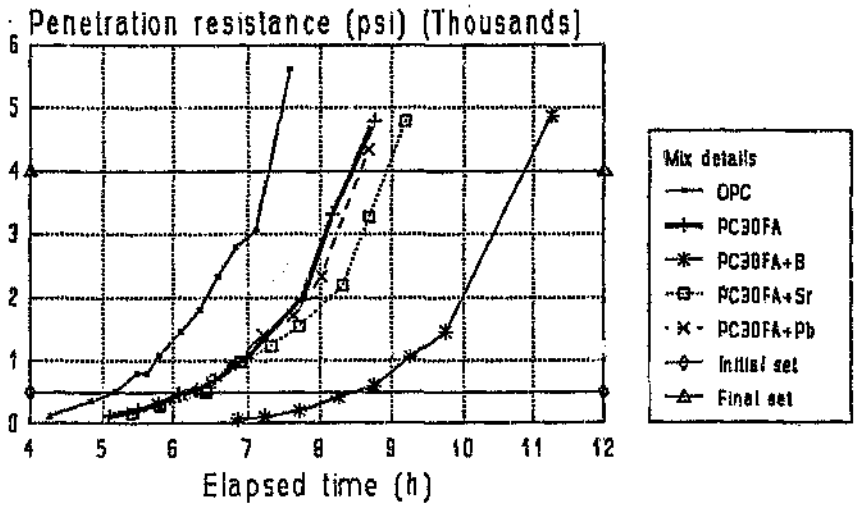
Kasayi et al[114] indicated that boron in the fly ash seemed to be responsible for severe retardation of setting. Some experimental work was done in the laboratory to evaluate the effect of some cations on the setting time. The cations chosen for these tests were boron (in the form of H_3BO_3), strontium (in the form of $Sr(NO_3)_2$) and lead (in the form of $PbNO_3$). In each case 1000 parts per million of cation was added to the mortar mixes and the setting time was compared against that of a similar fly ash mortar without the addition of the cation.

Table 5.9 gives the results of these tests and these data are shown graphically in figure 5.14. In this case both the opc and fly ash mixes were designed to give equal compressive strength at 28 days using the mix proportions in table 4.11; the cations were added to the fly ash mix without further modification.

The increase in initial setting time over that of the ordinary portland cement with the use of fly ash is about 1 hour in this case. The Omega Index Factor of the fly ash mix in this case plots above that of the ordinary portland cement mix confirming that, according to Dodson,[107] the fly ash retardation is probably due to chemical effects. The addition of strontium or lead seems to increase the setting time of the fly ash mix only slightly. The boron, on the other hand seems to have a dramatic effect on the setting time of the fly ash mix, adding about 2,5 hours more to the initial and final setting times of the fly ash mix. This would therefore seem to confirm the conclusion of Kasayi et al[114] about the severe impact that boron has on the setting time of fly ash mixes. This does not definitely implicate boron in this particular case as the order of magnitude of

boron addition in these experiments is well in excess of the fluctuation that occurred in the fly ash tested.

Figure 5.14
Setting time of mortars with and without added cations



Boron is an extremely difficult element to test for as it is present and available from most glasses – extractions can therefore not be done using glass equipment. This makes testing for this element rather expensive and this line of thought has therefore not been pursued. It is also unlikely that it would be feasible to reduce the boron content of the raw fly ash. It is therefore perhaps sufficient to indicate that boron is a possible cause of some of the retardation that results from the use of fly ash.

A summary of a series of analyses of the chemical constituents of Matla fly ash is given in table 5.10a together with the calculated means, standard deviations and coefficients of variation. It is evident that the quality of the fly ash is fairly uniform, particularly with regard to the silica, alumina and calcium contents, although there is some variability in the values for the alkali contents and the sulphur trioxide levels. The phosphate level is shown here not to be a component that varies significantly.

Table 5.10b gives a similar set of results for Lethabo fly ash for comparison purposes – these data are not again referred to.

Further tests were done to determine the effect of an increase in anions such as sulphates and phosphates, and fly ash fineness on the setting time. The results of these tests are given in table 5.11 and depicted graphically in figure 5.15. The anions added were sulphate in the form of sodium sulphate, and phosphate in the form of

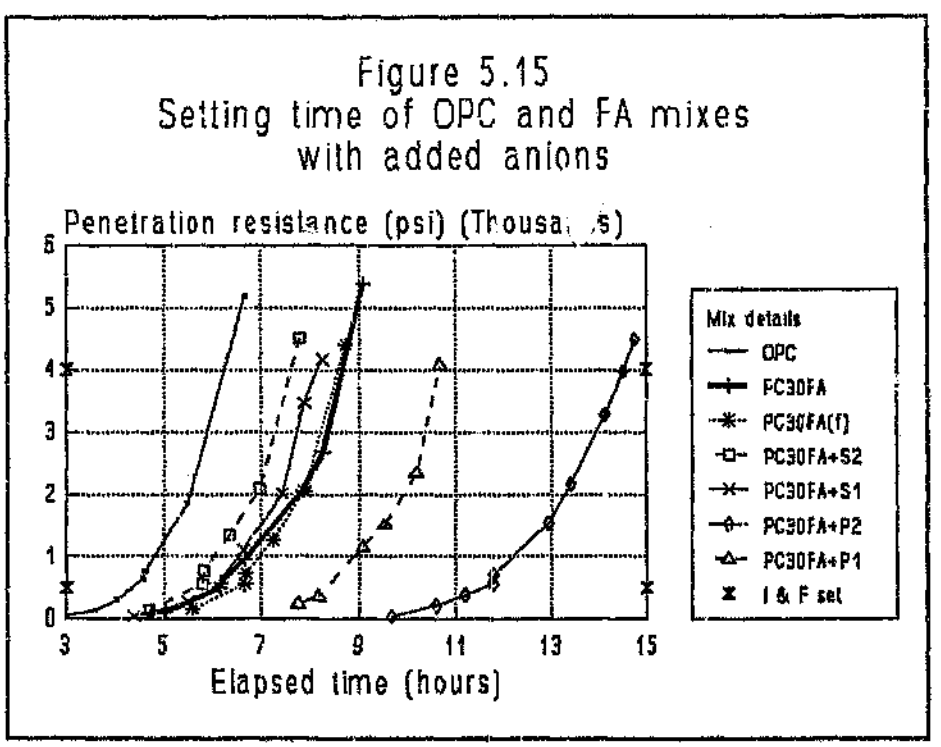
sodium hexametaphosphate. The proportions of the anions were increased over the average level by 3 and 6 standard deviations each (identified in figure 5.15 as S1 and S2 for sulphates, and P1 and P2 for the phosphates) based on the mean and standard deviation figures calculates from a series of analyses made available by Messrs. Ash Resources. These data are shown in table 5.10a for the Matla fly ash used in these tests.

A sample of fly ash was also screened on a 45 micrometre sieve. The performance of the screened sample (identified in figure 5.15 as PC30FA(f)) was compared against that of a normal unscreened sample.

These data were presented in a paper by Grieve and Kruger[274] to the First National Symposium of the South African Coal Ash Association in 1990. In this paper it was reported that the sulphate had an accelerating effect on the setting time, the phosphate retarded the setting time to a similar or greater extent as the boron, and the sieved fine fly ash had a very similar effect on the setting time to the unscreened coarse fly ash. The conclusion in this paper was that boron and phosphates are the most significant retarders of the materials tested.

In terms of the likelihood of either of these two ions being responsible for changes in the setting time of fly ash mixes, the phosphate is the more apparent culprit. The phosphates, at 6 standard deviations of added phosphate, resulted in approximately 24 hours retardation of final set. Further tests at 0,5 and 1,0 standard deviations of additional phosphate gave more severe retardation than was the case for boron.

Figure 5.15
Setting time of OPC and FA mixes
with added anions



Subsequent tests, reported in the paper by Grieve and Kruger,[274] showed that the actual level of phosphate available from the Matla fly ash which could have taken part in influencing the setting times was negligible. The levels of addition made in these tests were thus somewhat higher than expected when the figures in table 5.10 are considered. The conclusion reached from the limited evidence reported in the paper by Grieve and Kruger[274] was that boron was more likely to be a factor in variations of setting time of mixes containing fly ash.

It should be noted that the alkali content of fly ashes has been reported to influence the setting time, with, in theory, a high alkali content leading to shorter setting time[79]. The order of magnitude of the variation in alkali contents of the Matla fly ash is similar to that reported by Ravina and Mehta[79] but they found that the change in setting time did not correlate well with the change in total equivalent alkali content of the fly ash: they postulated that this might be due to the fact that the setting time would correlate better with the water soluble alkali content. The variation in the total equivalent alkali contents of the two ash samples for which setting time comparisons are available, i.e. those given in table 5.8, is small and therefore, barring the possibility of the water soluble alkali contents being very different to each other, the alkali content is probably not responsible for the change in setting time. A further point to consider here is that, as in the case of the phosphates, the level of equivalent alkali which is available during the period leading up to setting of the mix is probably much lower than the figures given in table 5.8.

However both Ravina and Mehta[79] and Haque et al[51] believe that the sulphate content has an influence on the setting time. In this case there is a significant difference between the values reported for the two ashes in table 5.8. The indication from the results given in table 5.11 confirms that an increase in the level of sulphates in a fly ash will tend to result in a greater delay to setting time.

5.3.5 Temperature effects

Table 5.12a gives the results of tests done to establish the initial setting time of mortars at different temperatures. This information is depicted graphically in figure 5.16a. It is evident from figure 5.16a that the use of fly ash makes the mortar more sensitive to the curing temperature. This finding is in agreement with those of Rivera[93] and Collepardi.[118] The effect of low temperatures is to aggravate the retardation caused by the fly ash. On the other hand the fly ash mortars respond better to high temperatures, and the degree of retardation is reduced.

A similar conclusion can be reached after studying the results given in table 5.12b and figure 5.16b in which the setting times of some blends are compared against one another. The mix proportions of these concretes are given in table 5.12c. The general impression is that at the level of 15 % fly ash the impact is relatively small. For 30 % fly ash content the retardation effect is severe: more severe than is the case for the mix containing 50 % slag. Again it should be noted that the mixes with extenders have not been designed for equivalent strength at 28 days and such an adjustment can be expected to decrease the retarding effect.

Figure 5.16a
Setting time of OPC and FA mortar
at different temperatures

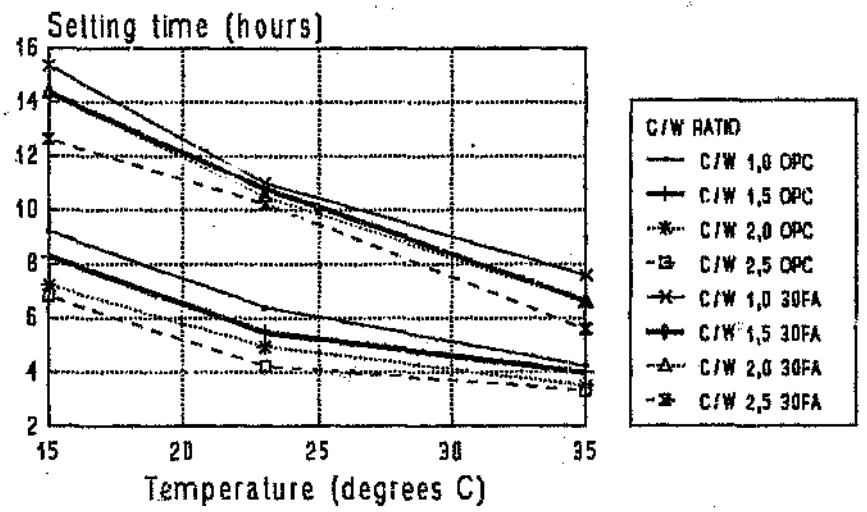
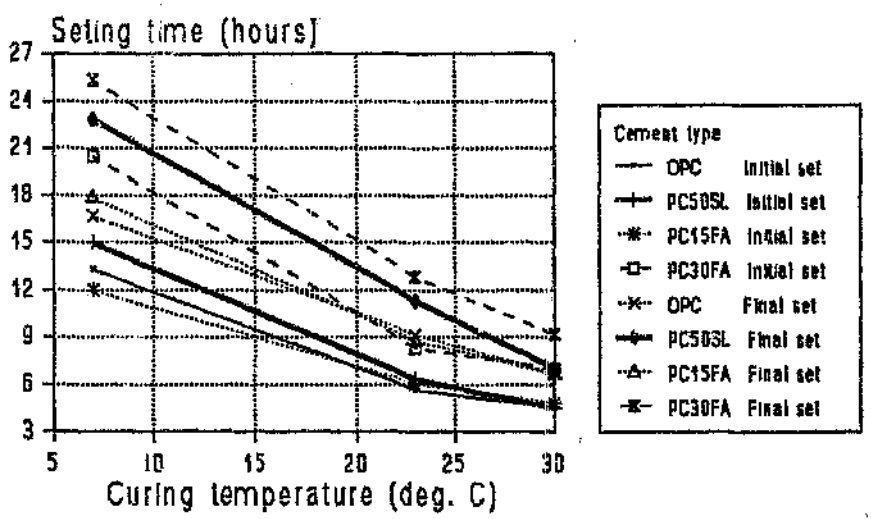


Figure 5.16b
Setting times of OPC, SL and FA mortar
at different temperatures



5.3.6 Results with Lethabo fly ash

Setting time tests were done on a series of combinations of Lethabo fly ash with 3 different samples of ordinary portland cement from the Pretoria–Witwatersrand–Vereeniging marketing area (PWV) under various curing conditions. For comparative purposes table 10.5b gives data on a spectrum of chemical analyses on Lethabo fly ash in a similar way to the information provided for Matla fly ash in table 10.5a. Unlike the case for Matla however, no further use was made of this information.

The mix proportions used are given in table 5.13a. The sand used in these mixes was a decomposed granite sand from the PWV area.

The results of these tests are given in table 5.13b and are shown graphically in figures 5.17a to 5.17f. The nomenclature used in the table and figures is as follows:

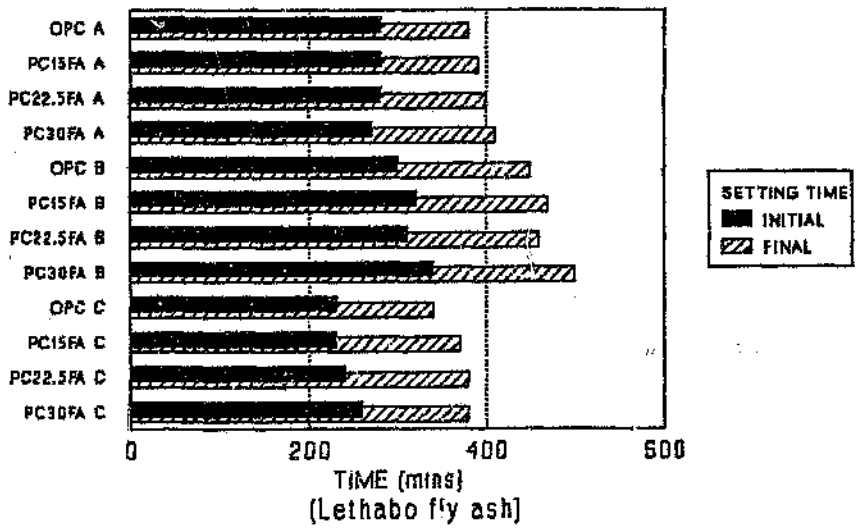
- EQ28 = equivalent 28 day compressive strength design
- DR = direct replacement of fly ash blend for opc cement
- HOT = curing condition ≈ 30 °C
- STD = curing condition ≈ 23 °C
- COLD = curing condition ≈ 7 °C

The cements were derived from three sources and have been identified as A, B and C. The fly ash source was Lethabo. Mixes with the ordinary portland cements were made to give 30 MPa as well as a mix with a fixed cement/water ratio of 1,9.

For EQ28 mixes the concrete was intended to give similar workability in the fresh concrete and similar 28 day compressive strength. The cement/water ratio is not necessarily the same as for the opc mixes. The direct replacement mixes are those where the blend completely replaces the opc mass for mass, but advantage is taken of the water reduction permitted by the fly ash to give the same slump as for the opc mix. Note that in this case the term "direct replacement" signifies the situation on site where the blended cement would be substituted for opc in a site mix with no other adjustment than to ensure that the slump remains constant at the level used for the opc mix. Here the direct replacement is with a blended cement and not with fly ash as referred to in chapter 3.

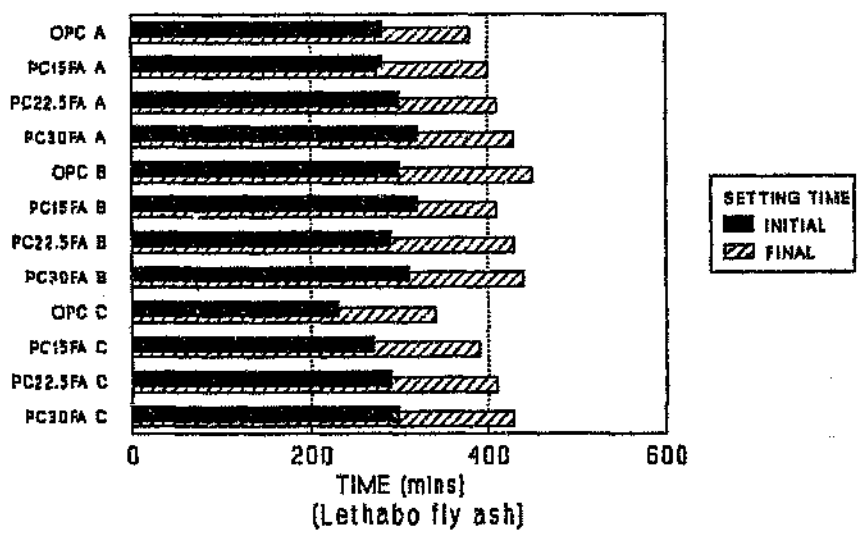
Again the cement/water ratio is not necessarily the same as for the opc mixes.

Figure 5.17a
Initial and final setting times for equivalent 28 day mixes (hot curing)



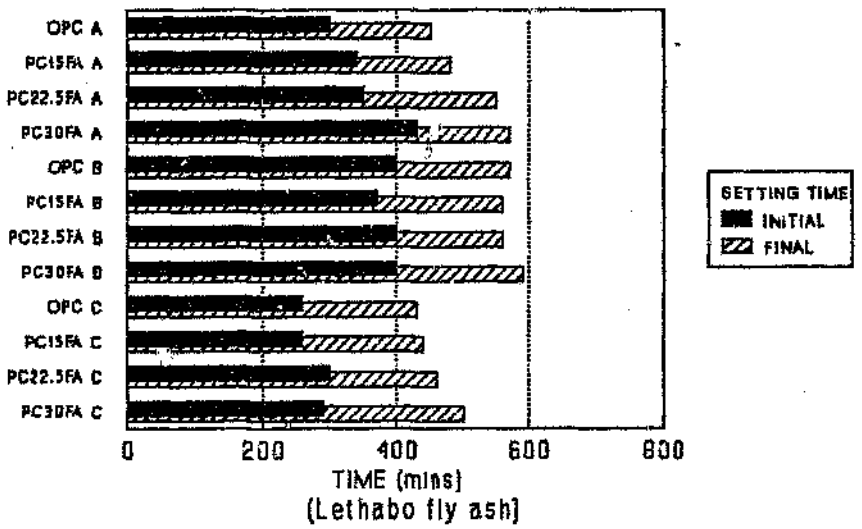
Lethabo fly ash

Figure 5.17b
Initial and final setting times for direct replacement mixes (hot curing)



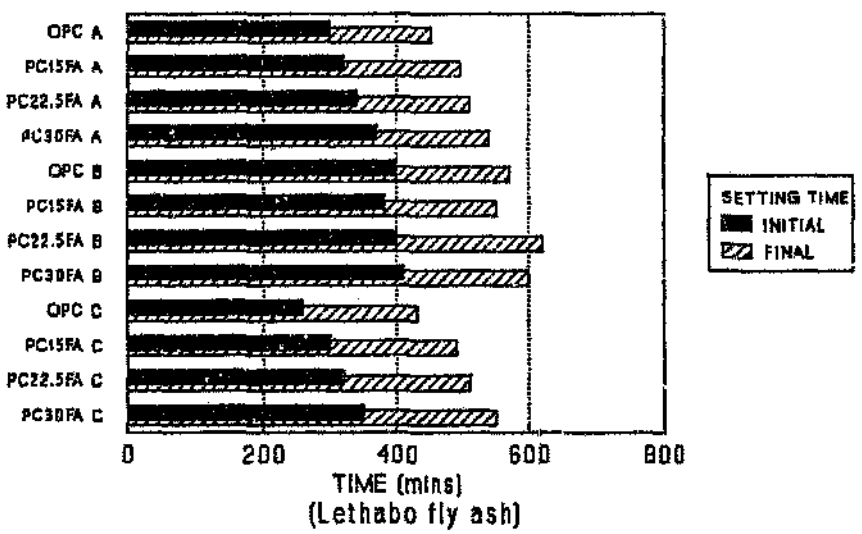
Lethabo fly ash

Figure 5.17c
Initial and final setting times for
equivalent 28 d mixes (standard curing)



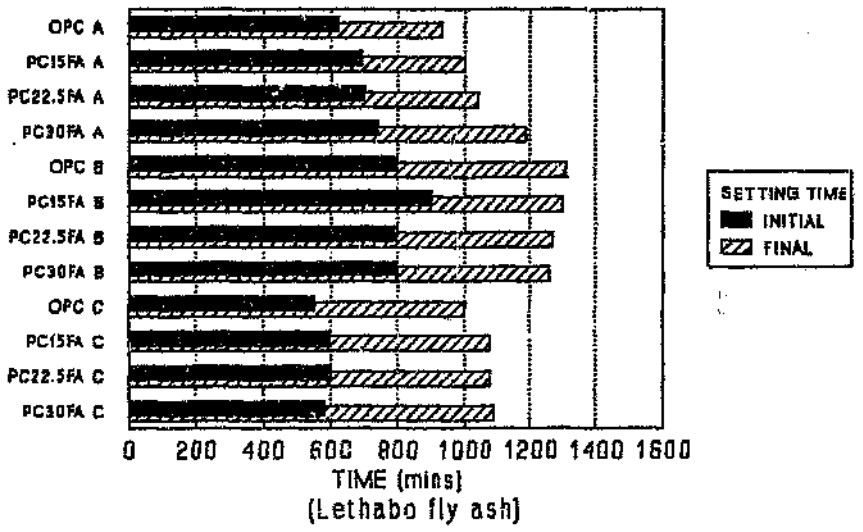
Lethabo fly ash

Figure 5.17d
Initial and final setting times for
direct replacement mixes (standard cure)



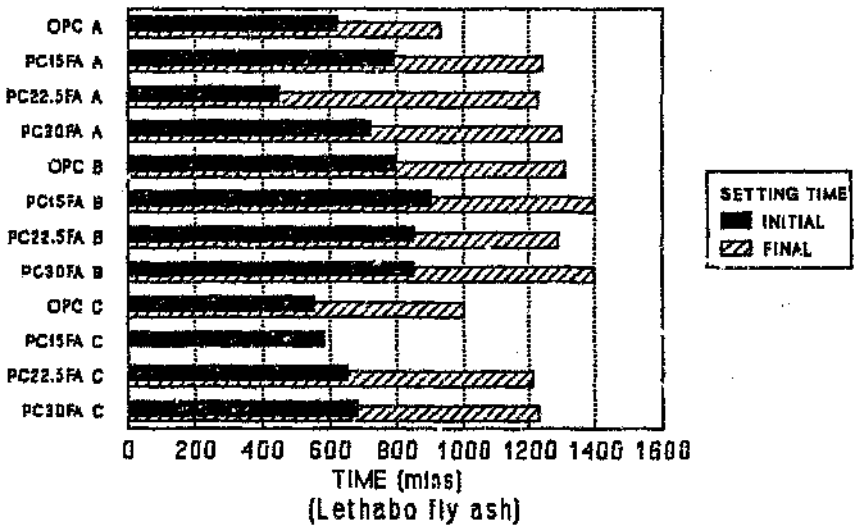
Lethabo fly ash

Figure 5.17e
Initial and final setting times for
equivalent 28 day mixes (cold curing)



Lethabo fly ash

Figure 5.17f
Initial and final setting times for
direct replacement mixes (cold curing)



Lethabo fly ash

The results indicate the following:

- The trend is for the initial and final setting times to show a small increase as the fly ash content increases under hot conditions.

- The trend under standard curing conditions is for the initial and final setting times to increase by more than 10 % in the case of the cement A blends in designed mixes. The other two cements showed little or no increase in setting time. Under direct replacement conditions this trend is evident for all three cements.

- A similar trend is evident for the cold curing conditions.

- The setting times of the blends generally fall within the ranges of the setting times of the three ordinary portland cements.

There seems therefore to be little impact on the setting times of mortars from the incorporation of Lethabo fly ash in mixes made using the three cements tested in this exercise. This may not however be true for cements from all sources.

5.3.7 Summary of the effect on setting time

In summary therefore it seems that the introduction of Matla fly ash into a mix is likely to increase the setting times with the degree of retardation being proportional to the fly ash content of the mix. Low fly ash contents below 15 % fly ash are unlikely to result in a significantly more retarded mix than might be the case were cements from different sources used. Matla fly ash has the effect of making the mix more sensitive to different curing temperatures.

In the case of the Lethabo fly ash there seems to be a less significant effect on the setting times, although some cements, notably Cement A, do show a similar retardation to that caused by the use of Matla fly ash.

5.4 Bleeding

Bleeding is the phenomenon of the dense components of a concrete or mortar mix settling through the water with the result that water appears on the surface of the compacted mix. If the evaporation rate from this surface is slower than the rate at which the water accumulates at the surface then the bleeding will be visible – when the evaporation rate is faster than the bleed rate then there will be no visible water at the surface and the concrete will be prone to plastic shrinkage cracking.

All cementitious mixes bleed, but the rate, the total volume and the ambient conditions to which the mix is exposed are all factors that determine how much bleed water will accumulate on the surface of the concrete. The problems that can result from heavy bleeding include poor finishes on horizontal or shuttered surfaces, settlement cracking, high permeability and low compressive and flexural strengths.

The bleed rate is dependent on the specific surface of the solid materials in the mix. If there is a lack of fines in the mix the specific surface of the solid components will be low and the bleed rate will be high. The incorporation of fly ash will, because it contributes more volume than the cement being replaced, tend to increase the surface area of the solid components and could therefore be expected to reduce the bleed rate.

On the other hand, because of the retarding effect of the fly ash on the initial setting time of the mix, there is more time in which bleeding can take place and therefore the total bleed volume may be expected to rise.

5.4.1 Test methods used and results obtained

In the initial experimental work done for this project use was made of the Rilem Recommendation MR-6, "Tendency of Water to Separate from Mortars"[275]. In this test similar but separate mortar specimens are prepared for readings at elapsed times of 15 minutes, 30 minutes, 1, 2 and 4 hours. After a reading is taken the specimen is discarded. It can be seen that using such a method it is possible, if the specimens are not identical, to get an apparent decrease in total bleed volume with time.

Tests were done using PPC Jupiter opc and selected Matla fly ash with the mix proportions given in table 5.14a. The results of these tests are given in table 5.14b. These data are depicted graphically in figures 5.18a to 5.18e. The summary of the total bleed volume against fly ash content is given in figure 5.18f.

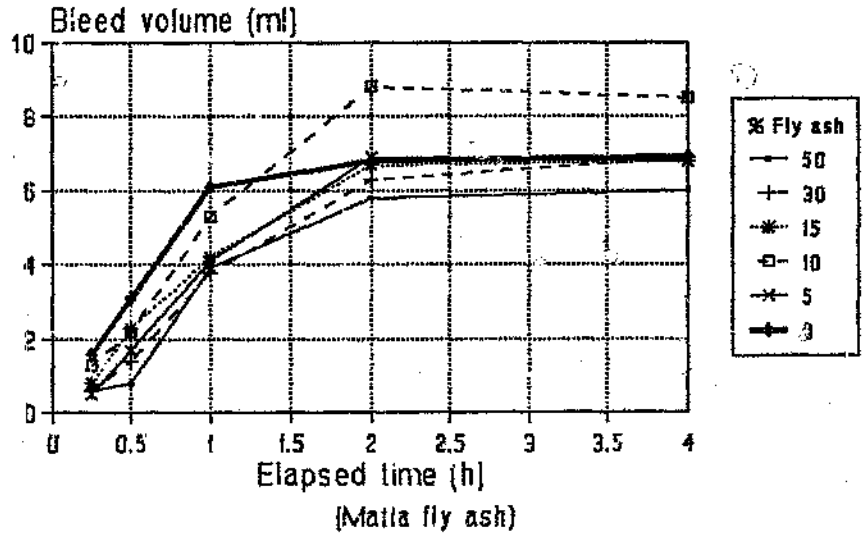
Subsequent tests for bleeding were done using ASTM method C-232[276] as it was felt that the Rilem test was not giving all the required information.

5.4.2 Discussion of findings

In figure 5.18f it seems, if the apparent anomaly at 10 % fly ash is ignored, that there is no definite trend in the bleed volume with the addition of fly ash. However it should be borne in mind that the fly ash tends to retard the setting of the mortar; a mix with a high fly ash content is therefore likely to continue to bleed for a longer period. It is possible that the mixes with the high fly ash contents were still bleeding at the end of the test, but as the Rilem test stops at 4 hours the additional bleeding that might have occurred beyond 4 hours was not recorded.

This is confirmed by looking at figure 5.19 which shows the time at which bleeding ceased for five different mixes. These tests were done using the ASTM method for bleed determination.[276] The fly ash used was from Matla. There is a definite trend for this time to increase as the fly ash content of the mortar mix increases. It is also notable that the time needed to reach the end of the bleeding process is in excess of 4 hours in the cases of both the fly ash mixes.

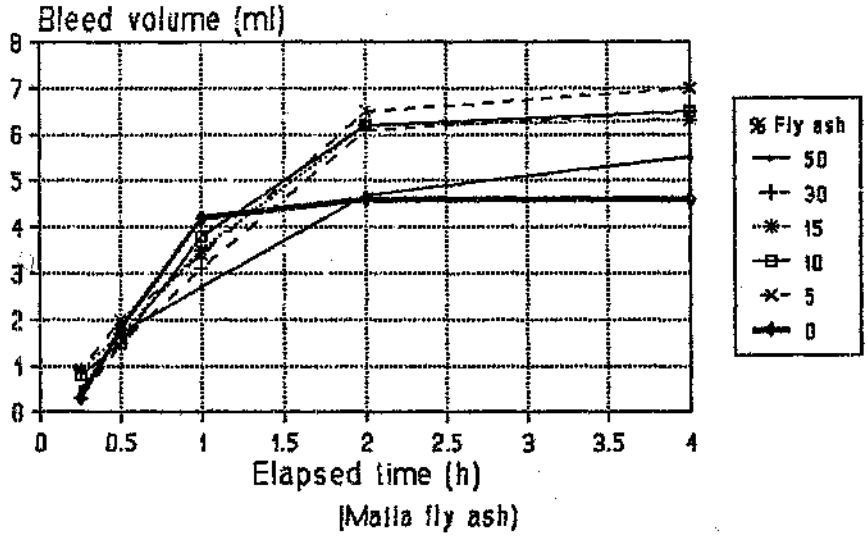
Figure 5.18a
Bleed volume at c/w = 1,0
For varying fly ash contents



(Matla fly ash)

Matla fly ash

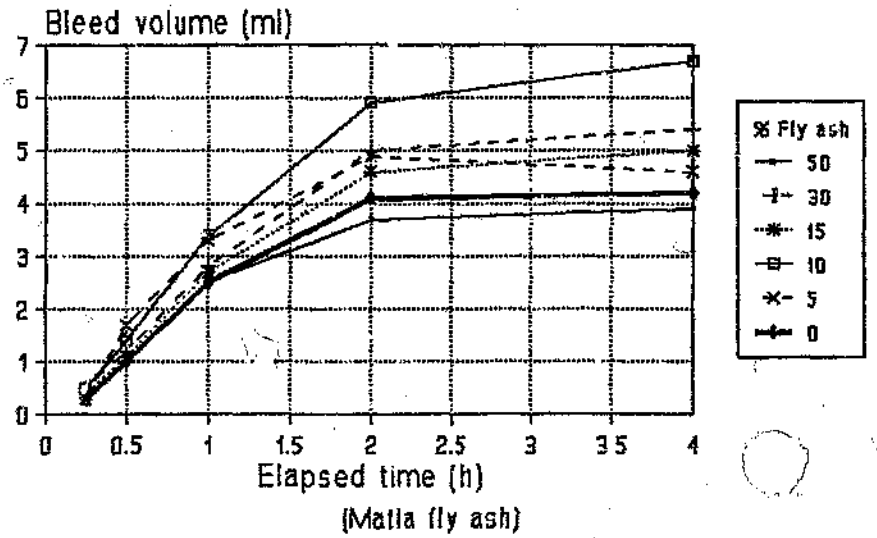
Figure 5.18b
Bleed volume at c/w = 1,5
For varying fly ash contents



(Matla fly ash)

Matla fly ash

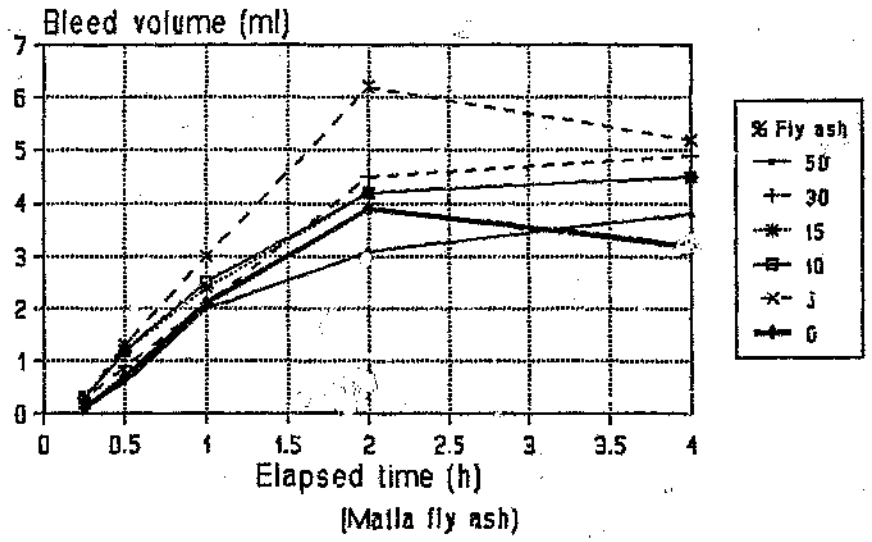
Figure 5.18c
Bleed volume at c/w = 2.0
For varying fly ash contents



(Matla fly ash)

Matla fly ash

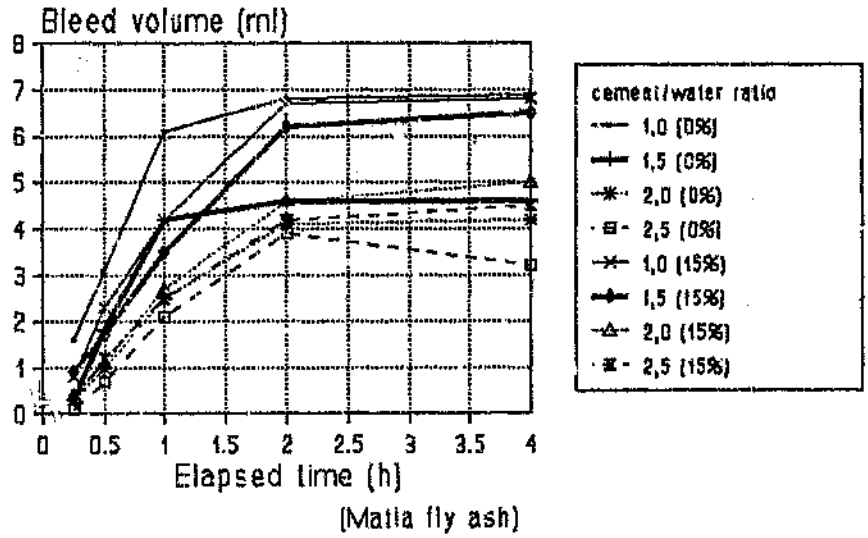
Figure 5.18d
Bleed volume at c/w = 2,5
For varying fly ash contents



(Matla fly ash)

Matla fly ash

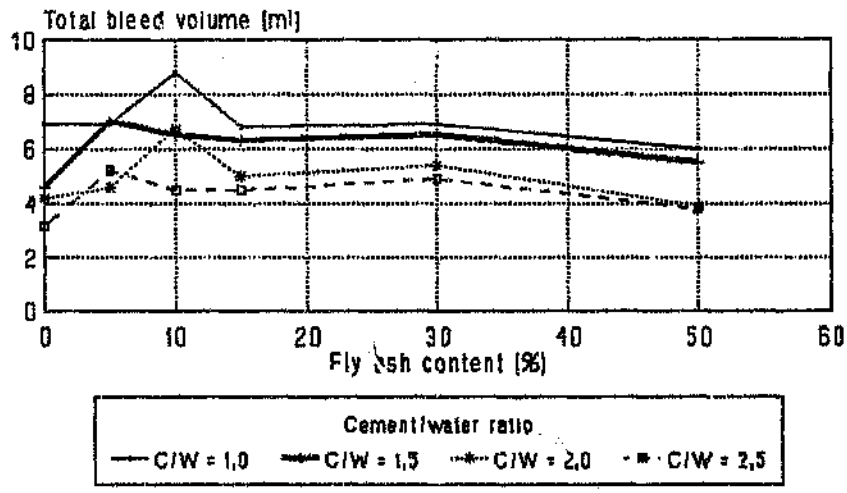
Figure 5.18e
Bleed volume at FA = 0 and 15%
For varying c/w ratios



(Matla fly ash)

Matla fly ash

Figure 5.18f
Bleed volume of mortar mixes
with and without fly ash



(Selected Matla fly ash)

Matla fly ash

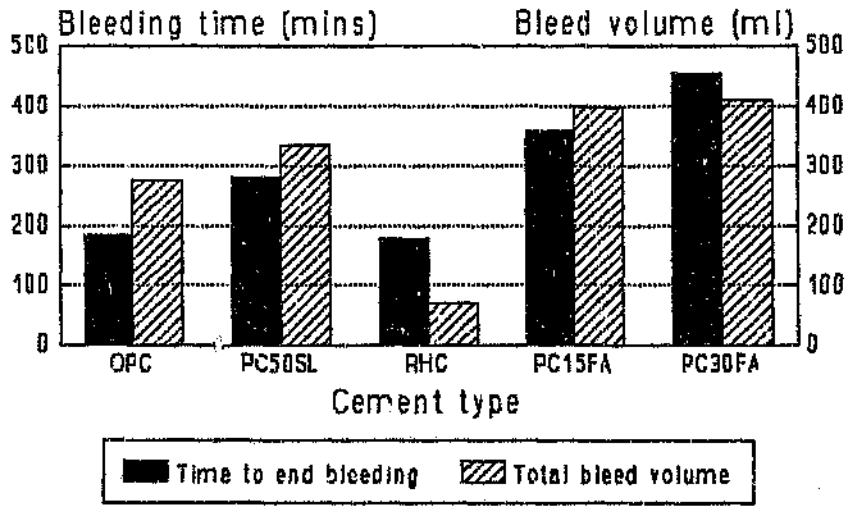
It is clear therefore that the arbitrary selection of the period of 4 hours used for the Rilem test method, while convenient, is inappropriate for the proper assessment of the full bleeding potential of fly ash mixes, particularly when the fly ash content is relatively high and when this results in an increase in the setting time of the mix.

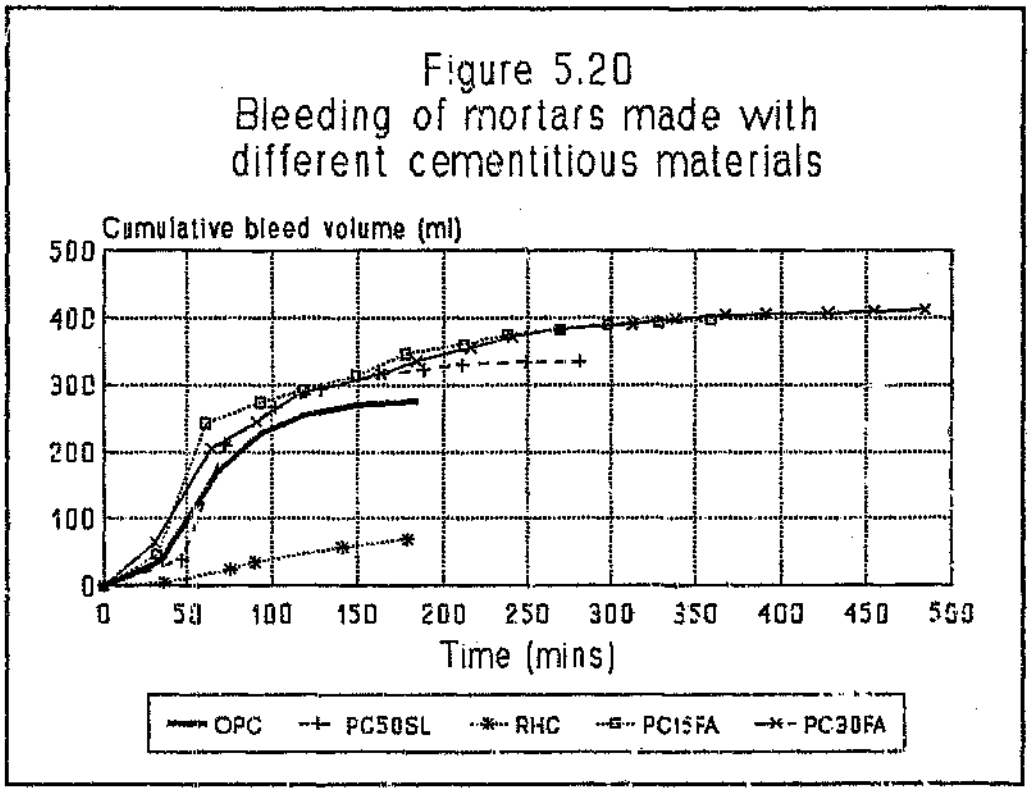
Results of these other ASTM tests on mortars with a combination of different cementitious materials shown in figure 5.19 are given in table 5.15. The proportions used for the concrete mixes from which the mortars were extracted by screening are shown in table 5.12c. In this case classified Matla fly ash was used. Although the cement used in the OPC and PC50SL tests was not from the same source that was used for the PC 15 FA and PC 30 FA cements it appears that the fly ash mixes have higher total bleed volumes than the other mixes tested in this work. The bleed volume as a percentage of total mix water of these mixes is also indicated in table 5.15 based on a test sample size of 13,4 litres. These data indicate that fly ash does indeed increase the bleeding of concrete.

Table 5.16 gives the data for the progression of bleeding with tie for these mixes. Figure 5.20 shows the information graphically. It seems that there is little significant change in the bleed rate with the use of fly ash.

No work was done on the effect on the bleeding of mixes resulting from the incorporation of Lethabo fly ash.

Figure 5.19
Bleeding performance of mortars
with and without fly ash (C/W = 1,67)





5.4.3 Summary on property of bleeding

The use of Matla fly ash seems to result in some increase in the bleed volume relative to the equivalent ordinary portland cement mix as shown in figure 5.18. Table 5.15 gives an indication that a greater proportion of the bleed capacity of a concrete can be realised with fly ash mixes even though the water content of the mix is reduced. The rate of bleeding shown in figure 5.18e on the other hand seems to be lower for the fly ash mixes. This is contradicted by the information on figure 5.20. However as the mixes detailed in table 5.15 all have the same cement/water ratio they will not reach compressive strength parity at 28 days; adjustments to the mix proportions to ensure 28 day compressive strength parity will tend to reduce the differences shown in this table and in figure 5.20.

As Lethabo fly ash seems to generally have a smaller impact on the setting times it is possible that with the bleed rate being similar to that fro opc, the overall bleed volume will probably also reduce.

It is believed that a wider spectrum of aggregates needs to be tested in this way to improve the level of understanding of the impact that fly ash has on bleeding of mortars and concretes.

5.5 Summary of fresh concrete properties

The effect that Matla (and in some cases Lethabo) fly ash has on the fresh properties of concrete and mortar are summarised in the paragraphs below.

5.5.1 Workability

- The inclusion of Matla or Lethabo fly ash in a cementitious mix improves the flow characteristics of the mix when compared with a similar mix without the fly ash.

- This effect can be expressed as the volume of water that can be removed from the mix while still giving the same slump, i.e. the water reduction.

- The magnitude of the water reduction depends on the source of the ordinary portland cement used, some sources allowing more improvement than others. More data is required for a better understanding of the interaction between cement and fly ash.

- There is no apparent link between the "water demand" of the cement and the magnitude of the water reduction that occurs with the use of fly ash.

- Introduction of fly ash makes only an insignificant difference to the overall concrete grading, and the fly ash particle shape and its dispersive effect are probably more significant mechanisms in the water reduction process.

- A first approximation for the magnitude of the water reduction which will occur on using Matla fly ash is:

  Water reduction (l/m^3) = 0,55 x fly ash content (%)

  In the case of Lethabo fly ash the available data suggests that this fly ash is a slightly more effective water reducer giving a constant in the above formula of 0,59.

5.5.2 Viscosity

The information obtained from the viscosity tests is of some use to the users of cement. However it is difficult to interpret what the implications of a moderate increase in viscosity is to the user, as it is not clear whether this means a reduction in the water requirement of the concrete mix or not. As this test requires relatively sophisticated equipment and careful execution it cannot be regarded as a serious substitute for the site slump test on concrete. Moreover the slump test gives direct information about the degree of workability afforded by the concrete mix at any particular water content.

5.5.3 Setting times

The introduction of Matla fly ash into a mix is likely to increase the setting times with the degree of retardation being proportional to the fly ash content of the mix. Low fly ash contents below 15 % fly ash are unlikely to result in a significantly more retarded mix than might be the case were cements from different sources used. Matla fly ash has the effect of making the mix more sensitive to different curing temperatures.

In the case of the Lethabo fly ash there seems to be a less significant effect on the setting times, although some cements, notably Cement A, do show a similar retardation to that caused by the use of Matla fly ash.

5.5.4 Bleeding

The use of Matla fly ash seems to increase the bleed volume slightly relative to the equivalent ordinary portland cement mix as shown in figure 5.19. The use of fly ash seems to permit a concrete to bleed a greater proportion of the total mix water than for an OPC mix. The rate of bleeding on the other hand seems only marginally higher; for equivalent 28 day compressive strength mixes the rates would probably be similar to the opc bleed rate.

As Lethabo fly ash seems to generally have a smaller impact on the setting times it is possible that with the bleed rate being similar to opc, the overall bleed volume will probably also reduce.

It is believed that a wider spectrum of aggregates needs to be tested in this way to improve the level of understanding of the impact that fly ash has on bleeding of mortars and concretes.

Table 5.1a
Mix proportions of concrete mixes (kg/m^3)

% Fly ash	Materials	c/w 1,0	c/w 1,5	c/w 2,0	c/w 2,5
0	Water	209	205	203	207
	Cement	209	308	406	518
	Fly ash	–	–	–	–
	Stone	1065	1090	1110	1129
	Sand	979	884	789	675
5	Water	206	201	199	203
	Cement	196	286	378	482
	Fly ash	10	15	20	25
	Stone	1070	1095	1115	1125
	Sand	982	892	797	684
10	Water	203	198	196	199
	Cement	183	267	353	448
	Fly ash	20	30	39	50
	Stone	1075	1100	1120	1130
	Sand	986	895	800	691
15	Water	200	194	193	194
	Cement	170	247	328	412
	Fly ash	30	44	58	73
	Stone	1085	1110	1130	1140
	Sand	985	898	800	701
30	Water	193	188	185	188
	Cement	135	197	259	329
	Fly ash	58	85	111	141
	Stone	1110	1130	1150	1160
	Sand	980	894	803	694
50	Water	186	179	176	179
	Cement	93	134	176	224
	Fly ash	93	134	176	224
	Stone	1135	1160	1180	1190
	Sand	973	890	798	688

Note: Fly ash ex Matla; Sand, grit ex Kendal; Stone, dolerite ex Rooikraal

Note: c/w above refers to total cementitious material to water ratio.

Table 5.1b
Slumps recorded from standard mixes (mm)

% Fly ash	Cement source	Mix using			
		c/w 1,0	c/w 1,5	c/w 2,0	c/w 2,5
0	PPC Jup	65	70	65	60
	BC Licht	80	80	65	45
	A–A Rood	65	60	60	60
5	PPC Jup	70	65	65	60
	BC Licht	60	70	60	45
	A–A Rood	55	60	55	60
	PPC Blend	70	70	80	80
	PPC Grind	80	60	80	70
10	PPC Jup	50	70	70	65
	BC Licht	60	65	50	50
	A–A Rood	60	75	60	50
15	PPC Jup	70	60	65	65
	BC Licht	75	50	50	50
	A–A Rood	70	65	65	50
	PPC Blend	65	75	65	65
	PPC Grind	60	65	65	65
30	PPC Jup	75	70	65	65
	BC Licht	60	55	65	50
	A–A Rood	60	70	85	40
50	PPC Jup	70	65	70	75
	BC Licht	50	60	50	55
	A–A Rood	60	65	55	40

LEGEND:
PPC Jup = PPC Jupiter
BC Licht = Blue Circle Lichtenburg
A–A Rood = Anglo Alpha Roodepoort
PPC Blend = Blended PPC cement
PPC Grind = Interground PPC cement

Table 5.1c
Water reductions given by fly ash mixes relative to opc control mixes (litres per m^3); Matla fly ash

Fly ash	Cement source	c/w 1,0	c/w 1,5	c/w 2,0	c/w 2,5
0	PPC Jup	0	0	0	0
	BC Licht	0	0	0	0
	A-A Rood	0	0	0	0
	PPC Blend	–	–	–	–
	PPC Grind	–	–	–	–
5	PPC Jup	3	4	4	4
	BC Licht	3	4	4	4
	A-A Rood	-2	4	-1	4
	PPC Blend	3	4	4	4
	PPC Grind	3	4	4	4
10	PPC Jup	1	7	7	8
	BC Licht	6	7	2	8
	A-A Rood	6	7	7	3
	PPC Blend	–	–	–	–
	PPC Grind	–	–	–	–
15	PPC Jup	9	11	10	13
	BC Licht	9	8	5	13
	A-A Rood	9	11	10	8
	PPC Blend	9	11	10	13
	PPC Grind	9	11	10	13
30	PPC Jup	16	17	18	19
	BC Licht	16	17	13	19
	A-A Rood	16	17	18	9
	PPC Blend	–	–	–	–
	PPC Grind	–	–	–	–
50	PPC Jup	23	26	27	28
	BC Licht	18	26	22	28
	A-A Rood	23	26	22	18
	PPC Blend	–	–	–	–
	PPC Grind	–	–	–	–

Table 5.1d
Additional data on water reductions using Matla fly ash (in litre per m^3); Mixes as per table 4.8

% Fly ash	Cement source	c/w ratio	Water reduction (litre/m^3)
15	PPC Slurry	2,00	10,5
	BC Lichtenburg	1,80	12,0
	A–A Ulco	1,80	11,0
30	PPC Slurry	2,13	23,5
	BC Lichtenburg	1,93	23,0
	A–A Ulco	1,93	15,0
These data obtained from commercial work at PCI.			

Table 5.1e
Water contents (ℓ/m^3) of OPC/fly ash mixes at 75 mm slump using Lethabo fly ash; mixes as per table 4.9

c/w ratio	Fly ash content %	Cement source		
		A	B	C
1,7	0	205	204	209
1,9	0	204	203	209
2,1	0	205	204	212
1,8	15	200	196	205
2,0	15	200	193	200
2,2	15	200	195	202
1,9	22,5	197	192	197
2,1	22,5	197	195	197
2,3	22,5	200	192	197
2,0	30	195	194	190
2,2	30	195	190	188
2,4	30	195	187	188

Table 5.1f
Water reduction in litres/m³ relative to the OPC mix using Lethabo fly ash

c/w ratio	fa content %	Cement source		
		A	B	C
2,1	0	0,0	0,0	0,0
1,8	15	4,7	7,7	5,0
2,0	15	4,7	10,7	10,0
2,2	15	4,7	8,7	8,0
1,9	22,5	7,7	11,7	13,0
2,1	22,5	7,7	8,7	13,0
2,3	22,5	4,7	11,7	13,0
2,0	30	9,7	9,7	20,0
2,2	30	9,7	13,7	22,0
2,4	30	9,7	16,7	22,0

Table 5.2
Quantities of materials used for paste mixes (gram); Matla fly ash

Material	c/w	OPC	Fly ash	Slag	CSF	Water
Pure cement	1.30	505.6	–	–	–	389.0
	1.67	599.6	–	–	–	359.0
PC5FA	1.30	477.8	25.1	–	–	386.9
	1.67	566.0	29.8	–	–	356.8
PC15FA	1.30	423.0	74.6	–	–	382.8
	1.67	500.1	88.3	–	–	352.3
PC50FA	1.30	240.0	240.0	–	–	369.2
	1.67	281.9	281.9	–	–	337.6
PC50SL	1.30	250.9	–	250.9	–	385.9
	1.67	297.0	–	297.0	–	355.7
PC5CSF	1.30	477.4	–	–	25.1	386.5
	1.67	565.4	–	–	29.8	356.4
Fly ash	1.30	–	456.8	–	–	351.4
	1.67	–	532.2	–	–	318.6
Slag	1.30	–	–	497.8	–	382.9
	1.67	–	–	588.6	–	352.5

Table 5.3
Details of sources of materials for paste mixes
used for the viscosity testing

Mix No.	Cement source	Fly ash source	GGBS source	CSF source	% extender
1	BC Licht	–	–	–	0
2	BC Licht	Matla	–	–	15
3	BC Licht	Matla	–	–	50
4	A–A Rood	–	–	–	0
5	A–A Rood	Matla	–	–	15
6	A–A Rood	Matla	–	–	50
7	PPC Jup 1	–	–	–	0
8	PPC Jup 1	Matla	–	–	15
9	PPC Jup 1	Matla	–	–	50
10	PPC Jup 2	–	–	–	0
11	PPC Jup 2	Matla	–	–	15 blend
12	PPC Jup 2	Matla	–	–	15 grind
13	PPC Jup 1	Duvha	–	–	15
14	PPC Jup 1	Duvha	–	–	50
15	PPC Jup 1	–	Pretoria	–	50
16	–	–	Pretoria	–	100
17	PPC Jup 1	–	–	Pietersburg	5
18	–	Matla	–	–	100
19	PPC Jup 1	–	–	–	0
20	PPC Jup 1	Matla	–	–	15
21	PPC Jup 1	Matla	–	–	50

LEGEND:
BC Licht = Blue Circle Lichtenburg
A–A Rood = Anglo Alpha Roodepoort
PPC Jup 1 = PPC Jupiter (silo)
PPC Jup 2 = PPC Jupiter (additional sample)

Table 5.4a
Shear stress values (Pa) for paste mixes at various shear rates

Shear rate 1/s	c/w ratio = 1,30											
	Mix No. 1	Mix No. 2	Mix No. 3	Mix No. 4	Mix No. 5	Mix No. 6	Mix No. 7	Mix No. 8	Mix No. 9	Mix No. 10	Mix No. 11	Mix No. 12
109,7	2,2	2,1	2,3	2,0	2,0	2,1	2,0	1,9	1,9	1,8	1,8	1,9
163,9	2,6	2,5	2,7	2,5	2,4	2,5	2,4	2,3	2,4	2,1	2,2	2,2
216,6	3,0	2,9	3,1	2,7	2,7	2,8	2,7	2,7	2,7	2,4	2,5	2,5
273,6	3,4	3,3	3,4	3,1	3,0	3,1	3,0	3,0	3,1	2,7	2,7	2,8
327,7	3,8	3,6	3,6	3,4	3,3	3,4	3,2	3,3	3,4	2,9	3,0	3,1
327,7	4,2	3,9	3,8	3,5	3,4	3,4	3,3	3,3	3,3	3,0	3,1	3,2
273,6	3,7	3,5	3,4	3,1	3,0	3,1	3,0	3,0	3,0	2,7	2,8	2,9
216,6	3,3	3,1	3,0	2,7	2,6	2,7	2,6	2,6	2,6	2,4	2,4	2,5
163,9	2,8	2,7	2,6	2,5	2,3	2,3	2,4	2,3	2,2	2,1	2,1	2,2
109,7	2,4	2,2	2,1	2,1	1,9	2,0	2,0	1,9	1,8	1,8	1,8	1,9
Temp °C	20,6	20,9	20,7	23,7	23,7	23,3	23,5	23,3	23,3	23,6	23,2	23,8

Table 5.4a
Shear stress values (Pa) for paste mixes at various shear rates

Shear rate 1/s	c/w ratio = 1,30											
	Mix No. 1	Mix No. 2	Mix No. 3	Mix No. 4	Mix No. 5	Mix No. 6	Mix No. 7	Mix No. 8	Mix No. 9	Mix No. 10	Mix No. 11	Mix No. 12
109,7	2,2	2,1	2,3	2,0	2,0	2,1	2,0	1,9	1,9	1,8	1,8	1,9
163,9	2,6	2,5	2,7	2,5	2,4	2,5	2,4	2,3	2,4	2,1	2,2	2,2
216,6	3,0	2,9	3,1	2,7	2,7	2,8	2,7	2,7	2,7	2,4	2,5	2,5
273,6	3,4	3,3	3,4	3,1	3,0	3,1	3,0	3,0	3,1	2,7	2,7	2,8
327,7	3,8	3,6	3,6	3,4	3,3	3,4	3,2	3,3	3,4	2,9	3,0	3,1
327,7	4,2	3,9	3,8	3,5	3,4	3,4	3,3	3,3	3,3	3,0	3,1	3,2
273,6	3,7	3,5	3,4	3,1	3,0	3,1	3,0	3,0	3,0	2,7	2,8	2,9
216,6	3,3	3,1	3,0	2,7	2,6	2,7	2,6	2,6	2,6	2,4	2,4	2,5
163,9	2,8	2,7	2,6	2,5	2,	2,3	2,4	2,3	2,2	2,1	2,1	2,2
109,7	2,4	2,2	2,1	2,1	1,9	2,0	2,0	1,9	1,8	1,8	1,8	1,9
Temp °C	20,6	20,9	20,7	23,7	23,7	23,3	23,5	23,3	23,3	23,6	23,2	23,8

Table 5.4b
Shear stress values (Pa) for paste mixes at various shear rates

Shear rate (1/s)	c/w ratio = 1,67											
	Mix No. 1	Mix No. 2	Mix No. 3	Mix No. 4	Mix No. 5	Mix No. 6	Mix No. 7	Mix No. 8	Mix No. 9	Mix No. 10	Mix No. 11	Mix No. 12
109,7	4,6	4,7	4,7	4,4	4,2	4,3	4,1	4,0	4,0	3,7	3,7	3,9
163,9	5,5	5,6	5,6	5,2	5,0	5,1	4,9	4,8	4,8	4,4	4,4	4,6
216,6	6,3	6,4	6,4	5,8	5,7	5,8	5,5	5,4	5,5	5,0	5,0	5,2
273,6	7,1	7,1	7,0	6,4	6,1	6,4	6,1	6,0	6,1	5,5	5,5	5,8
327,7	7,7	7,6	7,7	6,9	6,5	7,1	6,8	6,7	6,6	5,9	6,0	6,3
327,7	10,0	9,2	8,2	8,0	7,6	7,3	7,6	7,1	6,8	6,7	6,6	7,1
273,6	9,2	8,5	7,6	7,0	6,8	6,7	6,8	6,5	6,2	6,1	5,9	6,3
216,6	8,3	7,5	6,7	6,2	6,0	5,9	6,0	5,8	5,5	5,4	5,2	5,6
163,9	7,4	6,6	5,9	5,4	5,2	5,2	5,3	5,1	4,8	4,7	4,6	4,8
109,7	6,2	5,7	5,0	4,6	4,4	4,3	4,5	4,4	4,0	4,0	3,9	4,1
Temp °C	21,0	21,1	21,0	24,3	24,0	23,7	23,9	23,8	23,3	23,8	23,5	24,0

Table 5.4c
Shear stress values (Pa) for paste mixes at various shear rates

Shear rate	c/w ratio = 1,30					
	Mix No.	Mix No.	Mix No.	Mix No.	Mix No.	Mix No.
1/s	13	14	15	16	17	18
109,7	2,3	4,2	2,1	1,9	4,9	2,5
163,9	2,8	5,3	2,6	2,3	5,4	2,9
216,6	3,2	6,3	2,9	2,7	5,9	3,3
273,6	3,5	7,2	3,3	3,1	6,5	3,7
327,7	3,9	7,9	3,6	3,4	7,1	4,2
327,7	3,7	7,7	3,7	3,4	6,5	4,2
273,6	3,4	6,8	3,3	3,1	6,1	3,7
216,6	3,0	5,5	2,8	2,6	5,5	3,3
163,9	2,6	4,9	2,5	2,1	5,0	2,9
109,7	2,2	3,9	2,1	1,7	4,5	2,4
Temp °C	24,2	23,6	23,5	23,2	24,0	23,0

Table 5.4d
Shear stress values (Pa) for paste mixes at various shear rates

Shear rate (1/s)	c/w ratio = 1,67					
	Mix No. 13	Mix No. 14	Mix No. 15	Mix No. 16	Mix No. 17	Mix No. 18
109,7	5,2	Too viscous	4,9	4,9	10,8	4,8
163,9	6,3		5,9	6,0	11,8	5,7
216,6	7,2		6,7	6,9	13,0	6,5
273,6	8,0		7,4	7,9	14,0	7,2
327,7	8,6		8,0	8,7	14,9	7,7
327,7	9,5		9,2	9,6	15,5	7,5
273,6	8,6		8,4	8,5	15,0	6,9
216,6	7,6		7,4	7,3	14,1	6,2
163,9	6,6		6,4	6,2	13,1	5,4
109,7	5,6		5,4	4,9	11,8	4,5
Temp °C	24,9	24,0	24,3	23,7	25,1	23,0

Table 5.4e
Shear stress values (Pa) for paste mixes at various shear rates
and the change with time (t) in hours

Shear rate ($1/s$)	c/w ratio = 1,67											
	Mix No. 19				Mix No. 20				Mix No. 21			
	t=0h	t=1,5 h	t=3h	t=5h	t=0h	t=1,5 h	t=3h	t=5h	t=0h	t=1,5 h	t=3h	t=5h
109,7	3,8	4,8	5,9	11,6	3,8	5,0	5,2	8,0	4,4	5,6	5,9	5,9
163,9	4,7	5,7	6,8	12,8	4,6	5,9	6,1	9,1	5,2	6,6	6,7	6,9
216,6	5,5	6,3	7,6	14,1	5,3	6,6	6,8	10,0	6,0	7,4	7,5	7,7
273,6	6,3	7,1	8,3	15,2	5,9	7,2	7,5	10,9	6,6	8,1	8,2	8,4
327,7	7,2	7,8	9,2	16,1	6,5	7,9	8,1	11,8	7,3	8,7	8,8	9,2
327,7	7,7	8,5	10,4	16,1	7,2	8,2	9,0	12,4	7,5	8,9	8,9	9,3
273,6	6,7	7,6	9,5	15,1	6,4	7,7	8,3	11,5	6,8	8,1	8,1	8,6
216,6	5,8	6,6	8,3	13,8	5,6	6,7	7,4	10,4	6,1	7,3	7,4	7,8
163,9	5,0	5,7	7,2	12,5	4,9	5,8	6,5	9,3	5,3	6,5	6,5	6,9
109,7	4,1	4,7	6,1	11,0	4,1	4,9	5,5	8,1	4,4	5,4	5,5	5,9
Temp °C	24,0	25,0	24,8	25,9	23,8	24,2	24,1	24,5	24,1	24,3	23,9	23,8

Table 5.5a
Evaluation of difference between concrete and mortar setting times using ASTM C403–88 for OPC (penetration resistance in psi at various times); to mixes in table 4.11

Concrete		Mortar 1		Mortar 2	
Time	Resist.	Time	Resist.	Time	Resist.
4,28	210	4,40	111	3,78	133
4,83	353	4,81	173	4,18	213
5,33	657	5,40	400	4,72	390
5,42	800	5,67	513	4,97	463
5,83	1083	5,78	573	5,08	533
6,58	1978	5,91	767	5,10	627
7,08	3520	6,44	1168	5,75	1027
7,45	4025	6,74	1363	6,12	1547
7,64	4640	7,23	2001	6,65	2107
8,33	6000	7,71	3387	7,08	3347
		8,09	4027	7,45	4027
				7,70	4373
NOTE: Mix using PPC Jupiter OPC at c/w = 1,9					

Table 5.5b
Evaluation of difference between concrete and mortar setting times using ASTM C403-88 for PC30FA (penetration resistance in psi at various times); to mixes in table 4.11

Concrete		Mortar 1		Mortar 2	
Time	Resist.	Time	Resist.	Time	Resist.
5.43	50	6.10	55	5.02	50
6,42	200	6,47	140	5,70	133
7,08	393	7,03	160	6,08	200
7,45	520	7,70	347	6,57	320
7,52	533	8,00	497	7,30	583
8,00	840	8,03	693	7,35	600
8,73	1453	8,67	1027	7,65	827
9,05	1873	9,48	1720	8,23	1107
9,68	3160	9,93	2200	9,02	2000
10,47	4500	10,38	3493	9,55	3200
10,92	5480	10,75	4053	9,95	3787
				10,35	4560

NOTE: Mix using PPC Jupiter OPC and classified Matla fly ash at c/w = 1,9

Table 5.6
Initial setting time in hours (at 22 to 25 °C)
to mixes in table 4.12

% Fly ash	Cement source PPC Jupiter			
	c/w 1,0	c/w 1,5	c/w 2,0	c/w 2,5
0	6,40	5,50	4,95	4,25
5	7,35	6,50	5,90	5,45
10	7,75	7,50	7,15	6,25
15	8,55	8,25	7,50	7,10
30	11,00	10,80	10,50	10,25
50	14,30	14,50	14,50	14,50
NOTE: Mix using PPC Jupiter OPC and selected Matla fly ash.				

Table 5.7a
Setting times of other cements with and without Matla fly ash; to mixes in table 4.8

Cement source	Cement water ratio	Percent fly ash	Initial setting time (h)	Final setting time (h)
Anglo–Alpha	1,82	0	4,75	6,75
	1,70	0	5,17	7,08
	1,80	15	6,25	8,75
	1,93	30	7,25	9,83
Blue Circle Lichtenburg	1,82	0	7,50	10,08
	1,70	0	7,67	10,17
	1,80	15	9,00	11,58
	1,93	30	10,83	14,00
PPC Slurry	1,90	0	5,75	8,33
	2,00	15	6,58	9,50
	2,13	30	9,58	12,50
NOTE: Classified Matla fly ash used				

Table 5.7b
Setting times of other cements with and without Matla fly ash

Cement source	Cement water ratio	% fly ash/slag content		Initial setting time (h)	Final setting time (h)
		fly ash	slag		
PPC Jup	1,67	0		5,67	9,17
PPC Jup	1,67	–	50	6,33	11,33
BC PC15FA	1,67	15	–	6,08	8,75
BC Licht	1,67	30	–	8,33	12,83

LEGEND PPC Jup = PPC Jupiter
BC PC15FA = Blue Circle 15 % fly ash cement
BC Licht = Blue Circle Lichtenburg

Table 5.8
Oxide and trace element analysis of two ashes

Compound	Matla classified	Matla selected
SiO_2 (%)	49,23	39,10
TiO_2 (%)	1,65	1,61
Al_2O_3 (%)	30,50	27,57
Fe_2O_3 (%)	3,49	5,28
MnO (%)	0,03	0,06
MgO (%)	2,18	3,67
CaO (%)	7,23	14,54
Na_2O (%)	0,37	0,57
K_2O (%)	0,99	0,81
Na_2O eq (%)	1,02	1,10
P_2O_5 (%)	1,21	1,83
H_2O (%)	0,07	0,13
LOI (%)	1,12	2,92
SO_3 (%)	1,23	2,21
Ba (ppm)	1958	2375
Sn (ppm)	36	35
Zn (ppm)	35	37
Cu (ppm)	54	65
Ni (ppm)	55	76
Co (ppm)	18	33
Mn (ppm)	281	514
Cr (ppm)	195	199
V (ppm)	123	161
La (ppm)	118	115
Ce (ppm)	234	231
Nd (ppm)	105	105
Mo (ppm)	19	24
Nb (ppm)	49	48
Zr (ppm)	486	443
Y (ppm)	82	80
Sr (ppm)	2828	4022
U (ppm)	7,5	5,9
Rb (ppm)	58	45
Th (ppm)	47	44
Pb (ppm)	85	65
Br (ppm)	<1,5	<1,7
Se (ppm)	9,4	8,3
Bi (ppm)	4,3	3,4
As (ppm)	16	20
Ge (ppm)	8,9	11
W (ppm)	11	18
Ga (ppm)	58	71

Table 6.9
Evaluation of effect of different cations on mortar setting times (in hours) using ASTM C403
(penetration resistance in psi at various times); to mixes in table 4.11

OPC		PC30FA		PC30FA+B		PC30FA+S.		PC30FA+Pb	
TIME	RESIST.	TIME	RESIST.	TIME	RESIST.	TIME	RESIST.	TIME	RESIST.
4,27	120	5,08	120	6,87	60	5,40	170	5,77	323
4,83	367	5,50	207	7,23	110	5,80	280	6,11	473
5,17	497	5,78	313	7,70	200	6,43	500	6,77	933
5,48	800	6,08	470	8,25	417	6,45	533	7,21	1406
5,63	790	6,31	540	8,75	598	6,90	937	7,63	1707
5,80	1093	6,55	680	9,25	1060	7,32	1240	8,02	2333
6,10	1455	6,98	1047	9,75	1453	7,70	1547	8,67	4346
6,36	1807	7,75	1973	11,25	4880	8,30	2187		
6,60	2325	8,,17	3320			8,68	3280		
6,85	2793	8,75	4800			9,18	4800		
7,11	3070								
7,58	5626								
NOTE: Classified Matla fly ash used.									

Table 5.10a
Variations with time in chemical properties (%) of Meda fly ash

SAMPLE DATE	Date	23	22	03	01	27	14	04	19	13	13	MEAN	SD	CV (%)
	Month	05	02	10	08	04	04	03	11	08				
	Year	89	90	85	86	86	86	86	87	87				
LOI		1,43	1,31	1,23	1,39	0,92	1,33	0,76	1,04	0,55	0,72	1,07	0,32	30
SiO_2		47,00	47,20	48,50	47,90	47,80	47,80	48,00	46,80	49,10	51,70	47,98	1,50	
Al_2O_3		30,70	28,60	28,80	29,90	29,80	30,70	29,80	27,80	29,90	28,90	29,49	0,94	
Fe_2O_3		3,79	3,96	4,74	4,06	3,96	3,83	3,96	4,26	4,20	3,71	4,05	0,30	7
TiO_2		1,61	1,56	1,69	1,69	1,66	1,66	1,62	1,66	1,44	1,56	1,70	0,15	9
P_2O_5		1,37	1,33	1,27	1,12	1,18	1,15	1,21	1,44	1,32	1,16	1,26	0,11	8
CaO		8,11	9,16	9,69	8,78	8,00	7,11	8,55	9,30	9,22	7,51	8,66	0,85	10
MgO		2,20	2,40	2,60	2,20	2,20	1,90	2,30	2,40	2,00	2,50	2,28	0,27	12
Na_2O		0,60	0,80	0,50	0,50	0,60	0,40	0,10	0,10	0,20	0,70	0,46	0,25	36
K_2O		0,76	0,76	0,87	0,98	0,75	0,80	0,77	1,09	0,53	1,23	0,85	0,19	23
Na_2O eq		1,10	1,29	1,07	1,14	1,09	0,93	0,81	0,78	0,55	1,51	1,01	0,30	30
SO_3		1,01	0,66	0,75	0,70	0,65	0,55	0,60	0,77	0,99	0,54	0,73	0,16	21
Cl		0,00	0,00	0,00	0,00	0,01	0,00	0,00	0,00	0,00	0,02	0,00	0,01	–

Table 5.10b
Variation with time in chemical properties (%) of Lethabo fly ash

Sample date	LETHABO 21-12-89	LETHABO W-20	LETHABO W-21	LETHABO W-22	LETHABO W-23	LETHABO W-24	LETHABO W-25	LETHABO W-26	LETHABO W-27	LETHABO W-28	LETHABO 23-04-90	LETHABO 10-09-90	LETHABO (GORDON)	MEAN	SD	CV
LOI	0,23										0,43	0,39	0,40	0,35	0,11	30,24
SiO2	53,20	55,60	53,50	55,50	55,20	55,10	55,50	55,00	54,50	56,00	53,40	52,90	50,93	54,56	1,06	1,94
Al2O3	32,40	32,20	34,20	33,10	32,40	32,80	32,20	32,60	32,50	31,20	31,90	31,30	35,97	32,40	0,79	2,45
Fe2O3	3,80	3,04	3,04	3,12	3,05	3,04	3,16	2,99	3,14	3,23	3,49	3,22	3,91	3,16	0,19	5,96
TiO2	1,95	1,68	1,71	1,70	1,68	1,69	1,69	1,69	1,68	1,61	1,8[illegible]	1,63	1,80	1,71	0,09	5,28
P2O5	0,60	0,32	0,33	0,32	0,35	0,36	0,35	0,35	0,41	0,33	0,54	0,45	0,66	0,39	0,09	23,56
CaO	4,98	3,60	3,20	3,20	3,50	3,40	3,30	3,20	3,60	3,70	4,68	4,41	4,66	3,74	0,61	16,24
MgO	1,20	1,31	1,06	1,21	1,19	1,31	1,15	1,1[illegible]	1,24	1,45	1,40	1,20	1,36	1,24	0,11	8,91
Na2O	0,30	0,00	0,00	0,00	0,00	0,10	0,10	0,10	0,10	0,10	0,40	0,30	0,32	0,13	0,14	108,5
K2O	0,55	0,52	0,46	0,56	0,47	0,48	0,49	0,49	0,53	0,55	0,58	0,45	0,53	0,51	0,04	8,45
Na2O eq.	0,86	0,34	0,30	0,37	0,31	0,42	0,42	0,42	0,45	0,46	0,78	0,60	0,67	0,46	0,15	31,86
SO3	0,17	0,26	0,26	0,26	0,18	0,22	0,32	0,29	0,29	0,31	0,17	0,18		0,24	0,06	23,66
Cl	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00				0,00	0,00	0,00
Note: period W-20 to W-26 represents 6 consecutive days																

Table 5.11
Setting time of mortars with fly ash and added anions
to mixes in table 4.11

Mix type	Setting time (% of opc)	
	Initial	Final
OPC	100	100
PC30FA	141	138
PC30FA+S1	141	130
PC30FA+S2	127	121
PC30FA+P3	2	169
PC30FA+P4	269	230
PC30FA(f)	149	136

LEGEND:

PC30FA	=	Portland cement with 30 % fly ash
S1	=	Addition of 3xsd Sulphate ion
S2	=	Addition of 6xsd Sulphate ion
P1	=	Addition of 3xsd Phosphate ion
P2	=	Addition of 6xsd Phosphate ion
(f)	=	Screened fine fly ash

Table 5.12a
Setting time at different temperatures (initial setting time)
with Matla fly ash; mixes detailed in table 4.12

% Fly ash	c/w ratio	Setting time (h)		
		T = 35 °C	T = 23 °C	T =15 °C
0	1,0	4,25	6,40	9,25
	1,5	4,00	5,50	8,30
	2,0	3,50	4,95	7,25
	2,5	3,35	4,25	6,85
30	1,0	7,60	11,00	15,35
	1,5	6,65	10,80	14,35
	2,0	6,60	10,50	14,35
	2,5	5,60	10,25	12,65
NOTE: Mix using PPC Jupiter OPC and selected Matla fly ash.				

Table 5.12b
Setting time at different temperatures (Initial and final setting time); Matla fly ash
Mixes as detailed in table 4.13

Cement source	% extender	c/w ratio	Initial set (h)			Final set (h)		
			T=30 °C	T=23 °C	T=7 °C	T=30 °C	T=23 °C	T = 7 °C
PPC	0	1,67	4,50	5,67	13,33	6,67	9,17	16,67
PPC	50 slag	1,67	4,50	6,33	15,00	7,00	11,33	22,83
Blue Circle	15 fly ash	1,67	4,83	6,08	12,00	6,67	8,[illegible]	17,83
Blue Circle	30 fly ash	1,67	7,00	8,33	20,50	9,17	12,83	25,33

Table 5.12c
Mix proportions for mixes to study effect of non-standard curing temperatures on setting times (proportions given in kg/m^3); Matla fly ash

Material	Mix No. 9	Mix No. 10	Mix No. 11	Mix No. 13	Mix No. 14
OPC*	342	171	–	–	216
RHPC	–	–	342	–	–
PC15FA	–	–	–	334	–
Slag	–	171	–	–	–
Fly ash	–	–	–	–	93
Stone	1000	1000	1000	1000	1000
Sand	818	805	818	826	873
Water	205	205	205	200	165
c/w	1,67	1,67	1,67	1,67	1,67

* The OPC used was from 2 sources; for mixes 9 and 10 ex PPC Jupiter
For mixes 13 and 14 the OPC came from Blue Circle Lichtenburg

Table 5.13a
Mortar mix proportions (kg/m^3) for setting time determinations; Lethabo fly ash

MIX	A	B	C	D	E	F	G	O
CEMENT	A	A	A	A	A	A	A	A
TYPE	OPC	PC15 FA	PC22.5 FA	PC30 FA	PC15 FA	PC22.5 FA	PC30 FA	OPC
DESIGN		EQ 28	EQ 28	EQ 28	DR	DR	DR	
C:W RATIO	1,75	1,87	1,99	2,1	1,75	1,75	1,75	1,9
WATER CONTENT	289	284	278	269	286	245	269	283
CEMENT CONTENT	505	532	554	565	500	429	471	538
SAND CONTENT	1432	1399	1383	1385	1423	1579	1470	1419
SLUMP	70	80	90	80	70	70	65	70
MIX	H	I	J	K	L	M	N	P
CEMENT	B	B	B	B	B	B	B	B
TYPE	OPC	PC15 FA	PC22.5 FA	PC30 FA	PC15 FA	PC22.5 FA	PC30 FA	OPC
DESIGN		EQ 28	EQ 28	EQ 28	DR	DR	DR	
C:W RATIO	1,67	1,82	1,93	2,06	1,67	1,67	1,67	1,9
WATER CONTENT	287	275	274	280	277	276	272	267
CEMENT CONTENT	479	501	529	576	462	461	455	508
SAND CONTENT	1457	1448	1416	1347	1479	1472	1477	1485
SLUMP	60	55	55	65	60	70	65	70
MIX	R	S	T	U	V	W	X	Q
CEMENT	C	C	C	C	C	C	C	C
TYPE	OPC	PC15 FA	PC22.5 FA	PC30 FA	PC15 FA	PC22.5 FA	PC30 FA	OPC
DESIGN		EQ 28	EQ 28	EQ 28	DR	DR	DR	
C:W RATIO	1,7	1,88	2,04	2,21	1,7	1,7	1,7	1,9
WATER CONTENT	285	281	265	274	290	285	281	297
CEMENT CONTENT	485	529	541	606	493	484	478	565
SAND CONTENT	1457	1409	1429	1334	1417	1428	1434	1360
SLUMP	40	70	50	70	60	75	75	50

Table 5.13b
Initial and final setting times of mortars made using proportions in Table 5.13a; Letlabo fly ash

CEMENT BLEND	REGIME	INITIAL SET (mins)	FINAL SET (mins)	CEMENT BLEND	REGIME	INITIAL SET (mins)	FINAL SET (mins)	CEMENT BLEND	REGIME	INITIAL SET (mins)	FINAL SET (mins)
OPC A (EQ 28)	HOT	280	380	OPC B (EQ 28)	HOT	300	450	OPC C (EQ 28)	HOT	230	340
	STD	300	450		STD	400	570		STD	260	430
	COLD	620	930		COLD	800	1310		COLD	550	1000
PC15 A (EQ 28)	HOT	280	390	PC15 B (EQ 28)	HOT	320	470	PC15 C (EQ 28)	HOT	230	370
	STD	340	480		STD	370	580		STD	280	440
	COLD	690	1000		COLD	900	1300		COLD	600	1080
PC22.5 A (EQ 28)	HOT	280	400	PC22.5 B (EQ 28)	HOT	310	460	PC22.5 C (EQ 28)	HOT	240	380
	STD	350	550		STD	400	560		STD	300	460
	COLD	700	1040		COLD	800	1270		COLD	800	1080
PC30 A (EQ 28)	HOT	270	410	PC30 B (EQ 28)	HOT	340	500	PC30 C (EQ 28)	HOT	260	380
	STD	430	570		STD	400	580		STD	290	500
	COLD	740	1190		COLD	800	1260		COLD	680	1090
PC15 A (DR)	HOT	280	400	PC15 B (DR)	HOT	320	410	PC15 C (DR)	HOT	270	360
	STD	320	495		STD	380	550		STD	300	490
	COLD	790	1240		COLD	900	1400		COLD	580	
PC22.5 A (DR)	HOT	300	410	PC22.5 B (DR)	HOT	290	430	PC22.5 C (DR)	HOT	290	410
	STD	340	510		STD	400	620		STD	320	510
	COLD	450	1230		COLD	950	1290		COLD	650	1210
PC30 A (DR)	HOT	320	430	PC30 B (DR)	HOT	310	440	PC30 C (DR)	HOT	300	430
	STD	370	540		STD	410	600		STD	350	550
	COLD		1300		COLD	850	1400		COLD	[illegible]	1230

Table 5.14a
Mortar mix proportions (kg/m^3) for preparation of specimens for Rilem Bleed test (PPC Jupiter opc, Matla fly ash)

% fly ash	Materials	c/w 1,0	c/w 1,5	c/w 2,0	c/w 2,5
0	Water	310	305	308	320
	opc	310	458	616	800
	fly ash	0	0	0	0
	sand	1567	1455	1314	1127
5	Water	305	302	303	314
	opc	290	430	576	746
	fly ash	15	23	30	39
	sand	1581	1462	1328	1146
10	Water	301	298	299	308
	opc	271	402	538	693
	fly ash	30	45	60	77
	sand	1591	1472	1338	1164
15	Water	296	293	294	302
	opc	252	374	500	642
	fly ash	44	66	88	113
	sand	1604	1485	1352	1183
30	Water	291	286	285	296
	opc	204	300	399	518
	fly ash	87	129	171	222
	sand	1611	1497	1369	1184
50	Water	284	276	275	286
	opc	142	207	275	358
	fly ash	142	207	275	358
	sand	1621	1515	1386	1196

Table 5.14b
Volume of bleed water in millilitres in mixes with
Matla fly ash [Rilem recommendation MR–6]

% Fly ash	Time (h)	c/w 1,0	c/w 1,5	c/w 2,0	c/w 2,5
0	0,25	1,6	0,3	0,3	0,1
	0,50	3,1	1,8	1,0	0,7
	1,00	6,1	4,2	2,5	2,1
	2,00	6,8	4,6	4,1	3,9
	4,00	6,9	4,8	4,2	3,2
5	0,25	0,5	0,9	0,3	0,3
	0,50	1,7	2,0	1,7	1,3
	1,00	4,1	3,4	3,3	3,0
	2,00	6,9	6,5	4,9	6,2
	4,00	6,8	7,0	4,6	5,2
10	0,25	1,3	0,8	0,3	0,3
	0,50	2,2	1,5	1,4	1,2
	1,00	5,3	3,6	3,4	2,5
	2,00	8,8	6,2	5,6	4,2
	4,00	8,5	6,5	6,7	4,5
15	0,25	0,8	0,9	0,4	0,3
	0,50	2,3	1,7	1,1	1,2
	1,00	4,2	3,5	2,7	2,4
	2,00	6,7	6,2	4,6	4,2
	4,00	6,8	6,3	5,0	4,5
30	0,25	0,6	0,3	0,5	0,3
	0,50	1,4	1,5	1,2	0,9
	1,00	3,8	3,1	2,8	2,1
	2,00	6,3	6,1	5,0	4,5
	4,00	6,9	6,5	5,4	4,9
50	0,25	0,6	0,5	0,3	0,1
	0,50	0,8	1,7	1,0	0,6
	1,00	3,9	2,7	2,5	2,0
	2,00	5,8	4,7	3,7	3,1
	4,00	6,0	5,5	3,9	3,8

Table 5.15

Mortar bleeding test results using ASTM method C–232 on mixes detailed in table 4.13 and 5.12c.

Cement Type	Time to end of bleeding (mins)	Total bleed volume (mℓ)	% of possible bleed water
OPC	184	275	10,0
PC50SL	281	335	12,2
RHC	179	69	2,5
PC15FA	359	397	14,8
PC30FA	454	410	16,6

Note: The proportion of the total mix water is calculated using the mix proportions in table 5.12c, a sample size of 13,4 litres and the bleed volume in column 3 of this table.

Table 5.16

Progression of bleeding with time for mortars made with different cements

OPC		PC50SL		RHC		PC15FA		PC30FA	
Time (min)	Bleed vol. (ml)	Time (min)	Bleed vol. (ml)	Time (min)	Bleed vol. (ml)	Time (min)	Bleed vol. (ml)	Time (min)	Bleed vol. (ml)
0	0	0	0	0	0	0	0	0	0
34	36	47	89	36	5	32	47	31	64
69	173	72	211	75	25	61	243	64	205
93	227	102	267	90	35	93	274	91	245
119	256	128	294	141	58	118	293	117	289
149	270	162	317	179	69	149	315	163	317
184	275	188	323			178	347	184	336
		211	330			212	361	216	356
		249	334			238	375	241	372
		281	335			270	383	269	383
						298	390	313	391
						328	394	338	399
						359	397	368	404
								391	406
								427	408
								454	410
								484	412

CHAPTER 6

6. HEAT OF HYDRATION

6.1 Introduction

The chemical reaction that occurs when cement is mixed with water is exothermic i.e. heat is generated during the reaction. The heat generated is known as the heat of hydration. The heat of hydration of a cement in a concrete is generated within the mass of the concrete; a temperature gradient usually exists between the warm core of concrete and the cooler surface. This phenomenon can cause problems in mass concrete pours due to the expansion which occurs while the concrete is still relatively plastic, followed some time later by the development of thermal contraction stresses as the concrete cools. The cooling occurs after the concrete has had a chance to develop a substantial proportion of its potential compressive and tensile strength and is therefore stiff relative to the stiffness that pertained when the expansion occurred. If the stresses resulting from the cooling exceed the tensile strength of the concrete, or if the strain capacity of the concrete is exceeded, then cracking is likely to occur.

The heat of hydration is also of concern in less massive concrete sections when exposure to extreme temperatures is likely to occur at the time of casting. A concrete that develops a reasonable degree of heat during the first few hours will be better able to withstand low temperatures. The same concrete will, if exposed to high ambient temperatures, develop high early strength but the long term strength is, according to Owens,[121] likely to be depressed.

Conversely, if a concrete mix develops a lower than normal level of heat of hydration it is likely to be more susceptible to damage due to exposure to freezing conditions than a mix which develops higher heat of hydration. The low heat of hydration concrete is however less likely to suffer damaging effects of exposure to high temperature conditions.

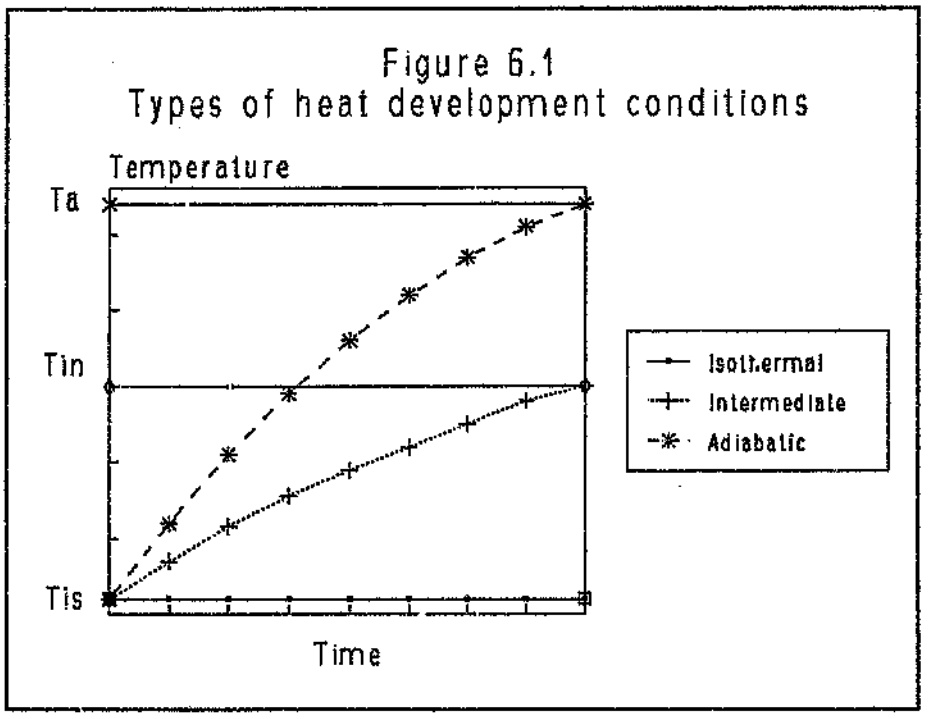
Climatic conditions in South Africa are generally such that exposure to high temperatures is more likely to occur than cold conditions, although consideration must be given to protection of thin sections in the winter conditions on the highveld. The South African engineer's interest in the heat of hydration is therefore most commonly in the effect it has of raising the temperature of concrete during hydration. The temperature rise of a site concrete at any given time can be expected to be equal to:

$$\frac{\text{(heat of hydration of cement} - \text{heat lost)}}{\text{heat capacity of the concrete materials used}}$$

It is generally taken that the heat of hydration of a cement at any time is a specific quantity ie that this is a time independent characteristic of the cement. Crawford[277] regards this as a gross simplification of a rather complex issue.

Crawford[278] points out that there are different ways of looking at the heat of hydration, ie isothermal, intermediate and adiabatic. These are depicted in the sketch given in

figure 6.1. Under isothermal conditions all the heat of hydration generated by the mix is lost to the surroundings and the temperature stays constant. Adiabatic conditions are those under which no heat is lost and are taken to represent the conditions at the centre of a large (bigger than say a 3 m x 3 m x 3 m cube) pour of concrete; this is a condition which lends itself to an accurate measurement of the temperature rise. The intermediate condition is where some, but not all, of the heat of hydration is lost to the surroundings; this is the condition to which most site concrete is exposed.



As the adiabatic condition simulates the worst condition in the centre of a large pour it is the most commonly used method for laboratory work. However the results of such testing are subject to the proviso that the temperature of the concrete at the start of the test should always be the same, as the rate at which any cement or cementitious blend hydrates is dependent on the temperature at which the reaction takes place, and this temperature is essentially independent of the characteristics of the cement used.

It is desirable therefore to control the starting temperature of the mix during a test for adiabatic heat rise. The mix proportions need to be standardised to ensure equivalent workability and 28 day compressive strength. By using the same aggregates the heat capacity of the mix will be standardised as far as is practical. There is also a need to understand the heat sensitivity of the mix, ie the degree to which the rate of hydration of the cementitious material is accelerated by the increase in temperature due to the development of its own heat of hydration.

Crawford[277] indicated that the effective heat of hydration H of a particular sample of cementitious material can be expressed as follows:

$$H = \frac{\text{Measured temp. rise x Sum of heat capacities(sample+container)}}{\text{Mass of cement in sample}}$$

The units of the heat of hydration are kilojoule per kilogram (kJ/kg).

Therefore, for accurate assessment of the true heat of hydration of any cement using adiabatic equipment it is necessary to fully evaluate the heat capacity of the equipment used as well as the concrete materials used in any mix. As this work forms only part of a larger investigation the evaluation of the heat capacities of the cell and the materials used will only be done at a later stage. For the purposes of this work these parameters will be assumed constant (as the cell and the material quantities will remain almost constant) and the relative differences between the heats of hydration of ordinary portland cement and fly ash mixes will illustrate the effect that the fly ash has on the heat generated in the mix.

6.2 Adiabatic calorimeter

An adiabatic calorimeter is an item that is not freely available in South Africa. It was therefore necessary to build suitable apparatus locally.

During a technical visit to Europe in 1986 an adiabatic calorimeter was seen at the Greenhithe laboratories of Blue Circle PLC in the UK. Blue Circle Ltd in South Africa was approached for access to this technology and the necessary details were very kindly made available.[278]

The Foundation for Research Development was approached for funding to make it possible to assemble the equipment necessary to make an adiabatic calorimeter. The application was approved and a start was made with final costing of the required components.

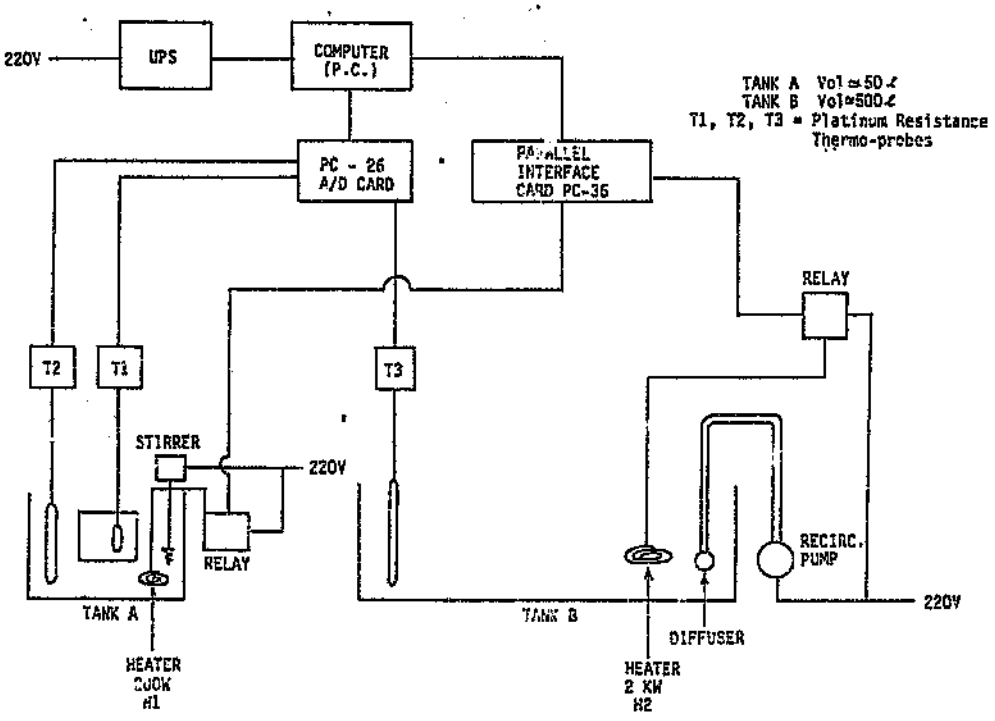
Unfortunately by the time that quotes were obtained for the various electronic components needed to assemble the apparatus, it was found that the models of the equipment used in the Blue Circle PLC apparatus had all been superseded by more sophisticated models at a much higher price. At Prof M Alexander's suggestion Mr G Gibbon of the Dept. of Electrical Engineering at the University of the Witwatersrand was approached for advice on how best to make an adiabatic calorimeter with reasonably priced components available in South Africa.

Mr Gibbon studied the control layout of the equipment used by the Greenhithe laboratory and suggested that a more flexible heat control device could be made by suitable modification to a standard IBM compatible XT computer with 640 kB RAM and two 360 kB disk drives. As the price of this equipment proved to fall within the budget available the suggestion was followed. Mr Gibbon further provided invaluable assistance, not only with the assembling of the equipment, but also with the programming of the computer to perform the desired function. A listing of the control

programme is given in appendix A.

The basic layout of the calorimeter is shown below in figure 6.2.

Figure 6.2: Schematic layout of adiabatic calorimeter



The detailed list of equipment used is as follows:

Uninterruptable power supply rated at 200 W for 15 minutes.
PC XT Computer with 640kB RAM and 2 x 360kB disk drives
9 pin Dot matrix graphics printer
PC 26 Analog to Digital card
PC 36 Interface card
Platinum resistance thermometers (PRT) + Transmitters
Opto 22 P240 D2 relay
Opto 22 240 D25 relay
200 W heater element
2000 W heater element
Labstir clip on paddle unit

Solarpump 3 speed continuous rating water pump
Suitable tanks and specimen containers

6.3 Development of the calorimeter equipment

The personal computer (PC) was fitted with the analogue to digital card PC–26 which enabled the system to read and act on the analogue signals generated by the platinum resistance thermo–probes. The parallel interface card PC–36 was added to allow the computer to control the switching on and off of heaters H1 and H2 in the two tanks, effected via the two relays.

The sizes of the two heaters H1 and H2 were selected after consideration of the operating capacities of the tanks they would be required to heat, and making an assumption about the rates at which these volumes of water would have to be heated. Advice on this subject was obtained from the suppliers Messrs. Heating Element Engineering (Pty) Ltd.

Tank A was obtained as a standard asphalt laboratory curing tank complete with Labstir stirrer, although the standard heater was not used. The walls of this tank were insulated and the top was covered with a 25 mm thick layer of polystyrene during a test. A deflector plate was added below the stirrer paddle (which agitated the water vertically) to circulate the water horizontally. Tank capacity under operating conditions was about 50 litres.

The size of Tank B was chosen to be able to accommodate the maximum number of test specimens thought likely for this test programme. No insulation was provided for this tank other than a 25 mm thick sheet of polystyrene resting on the top surface of the water. Tank B was fitted with the Solarpump and diffuser to ensure adequate circulation of the water to keep the temperature of the water as uniform as possible. The capacity of tank B under operating conditions was about 500 litres.

Platinum resistance thermo–probes were chosen in preference to the thermocouple used by Blue Circle in the UK[279] on the advice of Mr. Gibbon who indicated that a more accurate resolution could be obtained using such probes.

The computer was provided with a low capacity uninterruptable power supply (UPS) to allow proper shutdown of the system should a power failure occur. The system was fitted with a power sensor which was independent of the UPS and using this the full duration of any power interruption could be recorded. The capacity of the UPS proved to be inadequate, even though only the PC itself was run off this supply as during the initial phase of testing with this equipment, frequent power failures occurred, and most of these were longer in duration than the capacity of the UPS allowed. The control programme of the PC was structured to allow automatic restart once the power supply was reconnected. Nevertheless it was found that with long interruptions to the power supply the tank temperatures dropped to the extent that the conditions could no longer be regarded as adiabatic and the results had to be discarded.

The principle of the operation of the calorimeter is as follows:–

> The computer compares the temperature of the concrete sample measured by thermo–probe T1 against the temperature of the water in tanks A and B using thermo–probes T2 and T3. If the temperature of either of the tanks is found to be lower than the sample temperature by more than a preset amount (typically –0,1 °C) then the appropriate heater is turned on by the computer. This heater remains on until the preset amount (again typically 0,1 °C) above the sample temperature is met. In this way the water temperature in each tank is controlled to close to the concrete temperature, and, as it is likely that there is only a small time lag between the concrete and water temperatures the concrete would be exposed to adiabatic conditions.

The reason for having two tanks was that tank B allowed sufficient room for the other test specimens such as cubes and prisms to be cured under conditions matched to those experienced by the test sample. Tank A was intended for the sample only.

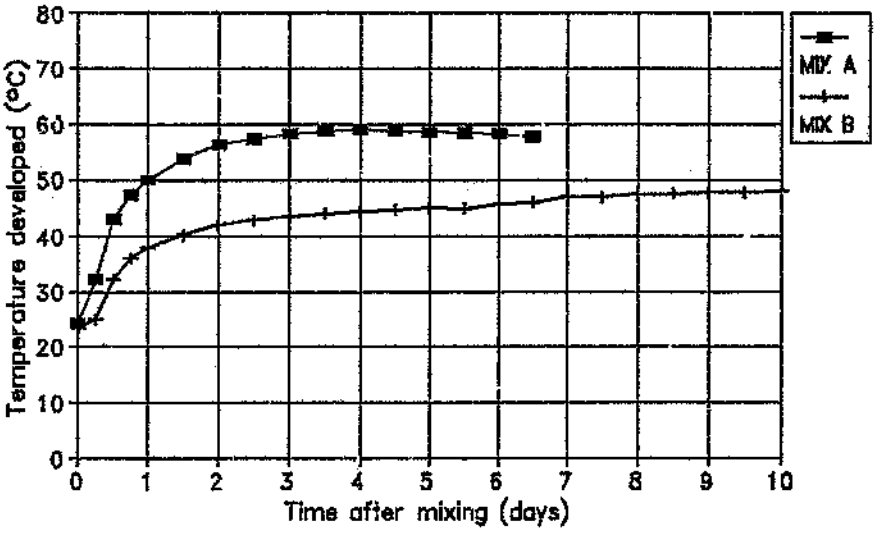
Several trials were done with this apparatus. The initial tests revealed that the heating capacity of the element in the small tank was inadequate. It was found that the heating could not keep up with the specimen when the hydration rate was high. Furthermore, losses through the probe resulted in a drop in the specimen temperature; a probe with a smaller exposed surface was substituted and this reduced the heat loss from the specimen. Some of the earlier work also revealed the need to provide some insulation between the specimen and the surrounding water as the response was found to be too dramatic otherwise.

The losses in temperature are illustrated by the curve for mix A in figure 6.3a which clearly shows the drop in temperature after the peak was reached at about 4 days. The mix proportions used here are given in table 6.2a.

The specimen container was eventually sealed into an insulating container and placed in the large tank for the duration of the test. These modifications to the original test procedure proved adequate to ensure an acceptable degree of repeatability in these tests.

On other occasions the temperature started rising again after having appeared to stabilise. This kind of anomaly is illustrated by mix B in figure 6.3a (from data in table 6.2a) with an apparent peak at about 5,5 days after which a further rise seemed to occur. This kind of behaviour was thought to be associated either with drift in the calibrations of the thermo–probes, or with settings for the tolerance for switching the heaters on and off being inappropriate for the equipment being used. Figure 6.3a gives only two of several problem sets of data which were produced during the learning process with this equipment.

Figure 6.3a
Heat of hydration: OPC and PC30FA mixes



The rest of this chapter describes the tests done to evaluate the effect of fly ash on the development of heat of hydration of portland cement concrete mixes to provide a better understanding of the changes that might occur to site concrete.

It should be noted that it took some time to identify the test conditions that would allow repeatable results to be obtained. This has resulted in fewer data being available for reporting and discussion in this work than was originally hoped. It should be noted that this trend of poor repeatability has not been experienced with tests done on a calorimeter built using the same principles and installed at the Department of Water Affairs laboratories in Pretoria West[280]. It is possible that discussion with the technicians involved could help identify the problem areas with the PCI apparatus, although it is believed that with the test procedure established after the initial series of tests, the repeatability should be acceptable.

The following paragraphs give the details of the final test procedure adopted. This was the test procedure from which the reported data were derived.

6.4 The detailed test procedure

Prior to mixing all materials were conditioned to the temperature to which the mixing room was controlled, ie 23,5 ± 1,5 °C. The concrete was mixed at this temperature and the temperature and other characteristics of the plastic mix were recorded.

The fresh concrete was compacted into the calorimeter cell and all other test specimens such as cubes or cylinders were made up after this was completed. While the calorimeter was being readied for introduction to the curing tank the other specimens were first covered and sealed with greased steel plates and then placed in the large curing tank.

The control platinum resistance thermometer was inserted into the centre of the concrete in the calorimeter cell. The programme was then initiated and all the relevant information was typed in. The information required is shown on the blank table shown in table 6.1. Control parameters governing the temperature differentials required for the test also had to be fed in. As noted before the differential was typically set at +0,1 °C and –0,1 °C.

Once the input data had been fed in the control system could take over and read and compare temperatures. If the temperature of the curing tank was lower than the concrete in the cell then the computer would turn on the heater in the curing tank. The heater would remain on until the temperature of the water in the tank was the specified difference above or below the cell temperature.

If the temperature of the curing tank was above that of the concrete in the cell then no action would be taken until the cell temperature caught up to and exceeded the curing tank water temperature.

The computer recorded the time at which the cell temperature crossed each whole degree Celsius and at every one hour interval. This information was also displayed on the monitor screen.

At appropriate chosen ages (typically 1, 3 and 7 days) some or all of the test specimens in the curing tank were removed and allowed to cool out of the water, but still sealed, for 2 hours before being tested. For the tests described in this work the testing was limited to compressive strength determination. The results of these tests will be discussed in more detail in the following chapter on compressive strength.

The effect that the adiabatic heat of hydration has on other properties of hardened concrete will be the subject of extended investigations using this apparatus. These data were not available for inclusion in this work.

6.5 Test results

Initially the test procedure was run a number of times to evaluate the degree of reproducibility with the equipment and method used. Once this was believed to be acceptable the basic series of tests was started.

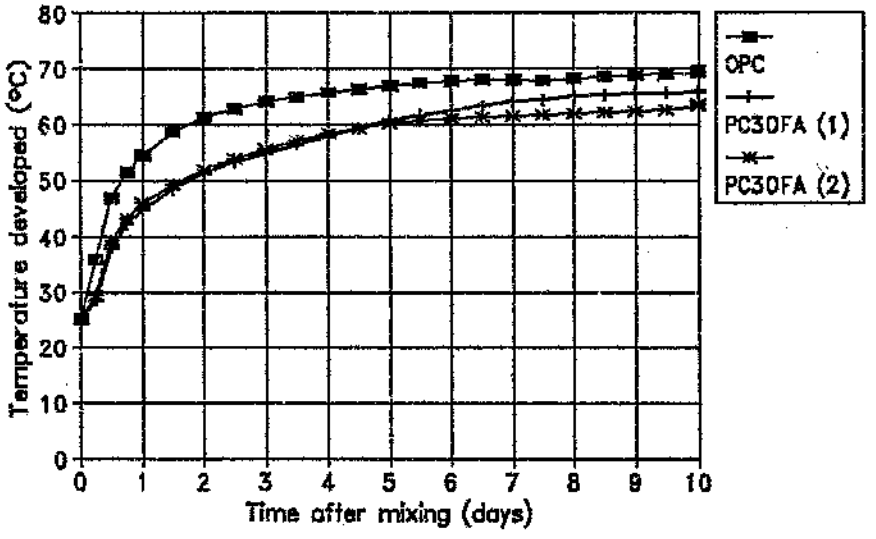
Table 6.2b gives the mix proportions of the mixes used for mixes 1, 2 and 3. Mix 1 was an OPC mix with cement/water ratio of 1,5. The OPC came from the PCI silo ie ex PPC Jupiter. Kendal sand and 13,2 mm dolerite aggregates were used. Mixes 2 and 3 contained 30 % Matla fly ash in addition to the other ingredients and were made

using a cement/water ratio of 1,7 so as to give a similar level of compressive strength at 28 days under standard curing to that of mix 1. All mixes were made to the same target slump of 75 mm. The temperature of the concrete at time of starting the calorimeter apparatus is also given in table 6.2b. As the materials were first acclimatised to laboratory conditions (22 to 25 °C) the initial temperature was commonly of a similar order.

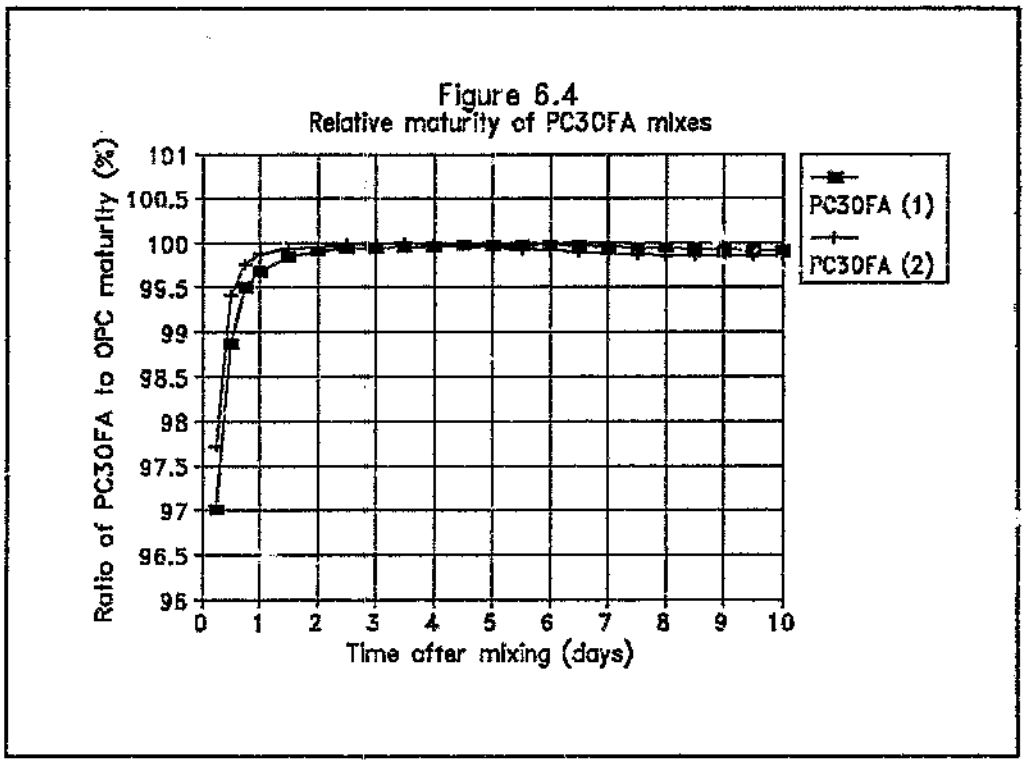
It should be noted that while the above adjustment to the cement/water ratio would normally be expected to give a very similar level of compressive strength at 28 days for the OPC and PC 30 FA mixes, in this particular case with the combination of OPC and fly ash used this did not occur for the standard curing conditions. This will be discussed in more detail in chapter 7.

The size of the database derived from each test is fairly substantial and too bulky to present in this work. To simplify the presentation of the heat of hydration curves for these tests extracts have been taken from the database for each test at preset time intervals. The data has also been modified to a common starting temperature for plotting purposes although this did not actually occur in the tests. The modification was done by the arithmetic addition or subtraction of the difference between the actual starting temperature and 25 °C to all the other values. This approach is not strictly valid but has been done simply to illustrate the difference between the heat developed in the OPC and PC 30 FA mixes. This information is presented in table 6.3b for the 3 mixes from table 6.2b.

Figure 6.3b
Heat of hydration: OPC and PC30FA mixes



These data are shown graphically in figure 6.3b. The agreement between the two PC 30 FA results is fairly good and they lie consistently below the curve for OPC as would be expected for a material that increases setting time and reduces early strength.



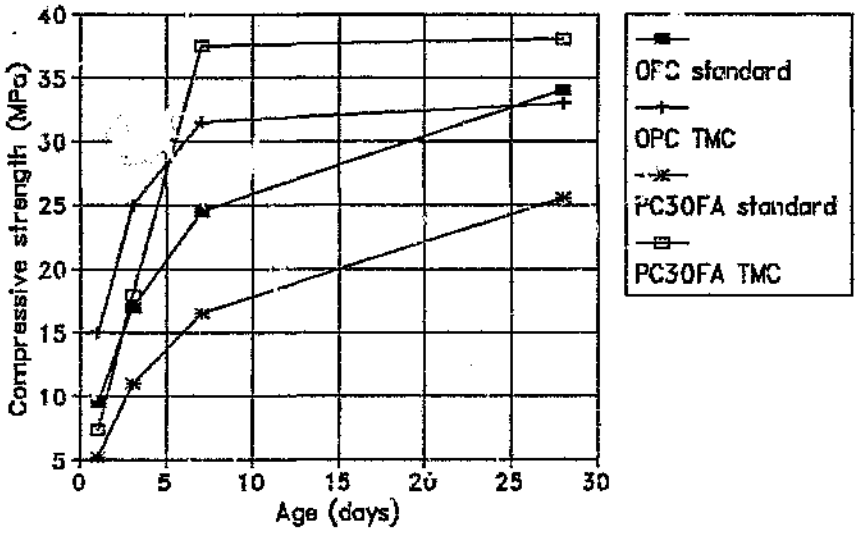
The adiabatic heat of hydration of the OPC mix resulted in a temperature rise of 44,5 °C while the average temperature rise for the PC 30 FA mixes was 39,8 °C. Table 6.4 gives the maturity of the OPC and first PC 30 FA mix calculated using –10 °C as the base temperature. The maturity calculations have been based on the actual data generated during the test without any modification.

Figure 6.4 shows the relative maturity of the two PC 30 FA mixes expressed as a percentage of the maturity of the OPC mix. Again the two mixes gave fairly similar results to each other even though the starting temperature of the two mixes was rather different. A notable feature of the maturity of the fly ash mixes is that at an age of about 6 hours the retardation and slow initial rate of reaction of the fly ash mixes results in a drop in their relative maturity.

Compressive strength results were recorded for the OPC mix and for the first PC 30 FA mix in both standard curing conditions (ie SABS Method 863) and under Temperature Matched Curing (TMC) conditions matched to the adiabatic heat development for the particular mix. These data are given in table 6.5. Figure 6.5 shows

the development of compressive strength under the two curing regimes. Note that the curing regime for adiabatic conditions is not the same for the ordinary portland cement and fly ash mixes but follows the temperatures shown in figure 6.3b. No compressive strength results are available for the second fly ash mix.

Figure 6.5
Performance of OPC and PC30FA mixes



It is notable that the compressive strength of the fly ash mix, while intended to provide equal 28 day compressive strength to the ordinary portland cement mix, failed in fact to reach this by quite a long margin under standard curing conditions. In spite of this, and the fact that for this mix the maturity was always below that of the OPC mix, under TMC conditions the fly ash mix performed considerably better than was the case for the ordinary portland cement mix under adiabatic conditions. This is a clear indication that the fly ash is more sensitive, and responds better to the increased temperature developed during the TMC curing. The OPC mix in fact shows a reduction in compressive strength under TMC conditions when compared against the results under standard curing which supports the view expressed by Owens[121] that the high temperatures are not beneficial to OPC mixes.

Neither mix shows much increase in compressive strength between 7 and 28 days under TMC conditions although this is not unexpected. A rapid compressive strength development at early ages caused by a higher than normal curing temperature generally results in a flatter, slower increase beyond 7 days than is the case where the initial strength development is slower under standard or cold curing conditions.[281]

An attempt was made to find a modification of the maturity calculation used for determining the values plotted in figure 6.4 so that the compressive strength results given in table 6.5 could be explained in maturity terms. It was soon evident that such a modification cannot be made by simply changing the starting temperature from the –10 °C used for figure 6.4 as the rates of compressive strength gain of the ordinary portland cement and fly ash mixes differ at different ages. As there is little data available this calculation was not pursued further. It is believed that this would make an interesting field for further study.

6.6 Discussion

Botha and Amtsbuchler[282] indicated that the heat generated in site mass concrete with 40 % fly ash in a mix with a cementitious/water ratio of 1,82 results in a temperature rise of about 11 to 15 °C above the starting concrete temperature. This was recorded for semi–adiabatic conditions (previously referred to by Crawford[278] as intermediate conditions – see paragraph 6.1 and figure 6.1) on site, whereas under adiabatic laboratory conditions for the same concrete mix the temperature rise was found to be about 43 °C. (Figure 6.3b shows a temperature rise of about 30 °C for a 30 % fly ash mix with a cement/water ratio of 1,7 for the PCI calorimeter). In the case of structural grade concrete with cement/water ratio 2,11 the temperature rise was found to be about 35 °C under site semi–adiabatic conditions; in this case no adiabatic data were supplied.

Data were also given[282] of the effect of the heat of hydration on the strength development of fly ash concrete mixes as compared against the values obtained under standard curing conditions. This information will be discussed in more depth in chapter 7.

Mani et al[283] showed the pattern of heat development to be a factor of the total cementitious material content of the concrete. While at low total cementitious material content (370 kg/m^3) the ordinary portland cement concrete had higher initial heat development, this was not the case with a high total cementitious material content (570 kg/m^3) as the early temperature rise for 5 % and 30 % fly ash content mixes exceeded that for the ordinary portland cement mix. Interestingly, they also showed that the time to reach peak temperature increased as the cement content increased. They indicated that the peak temperature dropped by some 9–10 °C at a fly ash content of 30 % and was equated to about 1 °C per 100 kg of cementitious content for each 15 % of fly ash replacement. The peak also occurred later with the 30 % fly ash content mixes than was the case with the ordinary portland cement mixes.

In the PCI study (shown in figure 6.3b) the peak does seem to be delayed by some days with a drop in peak temperature of about 5 °C at a 30 % fly ash content. The temperature rise apparently brought about by the OPC used (table 6.2b) seems to be about 14,5 °C per 100 kg of cement. If this is true (and little data is available from this work to substantiate this) then the fly ash used in table 6.2b would seem to produce about 8 °C per 100 kg of fly ash used.

The work done by Mani et al[283] was done under semi–adiabatic conditions. They also

showed the effect of the higher temperature on the compressive strength development of the various mixes. This information is covered in Chapter 7.

6.7 Recommendation

The discussion above covers sparse local experience. The South African Department of Water Affairs has similar apparatus to that used in this investigation and it is believed advisable that some pooling of ideas and experience should occur. A broader spectrum of South African materials and mixes needs to be tested for a better understanding of the performance of all types of concrete under adiabatic conditions. More work is required to evaluate the maturity concept for fly ash mixes using South African materials.

Table 6.1

Typical pro forma for information required at programme initiation stage

CEMENT TYPE		
EXTENDER TYPE		
SAND TYPE 1		
SAND TYPE 2		
STONE TYPE 1		
STONE TYPE 2		
ADMIXTURE TYPE		
CEMENT CONTENT		(kg/m^3)
EXTENDER CONTENT		(kg/m^3)
SAND 1 CONTENT		(kg/m^3)
SAND 2 CONTENT		(kg/m^3)
STONE 1 CONTENT		(kg/m^3)
STONE 2 CONTENT		(kg/m^3)
WATER CONTENT		(l/m^3)
ADMIXTURE CONTENT		(l/m^3)
INITIAL SAMPLE TEMPERATURE		(°C)

Table 6.2a

Mix proportions for OPC and PC30FA mixes per m^3 of concrete used in test method trials for adiabatic calorimeter

Material		Mix No. A	Mix No. B
OPC	(kg)	308	197
Fly ash	(kg)	–	85
Sand	(kg)	884	894
Stone	(kg)	1090	1130
Water	(l)	205	188
c/w ratio		1,5	1,5
f/(c+f)	(%)	0,0	30,1
Starting temperature	(°C)	23,5	24,0

Note: Materials used in the manufacture of these concretes are as follows:

OPC ex PPC Jupiter,
Fly ash ex Matla,
Kendal sand,
13,2-mm dolerite stone.

Table 6.2b

Mix proportions for OPC and PC30FA mixes per m^3 of concrete used for measurement of adiabatic heat of hydration

Material		Mix No. 1	Mix No. 2	Mix No. 3
OPC	(kg)	308	220	226
Fly ash	(kg)	–	94	97
Sand	(kg)	885	865	963
Stone	(kg)	1090	1136	1000
Water	(l)	205	185	190
c/w ratio		1,5	1,7	1,7
f/(c+f)	(%)	0,0	29,9	30,0
Starting temperature	(°C)	25,9	23,0	27,1

Note: Materials used in the manufacture of these concretes are as follows:

OPC ex PPC Jupiter,
Fly ash ex Matla,
Kendal sand,
13,2 mm dolerite stone.

Table 6.3

Measurement of the temperature due to the adiabatic heat of hydration of 30 MPa OPC and PC30FA concretes proportioned as in table 6.2b

Time after mixing (days)	Heat development of concrete mixes		
	Mix No. 1	Mix No. 2	Mix No. 3
	Corrected concrete temperature (°C)		
0,00	25,0	25,0	25,0
0,25	35,8	28,5	29,5
0,50	46,9	37,8	39,3
0,75	51,4	42,2	43,3
1,00	54,5	44,8	45,9
1,50	58,7	48,5	49,2
2,00	61,3	51,3	51,9
2,50	62,9	53,2	53,8
3,00	64,1	54,8	55,6
3,50	64,9	56,4	57,1
4,00	65,7	57,9	58,4
4,50	66,3	59,4	59,3
5,00	66,9	60,6	60,1
5,50	67,4	61,6	60,7
6,00	67,8	62,6	61,1
6,50	68,0	63,3	61,2
7,00	68,1	64,1	61,5
7,50	67,9	64,5	61,7
8,00	68,3	65,1	61,9
8,50	68,6	65,2	62,1
9,00	68,8	65,5	62,4
9,50	69,0	65,5	62,7
10,00	69,1	65,7	63,1
10,50	69,3	65,9	63,5
11,00	69,4	66,0	63,6
11,50	69,5	65,9	63,7
12,00	69,5	65,9	63,7

Table 6.4

Maturity of concrete cured under temperature matched curing cycle detailed in table 6.3

Time after mixing (days)	Maturity of concrete mixes	
	Mix No. 1	Mix No. 2
	Maturity (°C hrs)	
0,00	0,0	0,0
0,25	246,6	219,0
0,50	594,0	549,6
0,75	952,2	903,6
1,00	1324,0	1267,2
1,5	2102,4	2034,0
2,0	2928,0	2846,4
2,5	3768,0	3672,0
3,0	4644,0	4521,6
3,5	5535,6	5409,6
4,0	6480,0	6326,4
4,5	7430,4	7279,2
5,0	8412,0	8232,0
5,5	9398,4	9187,2
6,0	10396,8	10166,4
6,5	11419,2	11122,8
7,0	12482,4	12112,8
7,5	13536,0	13050,0
8,0	14611,2	14035,2
8,5	15667,2	14932,8
9,0	16718,4	15876,0
9,5	17784,0	16758,0
10,0	18888,0	17688,0

Table 6.5

Compressive strength (MPa) of mixes from table 6.2b under standard curing and temperature matched curing conditions

Age (days)	Mix Number 1		Mix Number 2	
	Standard	TMC	Standard	TMC
	Compressive strength (MPa)			
1	9,5	15,0	5,2	7,4
3	17,0	25,0	11,0	18,0
7	24,5	31,5	16,5	37,5
28	34,0	33,0	25,5	38,0

CHAPTER 7

7. COMPRESSIVE AND FLEXURAL STRENGTH

7.1 Compressive strength

7.1.1 Introduction

The compressive strength of concrete is that property of concrete which most structural designers are familiar with and feel that they understand. This is probably the reason that the compressive strength of concrete receives such attention while aspects such as watertightness or durability are, to some extent, neglected. The fact that the compressive strength can apparently be measured accurately using simple site techniques is probably also responsible for some of the blind faith put on this property.

There is little appreciation for the fact that the cube, or whatever other site test is done to assess the compressive strength of the concrete, is simply a means to provide information on the potential of the site concrete to meet the service requirements that it will face during its expected service life, ie it provides information about the degree and effectiveness of the quality control of the manufacture of the site concrete.

It is a fact that there are many intrinsic and extrinsic factors which can influence the compressive strength of the concrete.[283] Moreover, under typical site conditions many of these factors are present and will probably not be effectively controlled to any extent, even for the test specimens themselves, let alone for the site concrete.

In chapter 3 some attention was given to the different methods used in proportioning concrete mixes when using fly ash as part of the cementitious material. The aspect of adjusting the coarse aggregate content of the fly ash mix upward relative to an ordinary portland cement concrete mix was accepted, as mentioned in chapter 4, and this adjustment was applied when calculating some of the mix proportions for the mixes done in this work. However, no other changes were made to the method of proportioning normally used by PCI.[284] The reason for not making such changes was that it was considered better to evaluate the results of the tests done in the normal way and then determine which adjustments could or should be made to meet the requirements of simplicity and reliability in a method of mix proportioning.

7.1.2 Laboratory tests on cube specimens with Matla ash

Table 5.1a gives the mix proportions of the mixes made in this work to study both compressive and flexural strength. It can be seen that the adjustment in the stone content of the fly ash mixes amounts to about 1 kg more stone per 1 % of fly ash used. Naturally the relative density of the fly ash is taken into consideration in the recalculation of the mix so that the yield of the mix is correct. As noted in chapter 5 the workability of the mix, as assessed by the slump test, was not always as desired. This

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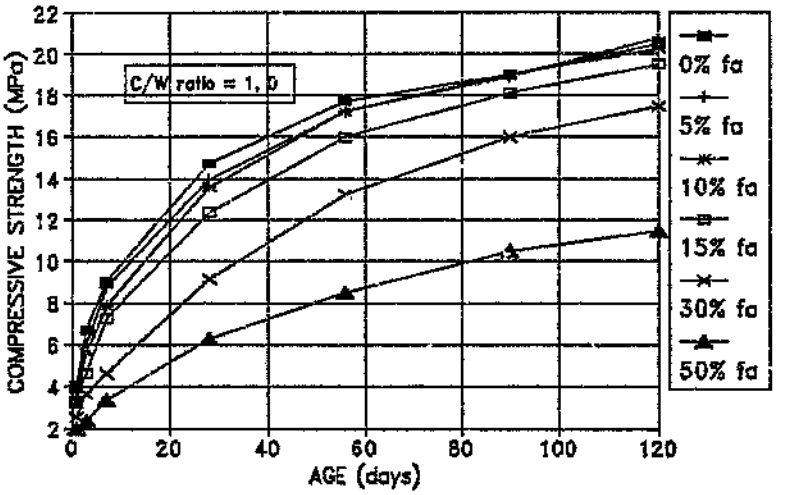
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factor is ignored for the time being in discussing the compressive strength results obtained.

The tests done to determine the compressive strength were done on 100-mm cube specimens which were made and cured in accordance with SABS Method 863.[285] Tables 7.1a to 7.1f give the information on the cube compressive strengths obtained for the mixes made using the various sources of ordinary portland cement alone or in combination with Matla fly ash at four different cement/water ratios at ages up to 120 days. Note that in some cases the 120 day tests were omitted.

These data have been combined to give the average for the 4 different cement samples used in these tests in order to give an average impression of the development of the compressive strength of concrete, without the individual differences that occur with cements from different sources playing too big a role. These average compressive strength development values are presented graphically in figures 7.1a to 7.1d for the range of fly ash contents tested to make comparisons more simple. Figures 7.1a to 7.1d represent the curves for a direct replacement type of mix proportioning. To give some idea of the spread of the results, the range from lowest to highest at 28 days was about 20 % of the mean values shown in the figures across the range of fly ash contents used.

Figure 7.1a
Compressive strength vs fly ash content



The mixes have been made to fixed c/w ratios; in this case the cement is taken to include the fly ash.

It should be noted that the results for the "factory blended or interground" cements from Jupiter have not been included in the averages as it was thought that this would bias the results to more closely represent what happens with PPC cements than a true

average It was thought that the fact that 2 of the cements included in the averages were obtained from Jupiter was not unreasonable as the two samples were taken some time apart.

Figure 7.1b
Compressive strength vs fly ash content

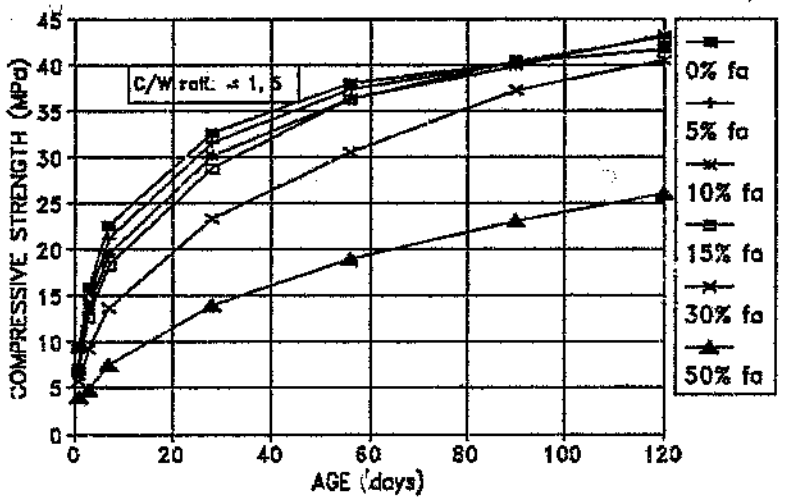
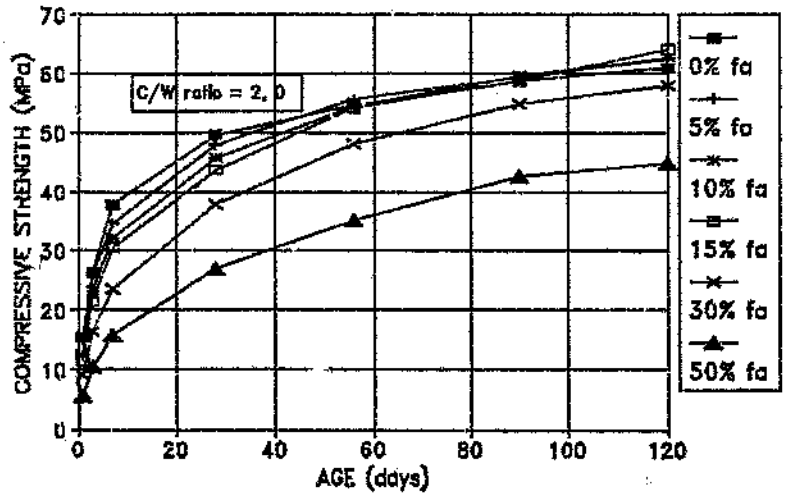
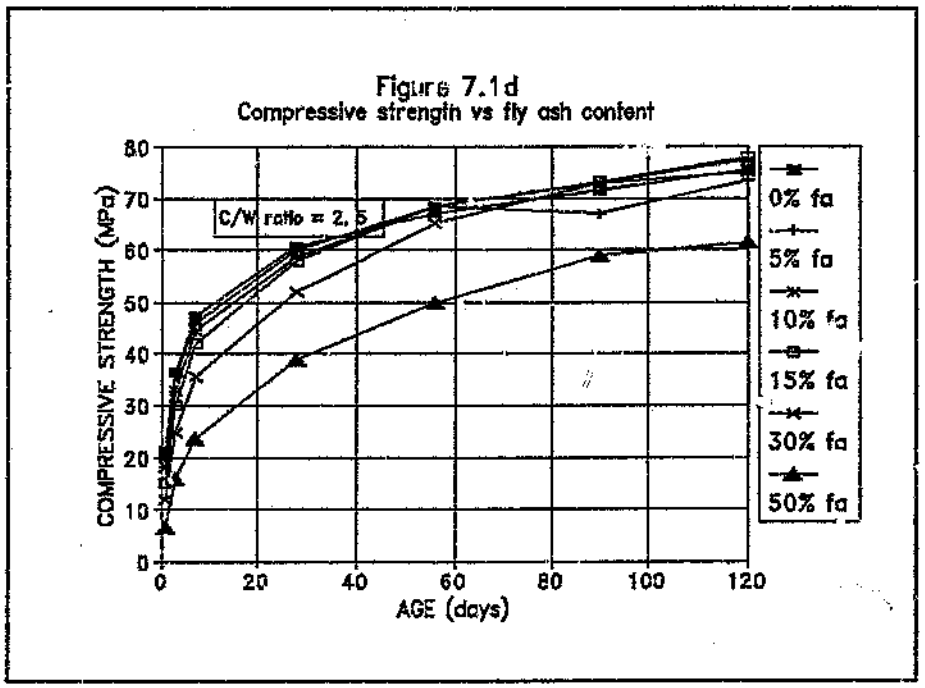


Figure 7.1c
Compressive strength vs fly ash content





Figures 7.1a to 7.1d show the following:

- As the fly ash content is increased the compressive strength at any of the ages for which results are available is reduced when compared against the control ordinary portland cement mix, ie that shown as 0 % fly ash. This confirms the statement made by Ravina and Mehta[78] regarding the slower strength development of fly ash mixes and the fact that fly ash tends to reduce the compressive strength. Chapter 3 gives many other references to similar findings by other authors.

- The difference between the compressive strength of the ordinary portland cement mix at any age and the corresponding value for the fly ash mixes is almost negligible for fly ash contents below 10 % and is small for fly ash contents up to 15 %.

- The difference between the compressive strength of the ordinary portland cement mix and that of the mixes containing 30 and 50 % fly ash decreases as the cement/water ratio increases. The ratio of the compressive strength of the 50 % fly ash mix to that of the ordinary portland cement mix at 120 days is about 55 % at cement/water ratio of 1.0 while at cement/water ratio 2.5 the ratio is about 80 %. This confirms the findings noted before in chapter 3 by Hobbs[76], Butler[61] and Dhir et al[4] amongst others that the value of the cementing efficiency k used in the partial replacement method of mix proportioning is not constant.

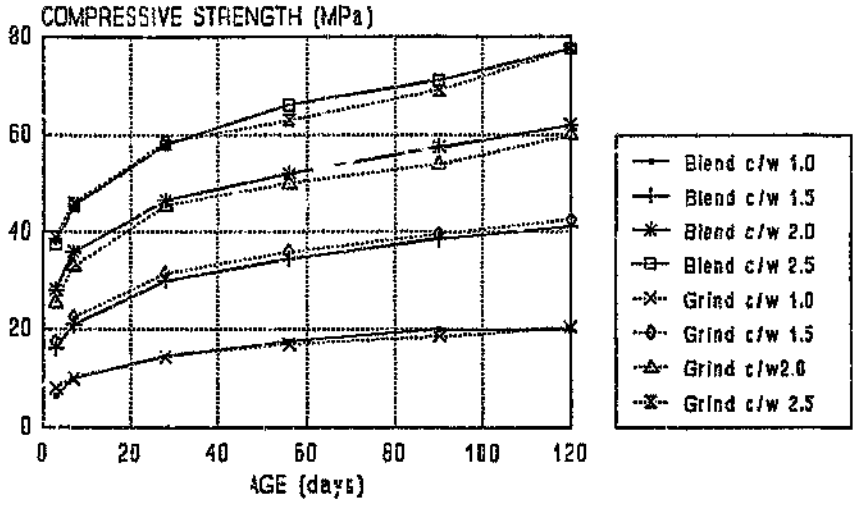
- For levels of fly ash content above 15 % the compressive strength may only

reach parity with the ordinary portland cement mix at ages greater than 120 days, if ever. The likelihood of reaching parity increases with an increase in the cement/water ratio of the mixes.

- The apparent anomaly for the 5 % fly ash content mixes at ages of 90 and 120 days is due the fact that only a two results were available at these points; accordingly the results are not as broad an average as otherwise shown in this figure.

Figures 7.1e and 7.1f show strength development curves for the PPC factory blended and interground cements. It can be seen that there is little significant difference between the performance of the blended or interground cements at the level of 5 % fly ash although the blended product showed a marginally better performance. At 15 % fly ash content however it does seem that the interground product performs consistently better than the blended cement. The difference is generally small and appears to reduce at ages greater than 90 days.

Figure 7.1e
Comparison of performance of 5% blended and interground cements



The average compressive strength at 28 days has been calculated for the various cement/water ratios and different fly ash contents and these results have been plotted in figure 7.1g against the cement/water ratio. These curves have been compared with the similar curves given in figure 11.4 in Fulton.[286] It is noted that the curves for ordinary portland cement and the lower fly ash content mixes are higher than is the case for the curves in Fulton. This means that for a given level of compressive strength

the data from these tests indicate that a lower level of cementitious content would be necessary than would be the case if the Fulton curves were used.

Figure 7.1f
Comparison of performance of 15% blended and interground cements

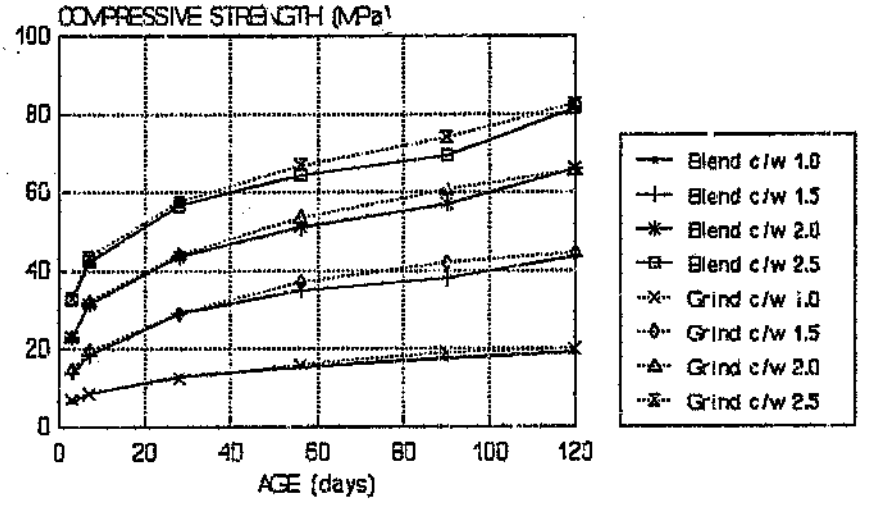
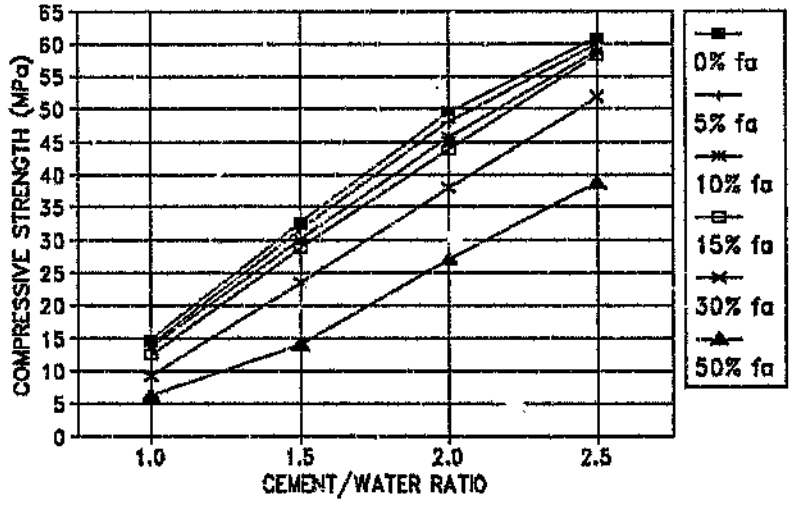


Figure 7.1g
28d Compressive strength vs C/W ratio



It should be noted that in the preparation of the information in Fulton the data given in tables 7.1a to 7.1f were taken into consideration. This indicates that the spectrum of ordinary portland cement strengths in the whole of South Africa is wider than indicated in these rather limited results, and that some of the compressive strengths are lower than indicated in the results presented in this work.

The line for the 50 % fly ash mix corresponds fairly closely to the 50 % line in the Fulton chart. This makes sense as there is only one source of fly ash used in both this study and the wider scope of results covered in the Fulton graph; the dilution effect of the single fly ash would tend to reduce the impact of the variability of the ordinary portland cement compressive strengths.

From the curves in figure 7.1g it can be seen that the fly ash does have a considerable impact on the 28 day compressive strength. The magnitude of the reduction in the 28 day compressive strength increases with an increase in the fly ash content. This is in agreement with most of the findings reported under 3.5.2 in chapter 3.

Figure 7.1g also provides the information needed to proportion fly ash concrete mixes to give similar levels of compressive strength at 28 days. The target compressive strength desired for a particular mix is used as the starting point on the y–axis; this is extended across to the curve for the chosen level of fly ash content and this indicates the appropriate level of cementitious/water ratio to be used. It must be noted however that these curves are averages and can thus provide only a starting point for a laboratory or site trial mix using the actual ordinary portland cement and fly ash for that site. The Fulton[266] curves are more likely to give a better generalised picture for the full spectrum of South African cements.

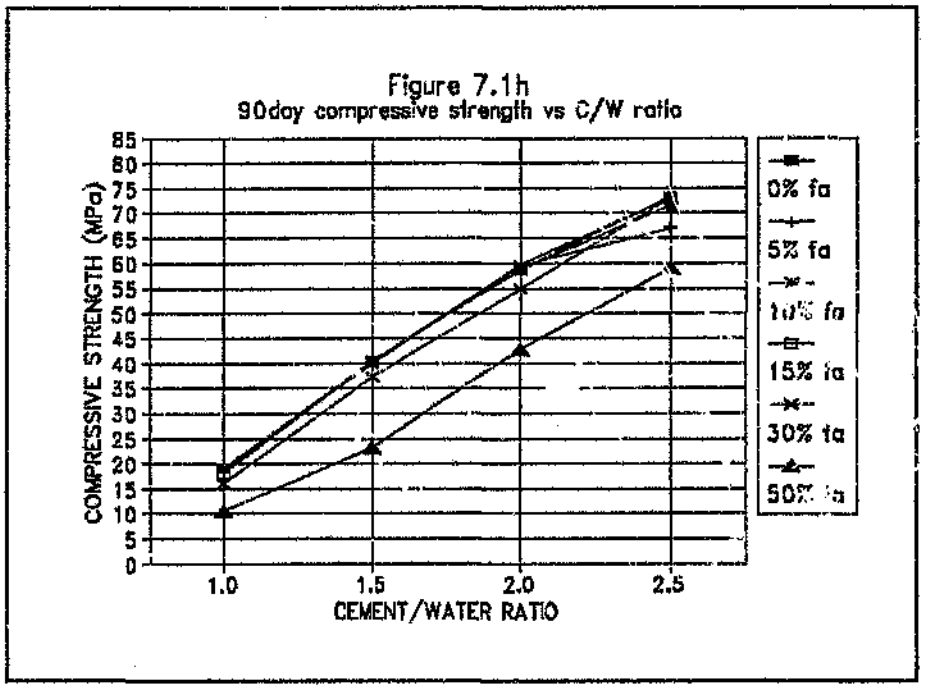
It would appear that fly ash mixes will usually have a higher cementitious content than their ordinary portland cement equivalent where the strength is intended to be equal to that of the opc mix at 28 days; the conclusion to section 5.2.1 in chapter 5 showing a water reduction of 0.55 x fly ash content (l/m^3) must however be taken into consideration as well. To illustrate this point a practical example is provided below.

A target compressive strength of 38 MPa is required; for an ordinary portland cement mix a cement/water ratio of 1.7 is required while in the case of a 10 % fly ash mix the cement/water ratio should be 1.85. If the water content of the opc mix is, say, 200 litres per cubic metre then the ordinary portland cement content will be 340 kg/m^3. The corresponding water content of the fly ash mix will probably be about 194 litres per cubic metre with the cementitious content of 343 kg/m^3 which is only slightly higher than the opc mix cementitious content. It is therefore not inconceivable that for a particular combination of ordinary portland cement and fly ash the total cementitious content could be lower than for the equivalent opc mix. This is only likely to be the case for low levels of fly ash content, as repeating the example for higher fly ash contents using figure 7.1g will demonstrate.

This has been done and summarised in table 7.1g for a 28 day target compressive strength of 38 MPa. In the data shown in table 7.1g the cementitious content of the fly ash mixes is always higher than that of the equivalent CPC mix. Other combinations

of materials may permit greater water savings and lead to fly ash mixes having lower total cementitious contents than the control.

Figure 7.1h is a similar graph but this time plotted for the 90 day compressive strengths at different cement/water ratios. In this graph it is noted that the curves for the fly ash contents of 5 %, 10 % and 15 % virtually coincide with that for the ordinary portland cement, except for an anomalous result at the cement/water ratio of 2.5. This result is low because in this case only two results were available and they were from cements that performed more poorly than the two for which no 90 day results were available.



In figure 7.1h the curves for the 30 % and 50 % fly ash content mixes are also closer to the ordinary portland cement curve. This indicates that for ages beyond 28 days the rate of compressive strength gain of the fly ash mixes is greater than for the ordinary portland cement mixes. This finding is also in agreement with many of the reports referred to in chapter 3 (section 3.5.2.). This characteristic of fly ash mixes could be translated into savings in cementitious content in cases where the concrete is only likely to carry its design load at ages much greater than 28 days, and where the compressive strength gain of the fly ash mix beyond 28 days has not been taken into account in the structural design procedure.

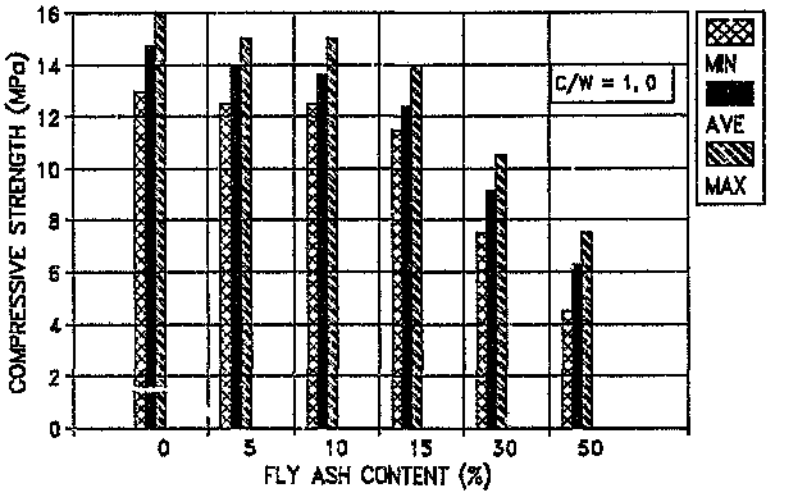
If, using figure 7.1h, a similar calculation to that done for figure 7.1g is carried out, it can be seen that, when the water reduction is taken into account, the total cementitious content of even a 30% fly ash mix will be lower than for the equivalent opc mix. This is shown in table 7.1h.

The adoption of 90 day compressive strength specifications is not common; to date the

writer believes that this kind of specification has only been considered appropriate in structures such as mass concrete and rollcrete dams. Hansen[287] has indicated that the compressive strength of concrete containing fly ash, when cured under water at 20 °C, continues to increase up until an age of 3,5 years after which little gain is apparent.

Figure 7.2a to 7.2d shows the range of compressive strength results for each combination of cement and fly ash tested at the various cement/water ratios. The trend for there to be little significant difference between the ordinary portland cement mix and those with fly ash contents up to about 15 % noted in figures 7.1a to 7.1d is supported by these graphs. This is particularly evident for the mixes with 5 and 10 % fly ash and also becomes more evident with increasing cement/water ratio of the mixes. It is possible that when the reduction in water content is taken into account, cements with 5 %, 10 % and perhaps even 15 % fly ash could be regarded as being suitable for direct replacement of ordinary portland cement in non–critical applications.

Figure 7.2a
28 day compressive strength range



Other results of tests done using some other cements and Matla fly ash show that the results for the ordinary portland cement compressive strengths fall either above or below the curves given in figure 7.1g for 0 % fly ash. For 15 % and 30 % fly ash the values recorded in these other tests fall either above or on the relevant curves in figure 7.1g. This is further support for the contention that this set of curves can only be used as a first approximation during a mix proportioning calculation; inevitably, even for an average for all ordinary portland cements in the country, there will be cases that do not fit the average and will therefore lead to strengths either higher or lower than predicted from the curves in figure 7.1g.

Figure 7.2b
28day compressive strength range

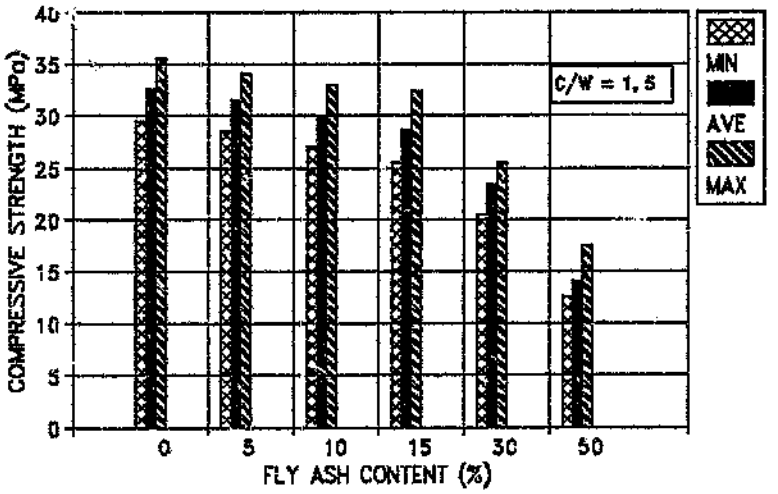
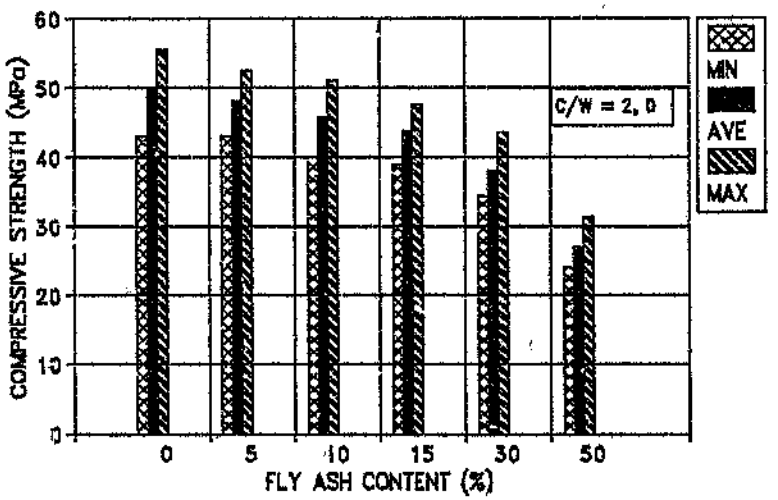
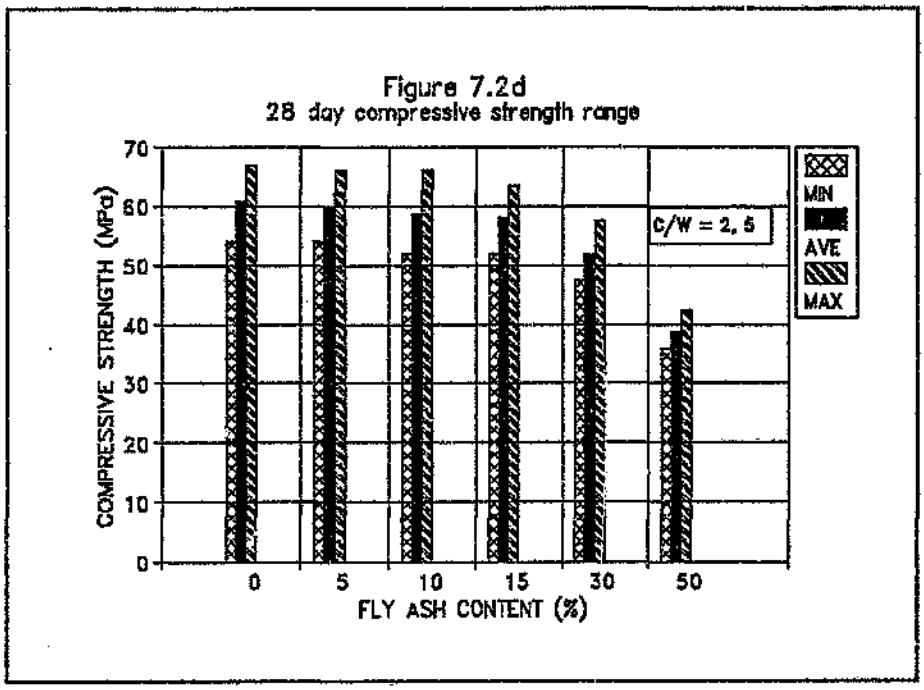


Figure 7.2c
28 day compressive strength range





7.1.3 Laboratory tests on cube specimens with Lethabo ash

Similar tests were carried out on a series of different ordinary portland cements with and without the use of classified Lethabo fly ash. These results were obtained as part of a large investigation done on behalf of the Cement Industry; only results that apply to standard curing temperatures are referred to in this part of the discussion.

The mixes used were concretes cured under the same conditions as indicated in paragraph 5.3.6 and using the same cementitious materials. In this case concrete mixes were made using 19 mm reef quartzite stone with the other materials. The mix proportions used are given in table 7.2a and the compressive strength results are given in tables 7.2b to 7.2f. Figures 7.3a to 7.3d show the relevant values for standard cured mixes designed for equivalent 28 day compressive strength and direct replacement conditions in both cured (ie protected by wrapping in a plastic bag) or uncured states (no protection against desiccation in an environment of c. 50 % relative humidity) at ages of 24 hours and 7, 28 and 56 days.

If the results for standard cured 28 day compressive strength given in table 7.2e are plotted on the graph given in Fulton[286] figure 11.4, then for the cements A and B the values plot on or close to the curves in Fulton. The cement C did not perform as well and these results plot well below the Fulton curves. Cement C generally performed below the levels shown by the other two cements.

Figure 7.3a
Compressive strength
Standard cured equivalent 28 day mixes

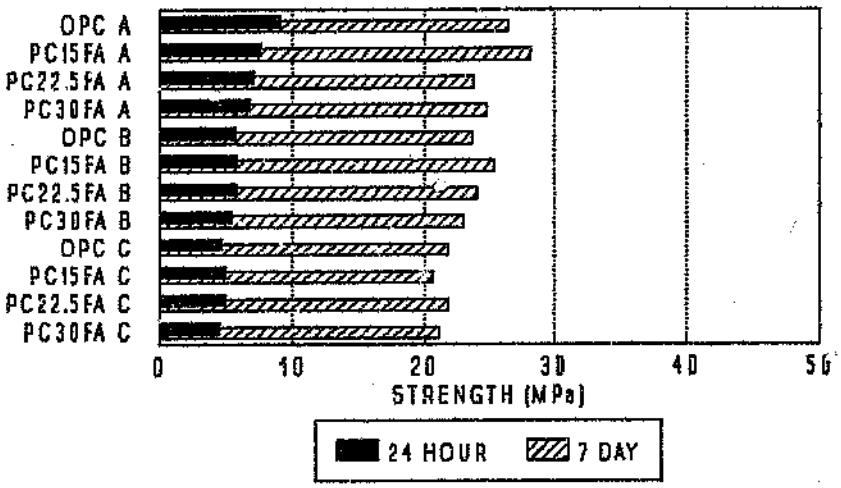
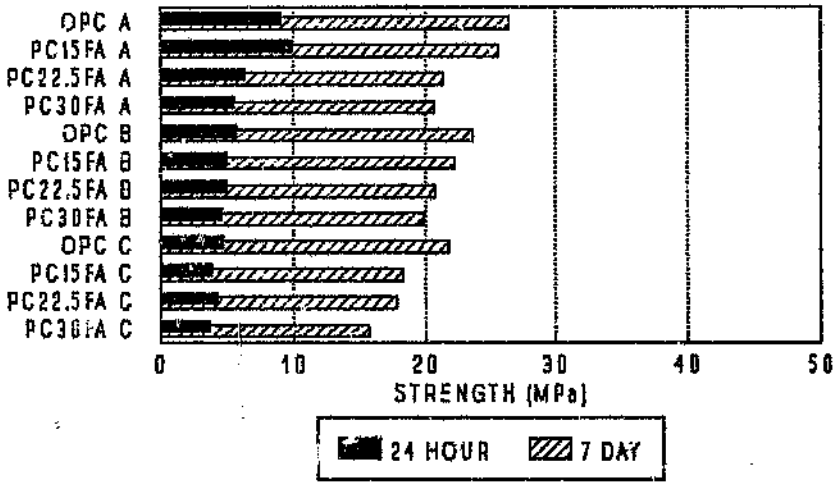
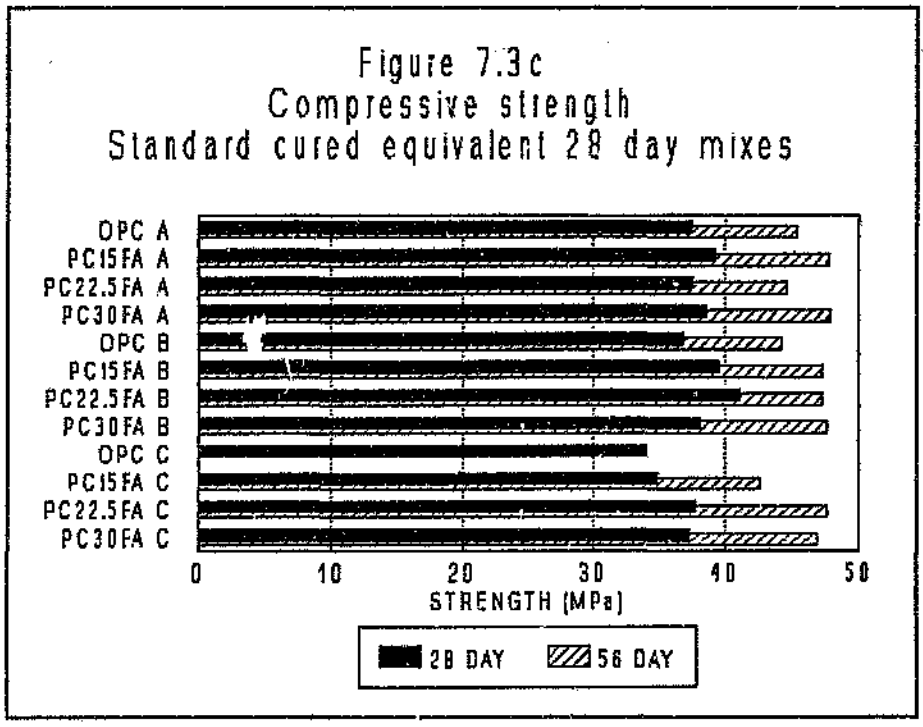


Figure 7.3b
Compressive strength
Standard cured direct replacement mixes

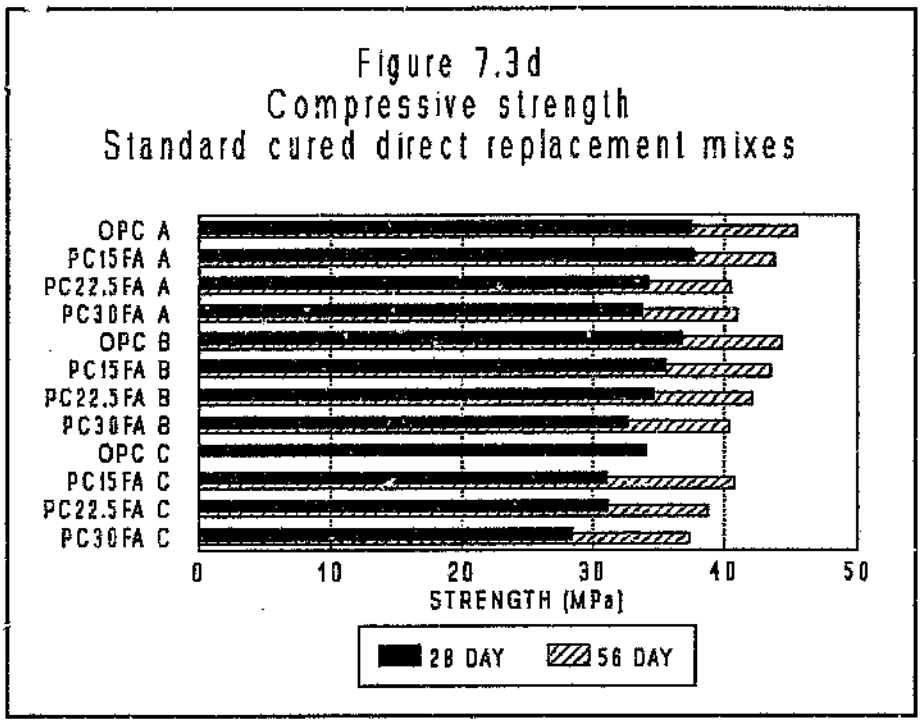


It can be seen from figures 7.3a and 7.3c that generally the compressive strength of the fly ash mixes under equivalent 28 day proportioning either falls within the range of compressive strength results achieved by the ordinary portland cement mixes, or exceeds this range at the ages of 24 hours and 7 , 28 and 56 days as shown.



Figures 7.3b and 7.3d show that under conditions of direct replacement the compressive strength of the fly ash mixes falls within or below the range of compressive strengths of the ordinary portland cement mixes. A contractor using the direct replacement technique with a Lethabo fly ash mix can therefore expect to stand a greater risk of non-compliance with his compressive strength requirements than would be the case on using an ordinary portland cement mix. This risk increases as the fly ash content increases.

Direct replacement in this case represents the practice of substitution of a bag of the fly ash blend for a bag of ordinary portland cement, but taking advantage of the reduction in water demand that the fly ash blend allows as would probably be the practice on site. The mixes given in table 7.2a do not show this practice, as in the mix proportions the cementitious/water ratio was kept constant. The results shown in the graphs of figures 7.3a to 7.3d have been adjusted to allow for the probable site practice by linear interpolation between the results obtained for the equivalent 28 day mixes, and those for the so called direct replacement mixes.



7.1.4 Simulated site curing – Matla fly ash

The kind of test results discussed in the preceding paragraphs are typical for laboratory studies, and have been carried out under the required laboratory curing regime of 28 days submerged in water at a temperature of 22 to 25 °C. Site concrete is seldom exposed to this kind of curing; an attempt was therefore made to evaluate the effects of "typical" site curing by casting relatively large blocks of concrete and exposing them to simulated site curing on an exposed site outside the PCI laboratory situated in Midrand, Transvaal.

The simulation of site conditions was achieved by casting relatively large blocks of concrete outside and exposing these to the sort of conditions that might occur on a poorly controlled construction site. These curing conditions consisted of leaving the shutter of the blocks in place for about 48 hours after which the forms were struck and the concrete left exposed to the weather without any further attempt to provide curing or protection.

A record was kept of the ambient temperature and humidity ranges during the period of curing up to the time for taking the test samples from the blocks. Obviously the temperature and humidity pattern during this period could have influenced the results obtained; it was therefore decided that in order to get a more realistic picture this testing should be done with both winter and summer exposures. A repeat of one of these tests was also planned to give some idea of the repeatability of the results under these uncontrolled conditions.

The blocks cast in winter were cast outside in the open; no rainfall was recorded during this period. The blocks cast in summer were stored out of doors but sheltered from the rain. In the test results reference is made to inner and outer or north and south cores. The inner core sections were cut from the part of the core near the centre of the block, while the outer section was cut so that the outermost face was about 50 mm below the surface. All cores were drilled horizontally. The north and south orientation gives a rough idea of the exposure; the approximately north facing side was exposed to more sunlight, while the south face had more shade.

The blocks had the following dimensions;

Width	620 mm
Length	710 mm
Height	600 mm

The blocks having these dimensions were cast in winter 1987, summer 1987/1988 and finally winter 1988. After the first series of tests a second size of specimen was added to the test programme, namely a beam section measuring 280 mm wide by 710 mm long by 230 mm high. The addition of this size of specimen was intended to allow the evaluation of the influence of the heat of hydration which was more likely to be significant on the large blocks. It was also thought that the greater surface area to volume ratio of the smaller specimens might make them more sensitive to the poor curing conditions.

The mixes that were used to evaluate the influence of cement extenders on the actual strength in the blocks (for blocks also read "structure") were as follows;

Mix No.	Cementitious blend
1	OPC
2	PC 15 FA
3	PC 30 FA
4	PC 50 SL

The last mix was included to provide information on the relative effects of ggbs (slag) and fly ash on the sensitivity of the compressive strength of the mixes to poor curing. Details of the mix proportions used are given in table 7.3a. Note that the source of fly ash in the case of the mixes for these large blocks was Matla.

The compressive strength testing of the large blocks was carried out by drilling 100 mm cores out of two opposite horizontal exposed faces of the blocks. The cores were drilled to a length of about 250 mm so that the compressive strength could be determined both near the outside of the block, where curing effects would be most pronounced, and near the centre of the block where the heat of hydration effects would be most pronounced.

In the case of the smaller beam specimens a similar approach was used except that the cores were drilled horizontally right through the beam. Two test specimens could be obtained from such a core, but in this case the centre of the concrete would not be represented.

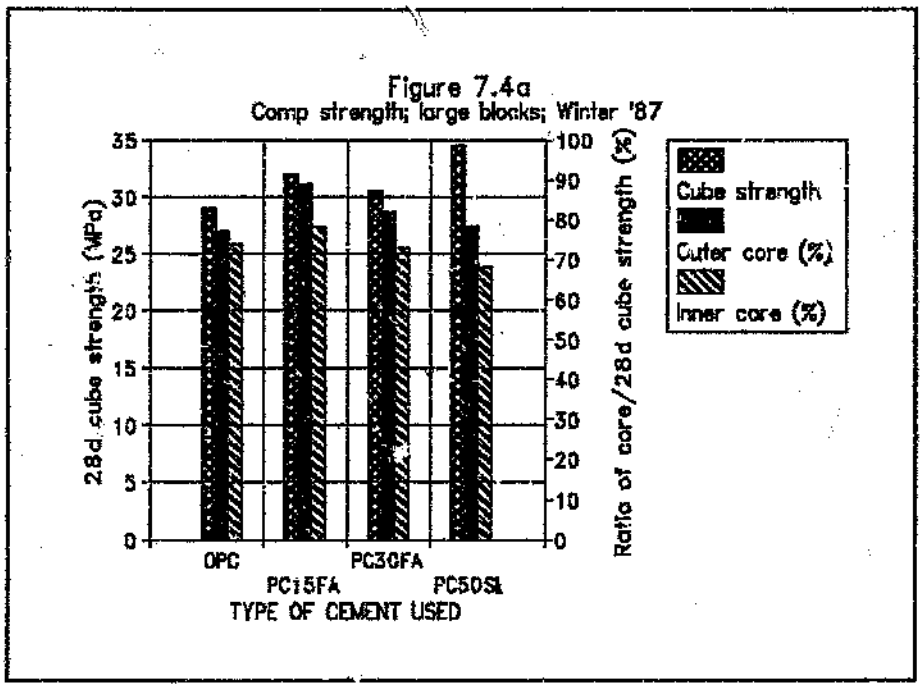
Other cores were drilled from the blocks to provide specimens for water absorption testing to DIN 1048 Part I, "Test Methods for Concrete, Section 4.7, Impermeability to Water".[288] The core diameter was 150 mm in this case. Abrasion testing was also done on these blocks; the blocks done during the winter of 1987 had the top surface tested, while the summer and second winter test were tested on the shuttered surfaces. The results of both the DIN water absorbtion and the abrasion resistance tests will be described in later chapters.

During the casting of the blocks note was made of the approximate duration of bleeding, and the time after placing at which it was possible to do the final trowelling of the exposed top surface of the specimen.

The cores for compressive strength testing were drilled to allow sufficient time for cutting, capping and soaking to be done in accordance with SABS Method 865[289] so that the 28 day values could be obtained. For each exposure face and depth from the exposed face 3 cores were taken and the results averaged. Cubes were also taken for each mix and these test specimens were exposed to standard SABS Method 863 curing[285] for testing at 7 and 28 days. The results of these tests are given in tables 7.3b and 7.3c for the tests in winter 1987, tables 7.3d, 7.3e and 7.3f for the tests in summer of 1987/88 and tables 7.3g, 7.3h and 7.3i for the tests in winter 1988. Some of this information is presented graphically in figures 7.4a to 7.4c.

The details of the temperature and humidity ranges for the summer 1987–88 and winter 1988 tests are given in table 7.4.

Studying figure 7.4a it can be seen that the cores all have lower strengths than reflected by the cubes made from the same mix but cured under standard conditions. The cube strength in MPa is shown by the bar on the left of each set; the other two bars show the core strength relative to that of the cubes for that mix. Interestingly, the relative strength for the cores taken from the outer zone of the block is higher than that for the cores taken from near the centre of the block where the heat of hydration could be expected to play a more significant role. The mix with 50 % slag seems to show the greatest degree of effect due to the poor curing when compared to the result of the cube test. On the other hand, none of the mixes exhibited a drop in compressive strength of the cores in excess of about 5 % of the equivalent opc results.


Figure 7.4a
Comp strength; large blocks; Winter '87
28d cube strength (MPa)
Ratio of core/28d cube strength (%)
Cube strength
Outer core (%)
Inner core (%)
OPC
PC15FA
PC30FA
PC50SL
TYPE OF CEMENT USED

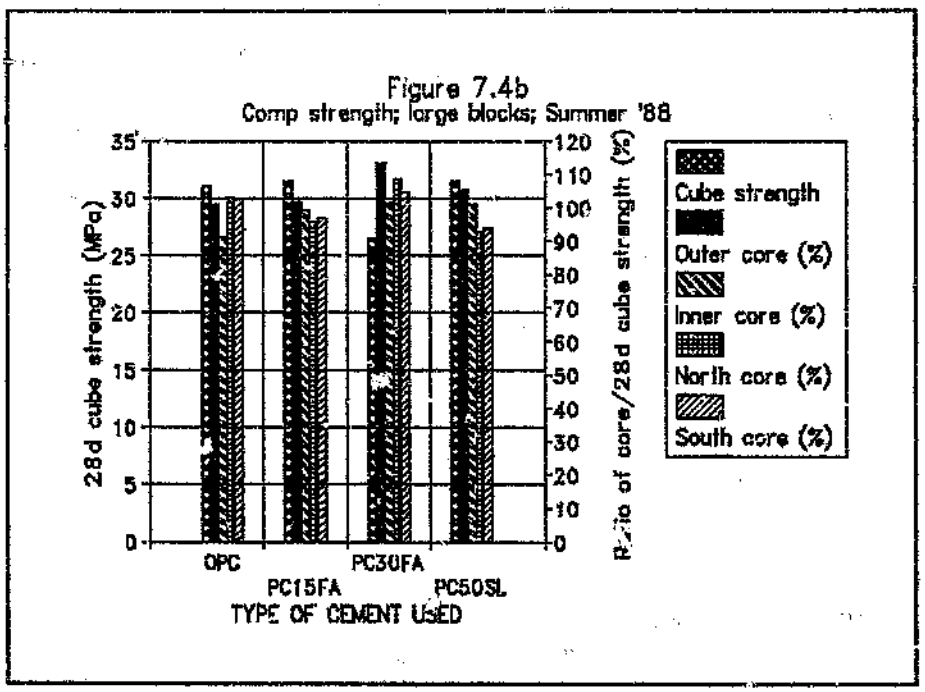
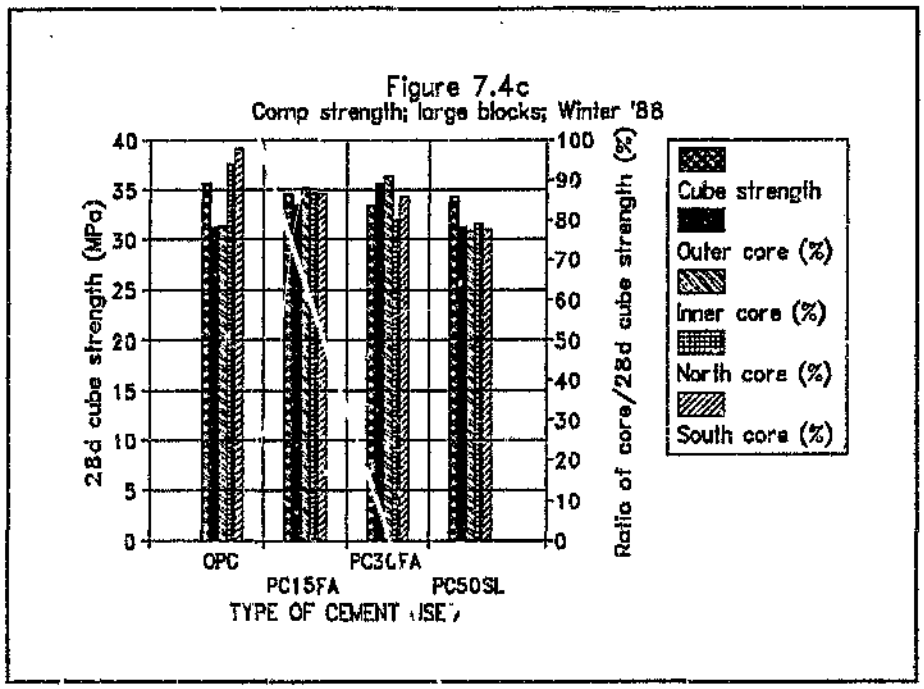

Figure 7.4b
Comp strength; large blocks; Summer '88
28d cube strength (MPa)
Ratio of core/28d cube strength (%)
Cube strength
Outer core (%)
Inner core (%)
North core (%)
South core (%)
OPC
PC15FA
PC30FA
PC50SL
TYPE OF CEMENT USED

Figure 7.4b gives similar information for the summer cast. In this case some of the core compressive strengths exceed the cube strengths: in all cases the core strength is higher than would be expected had the curing conditions been similar. In this case the mix containing 30 % fly ash seems to show the greatest benefit from this kind of exposure. Again it is seen that the compressive strength of the outer cores is higher than that of the inner cores. Both the opc and 30 % fly ash mixes seem to show less effect of poor curing in the smaller beam sections while the 15 % fly ash and 50 % slag mixes seem to show a greater effect.



This last observation is supported in the case of the opc mix in figure 7.4c for the winter exposure of 1988. None of the other mixes show any great impact of the cold weather on the beam sections.

The compressive strength reflected by a core from a concrete is generally believed to be about 80 % of the compressive strength of the same concrete in a laboratory cured and tested cube, provided that both specimens have a similar curing history.[260] In the case of the winter cured concrete blocks the results of the cores are fairly close to this value. The results of the tests in summer indicate that the strength development of all the mixes is greater in the relatively large specimens in these warm conditions.

It seems that the influence of poor curing on the compressive strength of these large blocks is rather insignificant, and further that the compressive strengths of the concretes made with extenders are not significantly more sensitive to poor curing than the ordinary portland cement concrete. This is most probably due to the fact that the outer 50 mm of concrete is trimmed off during the compressive strength test, thus removing the zone most effected by poor curing, and by the fact that the heat of hydration inside the blocks could have accelerated the hydration process.

7.1.5 Laboratory studies of temperature effects

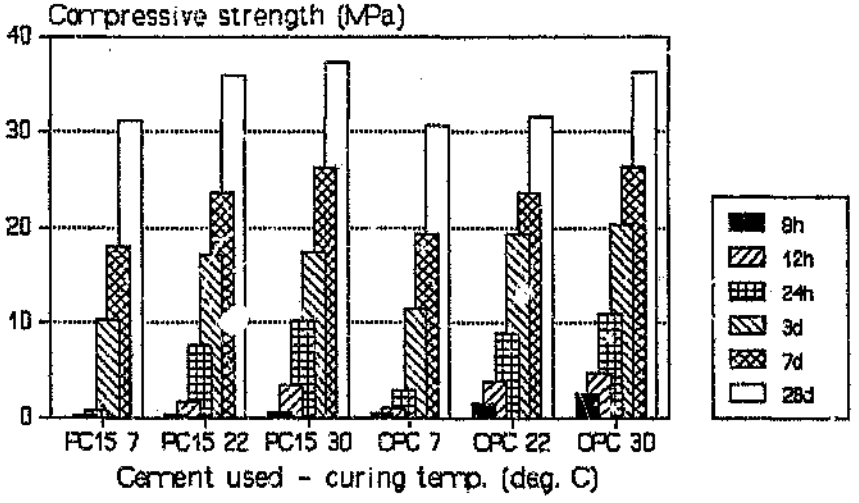
More work was done under controlled conditions in the laboratory to study the rate of compressive strength gain when the curing temperature was either higher or lower than the standard temperature range of 22 to 25 °C specified by SABS Method 863.

7.1.5.1 Matla fly ash

For some of these tests the mixes used were those shown in table 5.12c. It should be noted that the same cementitious/water ratio was used in these mixes and therefore the compressive strength at 28 days was not always the same as for the opc mix. The concretes were exposed to three different temperature regimes namely, a cold temperature of about 7 °C, the standard temperature as indicated above, and a warm condition with a temperature of about 30 degrees. In each case the specimens were sealed in plastic bags to restrict the moisture loss; the moisture conditions were therefore close to saturated.

The results of the compressive strength tests on the specimens exposed to these conditions are given in tables 7.5a, 7.5b and 7.5c, and these data are plotted in figures 7.5a to 7.5c showing the strength development of the various mixes. A further set of graphs Figures 7.5d to 7.5f show these data plotted relative to the opc strengths at each age to give an impression of the relative effect of the temperature.

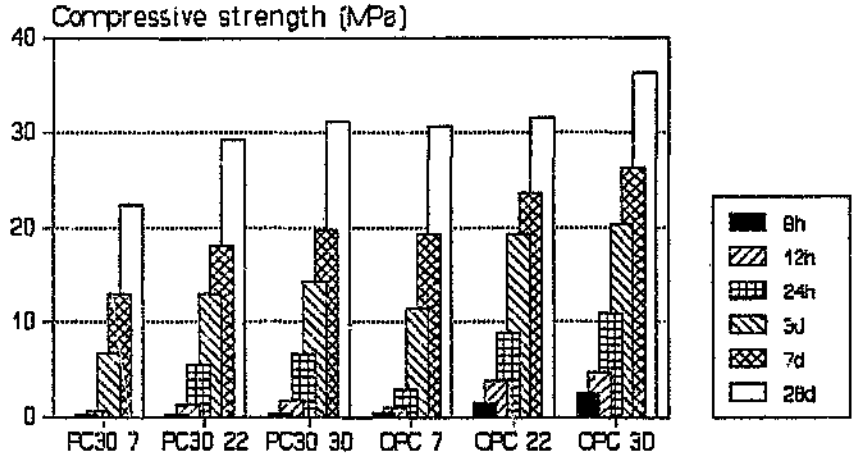
Figure 7.5a
Effect of curing temperature on comp. strength of OPC and fly ash concretes



Under standard conditions (figure 7.5e) with the mixes all made at the same cement/water ratio, it is clear that the level of compressive strength at ages up to 3 days for all the blends lags behind the compressive strength developed by the OPC mix. At 7 days the PC 15 FA mix reached strength parity although the compressive strength at 28 days was higher than the OPC mix. In the case of the PC 30 FA mix the 28 day compressive strength was still below that of the OPC mix.

It is interesting to note that the very early strength of the fly ash mixes is lower than the slag mix, although they catch up rather quickly, overtaking the compressive strength of the slag mix before 12 hours. This indicates that fly ash has a greater impact on the setting time of concrete and confirms the finding on setting time described in chapter 5.

Figure 7.5b
Effect of curing temperature on comp. strength of OPC and fly ash concretes



In the warmer environment a similar trend is evident as can be seen in Figure 7.5d.

Under the cold conditions the mixes containing the blends gain strength much more slowly than the ordinary portland cement mix, although after 3 days the PC 15 FA mix gives values which are not a great deal lower than those of the OPC. It is significant that while under hot or standard conditions the compressive strength of the PC 15 FA mix exceeds that of the OPC mix at 28 days, this is only just the case under cold conditions; this seems to indicate a greater sensitivity to low temperatures in the fly ash mix, under these conditions, ie on small laboratory specimens.

In Figure 7.5f the slag mix appears to suffer a greater drop in compressive strength relative to the OPC mix under the cold conditions than is the case for either the PC 15 FA or PC 30 FA mixes.

The OPC mix shows a small drop in the 28 day compressive strength when exposed to the cold curing when compared with the standard (ie a drop of about 3 %). The PC 15 FA mix has a more severe drop in 28 day compressive strength (about 13 %) relative to the standard conditions and this trend is even more marked in the case of the PC 30 FA mix (about 23 %).

The only cement to show any significant gain in 28 day compressive strength under warm conditions (when compared against the standard conditions) is the OPC; however the temperature in these warm conditions is still below that which would be expected under adiabatic conditions in a similar mix.

Figure 7.5c
Effect of curing temperature on comp. strength of OPC and slag concretes

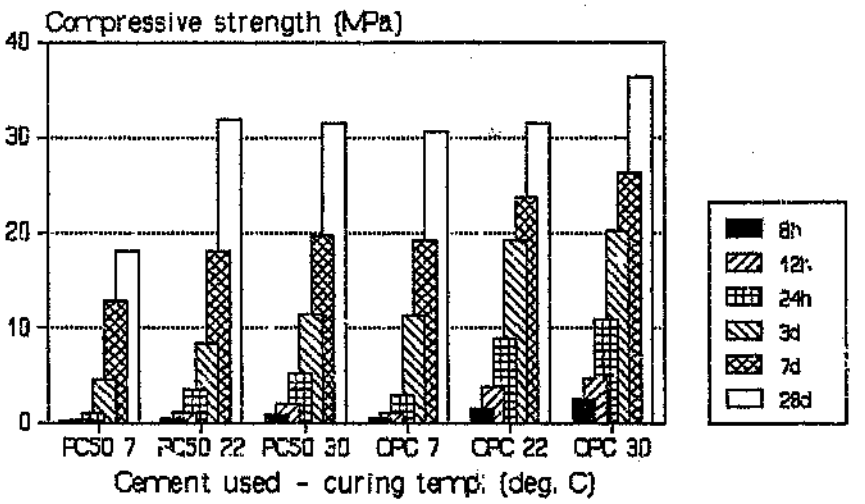


Figure 7.5d
Age strength ratio at 30 degrees

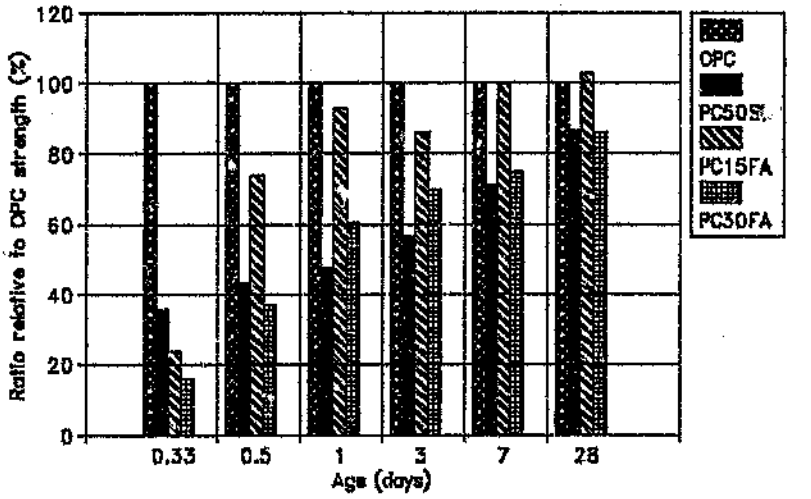
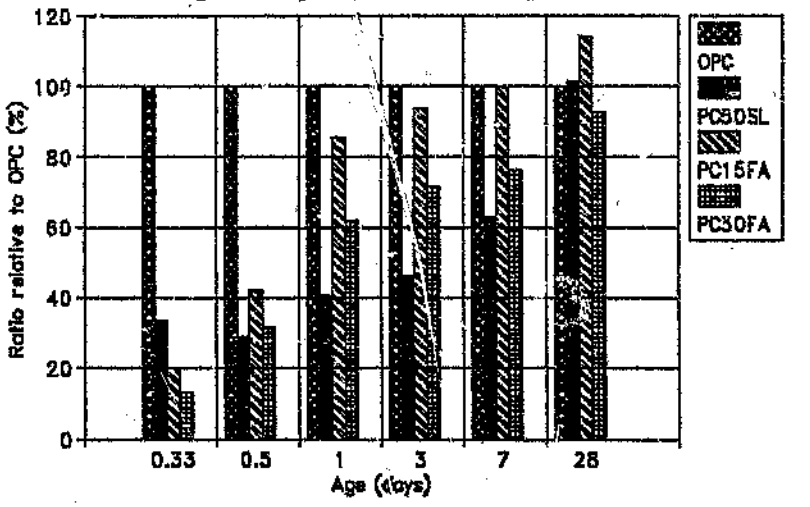
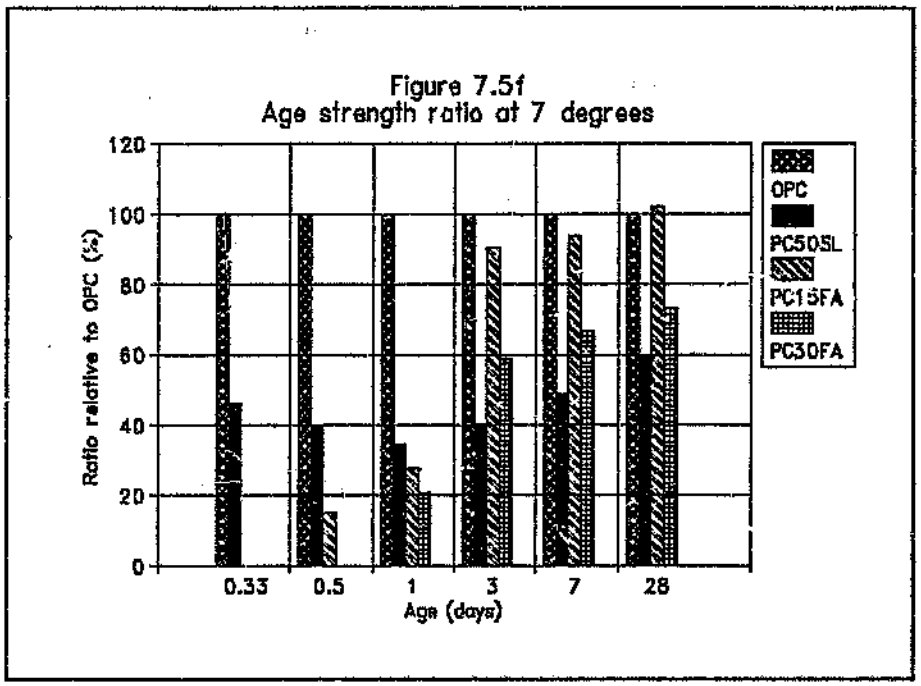


Figure 7.5e
Age strength ratio at 23 degrees





7.1.5.2 Lethabo fly ash

Some of the concrete specimens made from the mix proportions given in table 7.2a were also exposed to curing conditions in oven, standard or cold curing conditions. The 28 day compressive strength results for oven, standard and cold cured concretes for the equivalent 28 day and direct replacement mixes are shown in figures 7.5g to 7.5j. All specimens were sealed in plastic bags during such exposure to keep the concrete saturated. In some cases the bags may have become perforated during handling in which case there would have been partial exposure to the moisture conditions in these areas. These were as follows:

Location	Temperature °C		Humidity (% RH)	
	Average	Standard deviation	Average	Standard deviation
Oven	29	3,2	38	15,1
Standard	22	1,3	46	10,3
Cold	6	3,1	97	6,3

For each cement shown in figure 7.5g the oven, standard and cold cured fly ash specimens made to equivalent 28 day compressive strength show little effect of the different curing temperature regimes when compared against the ordinary portland cement control performance. In the oven cured case the fly ash mixes show a greater

improvement with the added heat than is the case with the ordinary portland cement mixes.

Under the direct replacement proportioning method shown in figure 7.5h this is not as evident. In this case the trend is a slight decrease in compressive strength as the fly ash content increases in the oven and standard curing conditions. In the cold conditions this trend is particularly marked.

Figures 7.5i and 7.5j show the results for 7 day compressive strengths for the same mixes. Again the equivalent 28 day mixes appear to perform similarly to the ordinary portland cement mix although cement C blends do show a slight decline in strength relative to the opc. In the direct replacement mixes the impact of the fly ash is even more marked than in the case at 28 days.

These graphs indicate that the Lethabo fly ash mixes, as is the case noted with the Matla fly ash mixes, have greater sensitivity to curing temperature than do ordinary portland cement mixes.

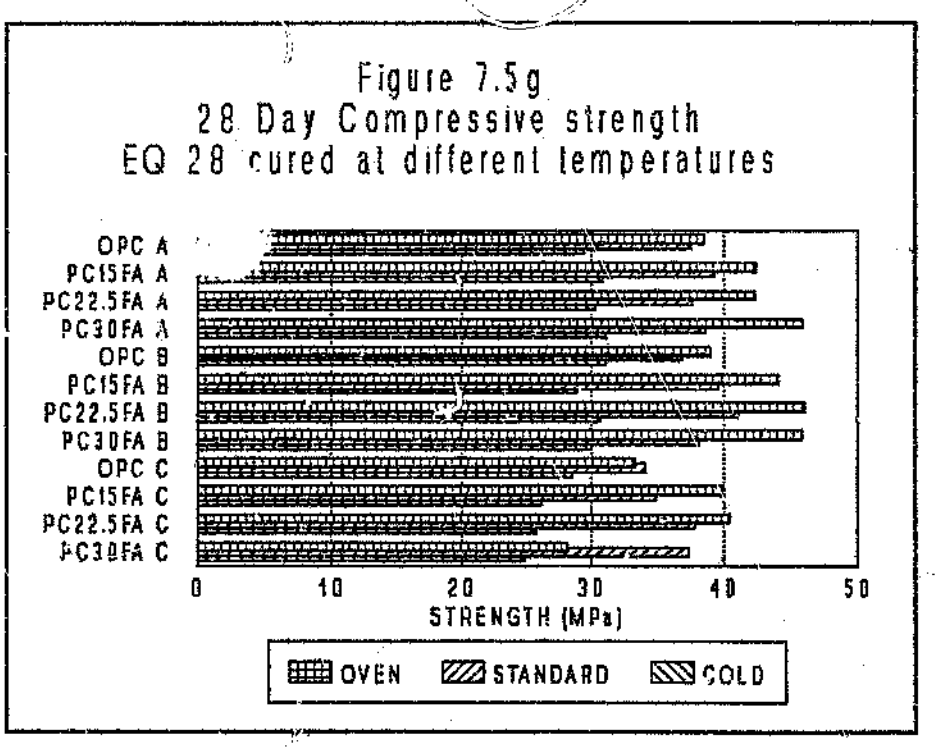


Figure 7.5h
28 Day Compressive strength
DR cured at different temperatures

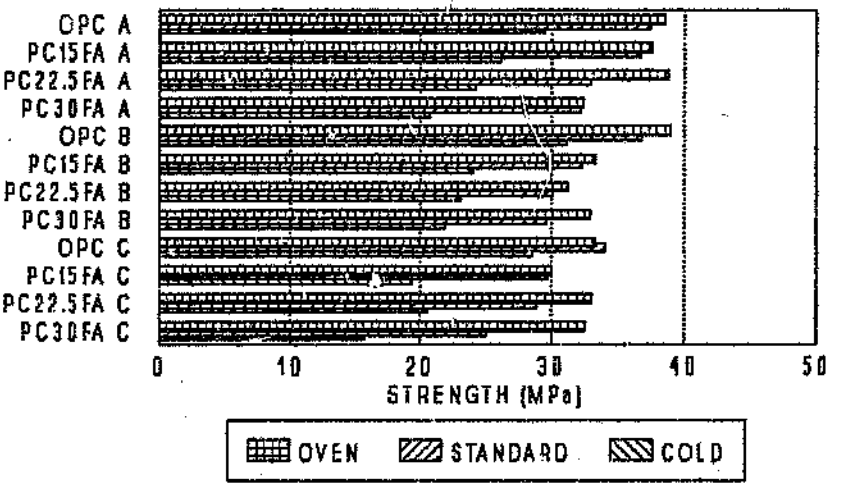
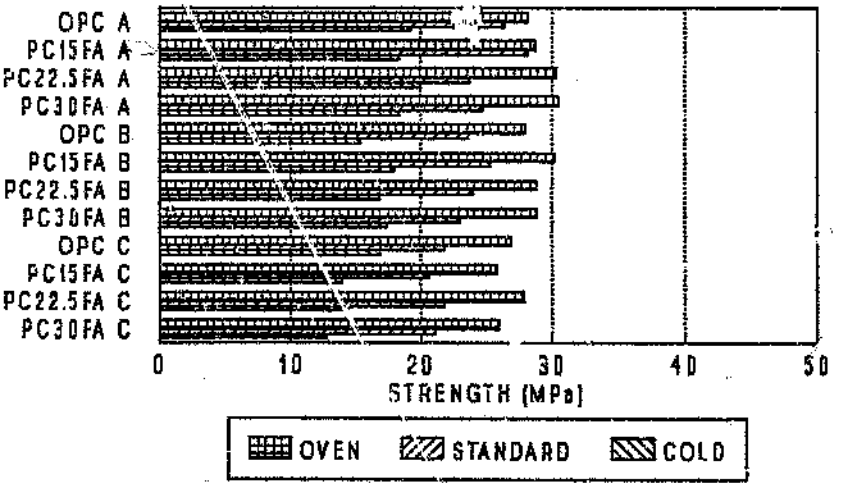
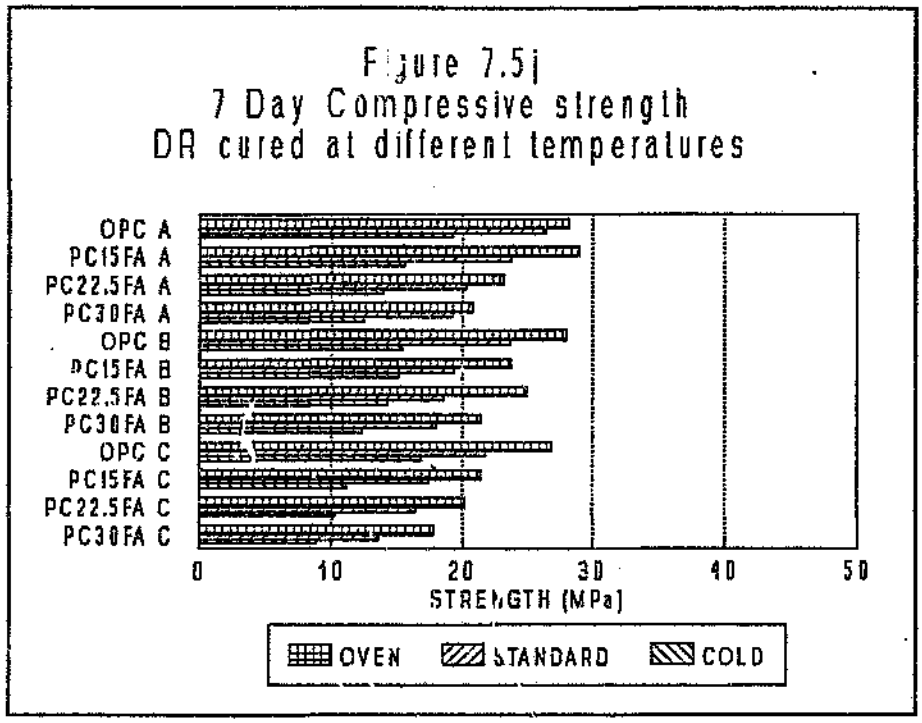


Figure 7.5i
7 Day Compressive strength
EQ 28 cured at different temperatures





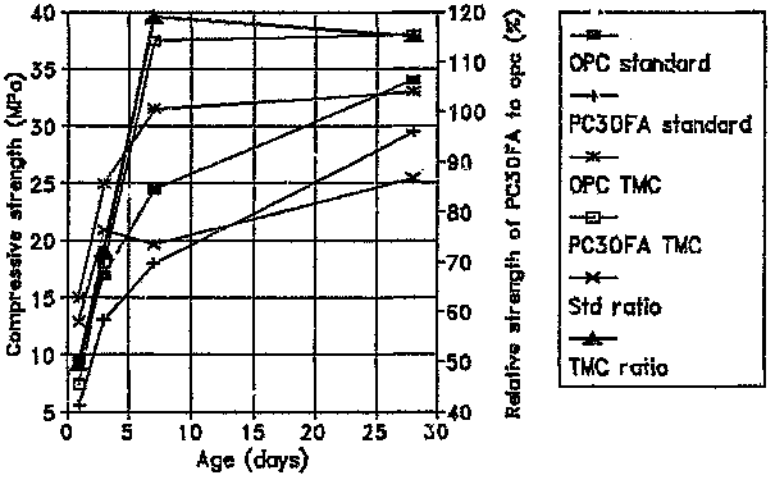
7.1.6 Temperature matched curing (TMC)

In the laboratory studies done to examine the effects of fly ash on the heat of hydration of concretes which have been described in chapter 6, cube specimens for compressive strength were exposed to the temperatures developed under adiabatic curing conditions. A comparison of the increase in compressive strength of an ordinary portland cement mix and a 30 % fly ash mix with the same 28 day compressive strength target under standard conditions is given in table 7.6. It can be seen that the fly ash mix shows greater gains in compressive strength at 3, 7 and 28 days under the temperature matched conditions than is the case with the opc.

This is not necessarily a contradiction of the high temperature (30 °C) results above as the temperatures involved with these TMC tests (cured in a range of 60 to 70 °C) are higher than in the results for the oven cured specimens shown in figures 7.5a to 7.5d and 7.5g to 7.5j.

The relative compressive strength of the fly ash mix against the ordinary portland cement mix is also shown on figure 7.6 for both standard and TMC conditions. It is evident from these curves that the fly ash shows a dramatic improvement in compressive strength development when exposed to these temperatures, particularly at the early ages. At 7 days the PC 30 FA mix achieved more than 2,1 x the compressive strength developed under standard conditions, while the OPC mix showed an increase of only 30 % relative to its standard cured specimens.

Figure 7.6
Age strength relationship for TMC



Botha and Amtsbuchler[281] gave results of the difference between the compressive strength results of two fly ash concrete mixes cured using standard conditions or temperature matched conditions. The beneficial influence of the additional heat on these fly ash mixes was evident on particularly the early compressive strength of the concrete. The effect was more marked with structural concrete, with a temperature rise of 35 °C over the standard conditions; the effect at this very elevated temperature is dramatic at the early ages but stabilises after about 7 days with little apparent increase after this age.

In the case of mass concrete[281] the temperature rise was more moderate at about 12 °C above the starting temperature. In this case the benefit seems to continue over a much longer period, but is not so marked at the early ages. This is a phenomenon that is also evident in concretes made with rapid hardening cement when compared against a similar ordinary portland cement concrete; a fast reaction results in a high early strength, but the benefit is diminished at later ages.

Mani et al[282] showed a slight drop in compressive strength of ordinary portland cement mixes at late ages if cured at high temperatures when compared against standard curing conditions. In the case of a 30 % fly ash mix there was little difference in the level of compressive strength under the two curing regimes after about 56 days. The early strength under the high temperature cured fly ash mix was much higher than under standard conditions, and the fly ash mix showed a much greater improvement than did the ordinary portland cement mix. It was noteworthy that under standard conditions the 30 % fly ash mix did not show a great improvement in long term compressive strength development relative to the ordinary portland cement mix although admittedly this work was done on a direct replacement basis. The chemical

analysis of the fly ash used in this work was rather similar to that of Lethabo fly ash.

The indication given by Cannon[231] is that the OPC mixes suffer compressive strength drops under high temperature conditions while the fly ash mixes show some benefit. The order of magnitude of the drop in compressive strength for OPC appears to be greater than shown by Mani et al.[232]

It is apparent that more work is required to provide more detail of this effect including data on the effect at ages greater than 28 days.

7.2 Summary of findings on compressive strength

The incorporation of fly ash as part of the cementitious material of a concrete mix using the partial replacement method of mix proportioning is likely to result in a reduction of the early compressive strength of the concrete when compared against an OPC control mix performance even though the 28 day compressive strengths are similar.

This effect will be more marked as the fly ash content of the mix increases.

The cement/water ratio of fly ash mixes should be higher than that of a similar OPC mix for equivalent 28 day compressive strength. The difference between the fly ash mix cement/water ratio and that of an OPC mix will increase as the fly ash content increases.

The use of fly ash will, as noted in the summary to chapter 5, allow a reduction in the water content required to give the same slump as the control OPC mix, with the water reduction increasing with increase in fly ash content. The fact that the cement/water ratio has to be increased does therefore not necessarily result in a substantial increase in the cementitious content of the mix if advantage is taken of the water reduction. It is possible that a fly ash mix with the same cementitious content as the control OPC mix could give a similar level of 28 day compressive strength if the water reduction permitted by the use of the fly ash counteracts the required increase in cement/water ratio.

The compressive strength of fly ash mixes will continue to increase at a rate greater than a similar OPC mix at ages beyond 28 days when exposed to good curing. This is evident from figure 7.1h where it can be seen the compressive strength of fly ash mixes with up to 30 % fly ash content will perform similarly to an OPC mix with the same cement/water ratio. This property can be used to further reduce the concrete cost if 28 day compressive strength is not important although particular attention to curing would be necessary if the fly ash concrete is to meet the expected level of compressive strength.

If concretes are proportioned by simply replacing the OPC with a fly ash blended cement then the effect of lower early compressive strength is likely to be more marked. Fly ash mixes proportioned this way are also less likely to reach 28 day compressive

strength parity with a control OPC mix.

Concretes containing slag or fly ash extenders can be expected to show a greater degree of slowing of the rate of gain in compressive strength when exposed in thin sections to cold ambient conditions than will be the case with an OPC concrete. This tendency is more evident with Matla fly ash mixes than is the case for Lethabo fly ash mixes.

Appropriate mix proportioning will tend to compensate for the slowing in the rate of compressive strength development of fly ash mixes, while direct replacement will tend to accentuate this effect.

Little improvement in the rate of compressive strength gain can be expected with blended cement concretes when exposed to high ambient temperatures unless the concrete temperature exceeds 30 °C.

Fly ash concretes do not appear to show a more severe compressive strength degradation (as determined by core strength determination) when exposed to poor "site" curing conditions than is exhibited by similar OPC concretes. This may be as a result of the fact that in preparing a core specimen in accordance with SABS Method 863 it is necessary to trim off the outer exposed concrete skin, thus eliminating the zone most likely to be affected by the poor curing.

The implications that the above changes, brought about by the use of fly ash in the concrete mixes, have to the practical use of fly ash mixes on construction sites in South Africa are as follows:

- Sophisticated users that modify the mix proportions of the fly ash mixes appropriately will achieve the desired target 28 day compressive strengths with mixes that have a similar amount of cementitious material to that of an OPC mix with the same target compressive strength.

- The early compressive strength of such mixes will be depressed relative to what would have been achieved with a similar OPC mix.

- These mixes will show a tendency to be more sensitive to ambient temperatures with cold curing conditions resulting in a greater reduction, and hot curing in a greater improvement in compressive strength than would be shown by a similar OPC mix.

- The effect of poor curing, as measured in cores cut from fly ash concrete mixes, will not show any negative impact on compressive strength.

- Unsophisticated users who use recipe mix proportioning will not get the full benefit of the use of fly ash by direct replacement of the OPC content, and will probably notice a reduction in 28 day compressive strength and reduced ability to handle concrete products at early ages. These effects will be emphasised when the fly ash content is above about 15 %, and will be more noticeable with Matla than Lethabo fly ash.

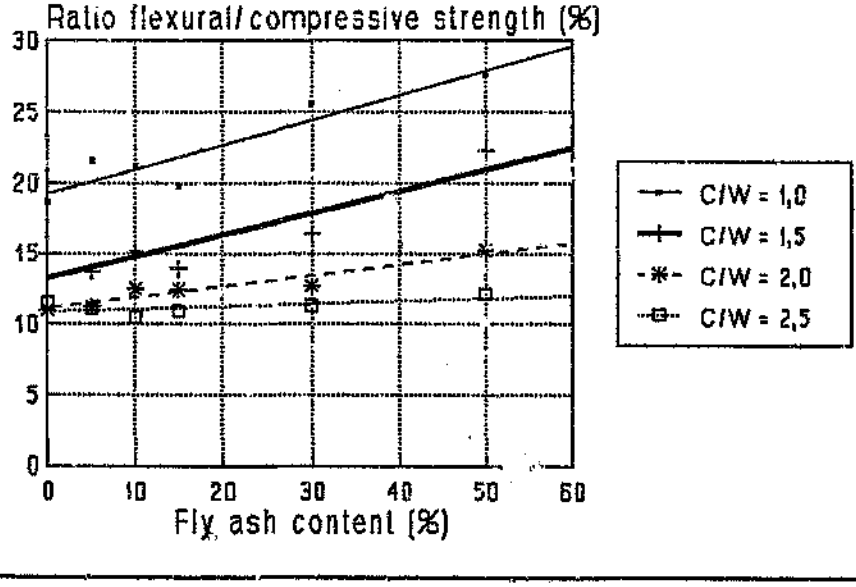
7.3 Flexural or tensile strength

The mix proportions used in making the beam specimens for testing in bending to provide the flexural strength values are those given in table 5.1a. Standard 100x100x500 mm beam specimens were made for testing at 23 days in accordance with SABS Method 864, "Flexural Strength of Concrete (Including making and curing of specimens)"[292].

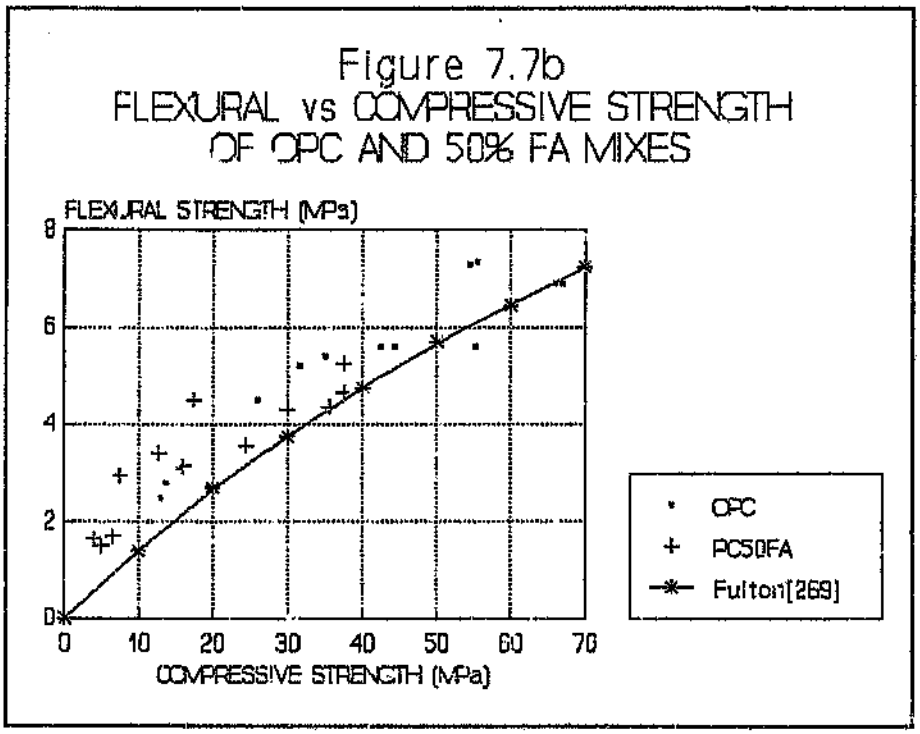
The results of the tests on these beams are given in table 7.7a.

These data have been compared against the compressive strength values for the same mixes and the ratio of flexural strength to compressive strength in % is given in table 7.7b. The average ratio for all the laboratory blends, ie not the 2 "factory" products, are shown in table 7.7c. These latter values are shown in figure 7.7a. The lines shown in figure 7.7a are best fit lines to the available data.

Figure 7.7a
Ratio of flexural/compressive strength



Looking at figure 7.7a it seems that there is a general trend for the ratio of flexural to compressive strength to increase with increasing fly ash content although this is not particularly noticeable for fly ash contents up to about 15 %. There is also a strong trend for the ratio to decrease as the cement/water ratio increases, although this effect becomes less marked once the cement/water ratio exceeds 2,0. The differences in the ratios for the different cement/water ratios increase as the fly ash content increases. It is worth noting that particularly high flexural to compressive strength ratios are obtained for low cement/water ratios at high fly ash contents.



The range of cement/water ratios that is commonly specified for pavement grade concrete in South Africa is from 1,9 to 2,1 with a minimum cement content of about 320 kg/m^3. Figure 7.7a shows little sensitivity of the ratio of flexural to compressive strength to fly ash content of the mix in this range, ie the ratio for a fly ash mix is similar to that for an ordinary portland cement mix, and the above finding is of little significance for paving quality concrete. Pavement quality concrete is that concrete in which the flexural strength is the most important property.

It should be noted that the sets of specimens for compressive strength and flexural strength were both made from the same mix. Therefore although the mixes containing fly ash do not necessarily reach compressive strength parity with the ordinary portland cement mix of the same cement/water ratio the influence of changing the cement/water ratio of the fly ash mixes will tend to increase both flexural and compressive strength and the ratio between them is not expected to change markedly. The trend of increasing ratio of flexural to compressive strength with an increase in fly ash content should therefore not be affected appreciably.

These findings seem to contradict the findings of most other authors who have reported on the topic.[111,116,153] Much of this work was done however over a range of strengths commonly used for structural concrete and was thus in the relatively insensitive area of the graph shown in figure 7.7a, ie cement water ratios of 2,0 and above.

Fulton[269], in his study of the effect of slag on the flexural strength of concretes, found that the flexural strength of the 50/50 slag mixes showed markedly higher values for the blended cement when compared against ordinary portland cement mixes at high compressive strengths. In this study there are insufficient data to be able to plot a similar graph to Fulton's figure 31 with confidence. Nevertheless such a plot is given in figure 7.7b showing only the opc and PC 50 FA data points from this study, together with the curve shown in figure 31 of Fulton[256]. These two sets of data have been selected to avoid confusing the picture with too many unrelated points.

Looking at figure 7.7b it seems possible that the fly ash mix curve could lie a little lower than the opc curve in the area of low compressive strength, but, as stated before, this cannot be said with great confidence.

In a study done using a selected fraction (field 2) of Lethabo fly ash Gordon[293] showed that the long term flexural strength gain between 28 and 90 days for fly ash mixes was greater than for ordinary portland cement mixes. His tests were done on specimens exposed to standard curing. The results in these tests showed that the incorporation of fly ash reduces the 28 day flexural strength of the fly ash mixes with the reduction being roughly proportional to the fly ash content; by 90 days the flexural strength of the fly ash mixes had caught up to that of the ordinary portland cement mixes. These results were similar to the effect noted in the compressive strength at 28 days.

As only 28 day flexural strengths were determined in this study, it is not possible to confirm this finding. The pattern of 28 day strengths shown by Gordon is sufficiently similar to the results given here for the Matla ash (table 7.7) to indicate that Lethabo ash has a similar effect on the flexural strength.

Gordon agues that the large increase in flexural strength of the fly ash mixes beyond 28 days would make it possible for reductions in the cementitious content of such mixes if it is assumed that the level of flexural strength reached by ordinary portland cement concrete at these later ages is all that is required. This argument unfortunately ignores the fact that an appropriate level of early (circa 24 hours) tensile strength of pavement concrete is essential to allow for the joints to be sawn before the cracking caused by drying shrinkage has an opportunity to occur. Based on PCI experience with problems with joint sawing in concretes made with slag extender, it is believed that a reduction in cementitious content would make the concrete more sensitive to such cracking – it could even occur before it was possible to saw without an unacceptable degree of spalling at the edges of the sawcut. Gordon also assumes that with the curing provided on site compressive and flexural strength gain of the fly ash concrete will be similar to that shown in the laboratory; this is probably a rather optimistic assumption.

It is believed therefore that more work is required to evaluate this property under site

conditions to determine whether a reduction in cementitious content to allow for the added long term development in flexural strength of fly ash concretes is warranted.

7.4 Summary of findings on flexural strength.

The effect of fly ash seems to be that it increases the flexural strength of concrete relative to the compressive strength to a greater degree than is the case for ordinary portland cement concretes. In the range where pavement quality concrete is normally specified this difference is insignificant for a fairly wide range of fly ash contents.

A warning is sounded against the simplistic argument that as the flexural strength of fly ash concrete at ages beyond 28 days is so much higher than an equivalent ordinary portland cement concrete, the cementitious content of such concrete could be reduced. This argument is based on the premise that the performance recorded in laboratory specimens will be matched by the performance of the pavement structure exposed to probably "imperfect" curing methods and ambient environmental conditions; to the writers knowledge this has not yet been shown to be the case for any concrete – with or without the use of extenders.

Table 7.1a:
Compressive strength results with PPC Jupiter (silo) cement

% Fly ash	Age at test (d)	Compressive strength (MPa) for mixes ●			
		c/w=1,0	c/w=1,5	c/w=2,0	c/w=2,5
0	1	3,5	9,5	14,5	20,0
	3	6,7	16,0	23,5	33,0
	7	7,0	21,5	35,0	42,5
	28	13,0	29,5	43,0	54,0
	56	15,5	34,5	48,0	61,5
	90	10,5	37,5	52,5	66,5
	120	–	–	–	–
5	1	3,5	8,5	14,0	19,5
	3	6,5	13,5	26,0	35,0
	7	8,5	20,0	32,0	43,0
	28	12,5	28,5	43,0	54,0
	56	15,0	33,0	52,5	62,0
	90	16,0	35,5	54,0	64,5
	120	–	–	–	–
10	1	3,0	7,0	11,0	17,5
	3	5,5	13,5	23,5	30,5
	7	7,0	18,0	29,5	39,5
	28	12,5	27,0	40,0	52,0
	56	16,0	32,5	49,5	62,5
	90	18,5	35,5	55,0	65,0
	120	–	–	–	–
15	1	3,0	6,0	10,0	16,0
	3	6,0	12,0	21,0	28,5
	7	7,0	17,0	27,5	39,0
	28	11,5	25,5	38,0	52,0
	56	15,5	32,5	49,5	60,5
	90	17,0	36,5	53,5	67,5
	120	–	–	–	–
30	1	2,0	5,5	8,0	9,5
	3	4,0	10,0	18,5	24,0
	7	5,5	13,5	24,0	32,5
	28	9,5	23,5	36,0	47,5
	56	12,5	30,5	46,5	61,0
	90	15,5	35,5	56,0	68,5
	120	–	–	–	–
50	1	1,0	1,5	4,0	6,0
	3	2,5	4,0	10,5	16,5
	7	4,0	8,5	16,0	24,0
	28	7,5	12,5	28,0	39,0
	56	9,0	15,5	35,0	51,0
	90	11,5	20,5	43,5	59,0
	120	–	–	–	–

Table 7.1b:
Compressive strength results with A-A Roodepoort cement

% Fly ash	Age at test (d)	Compressive strength (MPa) for mixes @			
		c/w=1,0	c/w=1,5	c/w=2,0	c/w=2,5
0	1	-	-	-	-
	3	8,0	15,0	26,0	35,0
	7	10,0	23,5	40,5	50,0
	28	15,5	35,0	54,5	68,0
	56	19,5	41,0	60,0	73,0
	90	20,5	45,0	64,5	76,5
	120	22,5	45,5	66,5	80,0
5	1	-	-	-	-
	3	5,5	14,5	25,0	32,5
	7	9,0	22,0	35,5	48,0
	28	14,5	34,0	52,0	62,5
	56	18,5	41,5	59,5	71,0
	90	21,5	45,0	64,5	-
	120	22,0	45,5	68,5	78,0
10	1	-	-	-	-
	3	5,0	12,5	21,5	31,0
	7	7,5	19,5	33,0	45,5
	28	13,5	31,5	48,0	61,5
	56	17,5	39,0	57,5	72,5
	90	-	43,5	63,0	77,5
	120	20,5	45,5	68,0	81,5
15	1	-	-	-	-
	3	3,5	13,0	21,0	26,5
	7	7,0	18,5	31,5	41,5
	28	12,5	31,0	47,5	62,5
	56	16,0	38,0	59,0	71,5
	90	19,0	42,5	61,5	78,0
	120	21,0	48,0	68,0	80,5
30	1	-	-	-	-
	3	4,0	8,0	14,0	24,5
	7	3,5	14,0	21,5	36,5
	28	7,5	24,0	38,0	54,5
	56	11,5	32,5	48,5	68,5
	90	15,0	39,5	57,5	75,0
	120	17,5	42,5	58,0	77,5
50	1	-	-	-	-
	3	2,0	5,5	9,0	14,5
	7	2,5	7,5	14,0	24,0
	28	4,5	13,0	24,5	37,5
	56	6,5	20,0	35,0	51,0
	90	9,5	26,5	41,5	60,0
	120	12,0	27,5	45,5	63,5

Table 7.1b:
Compressive strength results with BC Lichtenburg cement

% Fly ash	Age at test (d)	Compressive Strength (MPa) for mixes @			
		c/w=1,0	c/w=1,5	c/w=2,0	c/w=2,5
0	1	4,5	11,0	18,5	22,5
	3	7,5	16,5	29,0	39,0
	7	10,0	24,5	41,0	52,0
	28	16,0	35,5	55,5	67,0
	56	19,5	41,5	60,5	72,0
	90	21,0	42,0	63,5	76,0
	120	-	-	-	-
5	1	4,0	8,5	16,0	19,5
	3	6,0	14,0	25,5	37,0
	7	9,0	21,5	37,5	49,5
	28	15,0	33,5	52,5	66,0
	56	18,5	38,5	58,5	76,0
	90	19,0	41,0	63,5	-
	120	-	-	-	-
10	1	3,5	8,5	14,0	19,0
	3	6,0	14,0	23,5	36,0
	7	9,0	21,5	34,5	49,5
	28	15,0	33,0	51,0	66,0
	56	18,5	38,5	58,5	74,0
	90	19,5	42,0	63,0	81,0
	120	-	-	-	-
15	1	3,5	7,5	13,0	14,0
	3	5,0	13,5	22,0	32,5
	7	8,5	20,5	33,5	46,0
	28	14,0	32,5	47,5	63,5
	56	17,5	41,0	57,0	74,5
	90	19,5	45,0	63,5	77,0
	120	-	-	-	-
30	1	3,0	6,0	10,0	14,5
	3	3,5	10,5	17,0	26,5
	7	5,5	15,0	26,0	39,5
	28	10,5	25,5	43,5	57,5
	56	15,5	33,0	51,5	70,0
	90	17,0	39,0	52,0	78,5
	120	-	-	-	-
50	1	3,0	6,5	7,0	8,0
	3	3,0	6,5	13,0	17,5
	7	4,5	9,5	19,0	25,0
	28	7,5	17,5	31,5	42,5
	56	11,5	23,5	39,5	51,5
	90	12,5	27,5	50,0	64,5
	120				

Table 7.1d:
Compressive strength with RPC Jupiter cement

% Fly ash	Age at test (d)	Compressive Strength (MPa) for mixes @			
		c/w=1.0	c/w=1.5	c/w=2.0	c/w=2.5
0	1	–	–	–	–
	3	6.5	16.0	27.5	38.5
	7	9.0	21.0	34.5	44.5
	28	14.5	30.5	45.5	56.5
	56	16.5	35.0	50.0	62.5
	90	18.0	36.5	54.0	67.0
	120	18.5	38.0	55.5	71.0
5	1	–	–	–	–
	3	8.0	16.5	27.0	36.5
	7	8.5	21.5	34.0	44.5
	28	14.0	30.5	44.5	57.5
	56	17.0	36.5	52.0	64.5
	90	19.0	39.5	55.5	69.5
	120	19.5	40.5	56.5	69.0
10	1	–	–	–	–
	3	6.0	14.5	24.5	34.0
	7	6.0	19.0	31.5	43.0
	28	13.5	29.0	44.0	56.5
	56	17.0	36.5	52.5	65.0
	90	19.0	38.5	57.5	68.5
	120	20.0	41.0	59.5	73.0
15	1	–	–	–	–
	3	4.0	12.0	22.0	32.5
	7	6.5	17.0	30.0	41.5
	28	11.5	26.0	41.0	54.5
	56	15.0	33.5	51.0	67.0
	90	17.0	37.5	56.5	70.5
	120	18.0	40.0	60.0	75.5
30	1	–	–	–	–
	3	3.0	8.5	18.0	24.5
	7	4.0	12.5	23.0	34.0
	28	9.0	20.5	34.5	48.0
	56	13.5	28.5	44.0	61.5
	90	16.5	35.0	54.0	70.0
	120	17.5	38.5	58.0	72.5
50	1	–	–	–	–
	3	2.0	3.0	9.0	15.0
	7	2.5	6.5	14.0	21.5
	28	5.5	13.0	24.0	36.0
	56	7.0	17.0	31.0	45.5
	90	8.5	19.0	36.5	52.5
	120	11.0	24.5	44.0	59.5

Table 7.1e:
Compressive strength results with PPC blended cements

% Fly ash	Age at test (d)	Compressive strength (MPa)			
		c/w=1,0	c/w=1,5	c/w=2,0	c/w=2,5
5	1	–	–	–	–
	3	6,5	16,0	28,0	37,5
	7	10,0	21,0	36,0	45,5
	28	14,5	30,0	46,5	58,0
	56	17,5	34,5	52,0	66,0
	90	20,0	38,5	57,5	71,0
	120	20,0	41,0	62,0	77,5
15	1	–	–	–	–
	3	6,5	14,0	23,0	32,5
	7	8,5	18,5	31,5	42,5
	28	13,0	29,0	43,5	56,5
	56	15,5	35,0	51,0	64,5
	90	17,5	38,0	57,0	69,5
	120	19,0	43,5	66,0	81,5

Table 7.1f:
Compressive strength with PPC interground cements

% Fly ash	Age at test (d)	Compressive strength (MPa)			
		c/w=1,0	c/w=1,5	c/w=2,0	c/w=2,5
5	1	–	–	–	–
	3	8,0	17,5	25,5	39,0
	7	10,0	22,5	33,0	46,0
	28	14,5	31,5	45,5	58,5
	56	17,0	36,0	50,0	63,0
	90	18,5	39,5	54,0	69,0
	120	20,5	42,5	60,0	77,5
15	1	–	–	–	–
	3	7,0	14,5	23,0	33,0
	7	8,5	19,5	32,0	43,5
	28	12,5	29,0	44,0	57,5
	56	16,0	37,0	53,5	67,0
	90	19,0	42,0	60,5	74,0
	120	20,0	44,5	65,5	82,5

Table 7.1g

Cementitious material contents of mixes designed to a 28 day target strength of 38 MPa calculated using figure 7.1g and a water reduction of 0,55 x fly ash content.

Fly ash content (%)	Water content (l/m^3)	OPC content (kg/m^3)	Fly ash content (kg/m^3)	Total cement+ fly ash (kg/m^3)
0	200,0	326,0	0,0	326,0
10	194,5	306,3	34,0	340,4
30	183,5	256,9	110,1	367,0
50	172,5	211,3	211,3	422,6

Table 7.1h

Cementitious material contents of mixes designed to a 90 day target strength of 38 MPa calculated using figure 7.1g and a water reduction of 0,55 x fly ash content.

Fly ash content (%)	Water content (l/m^3)	OPC content (kg/m^3)	Fly ash content (kg/m^3)	Total cement+ fly ash (kg/m^3)
0	200,0	280,0	0,0	280,0
10	194,5	245,1	27,2	272,3
30	183,5	193,3	82,9	276,2
50	172,5	159,6	159,6	319,1

Table 7.2a
Concrete mix proportions for evaluation of Lethabo fly ash (kg/m^3)

MIX	A	B	C	D	E	F	G
CEMENT TYPE	OPC A	PC15FA A	PC22.5FA A	PC30FA A	PC15FA A	PC22.5FA A	PC30FA A
DESIGN		EQ 28	EQ 28	EQ 28	DR	DR	DR
C:W RATIO	1,75	1,87	1,99	2,1	1,75	1,75	1,75
WATER CONTENT	200	195	192	190	19	192	190
CEMENT CONTENT	350	365	382	399	341	336	333
STONE CONTENT	1121	1121	1121	1121	1121	1121	1121
SAND CONTENT	707	692	677	659	713	718	719
SLUMP	70	90	70	75	55	85	100

MIX	H	I	J	K	L	M	N
CEMENT TYPE	OPC B	PC15FA B	PC22.5FA B	PC30FA B	PC15FA B	PC22.5FA B	PC30FA B
DESIGN		EQ 28	EQ 28	EQ 28	DR	DR	DR
C:W RATIO	1,67	1,82	1,93	2,06	1,67	1,67	1,67
WATER CONTENT	200	192	188	185	192	188	185
CEMENT CONTENT	334	349	363	381	321	314	309
STONE CONTENT	1121	1121	1121	1121	1121	1121	1121
SAND CONTENT	720	713	705	698	738	743	754
SLUMP	95	45	70	45	115	80	45

MIX	R	S	T	U	V	W	X
CEMENT TYPE	OPC C	PC15FA C	PC22.5FA C	PC30FA C	PC15FA C	PC22.5FA C	PC30FA C
DESIGN		EQ 28	EQ 28	EQ 28	DR	DR	DR
C:W RATIO	1,7	1,88	2,04	2,21	1,7	1,7	1,7
WATER CONTENT	205	200	195	190	200	195	190
CEMENT CONTENT	349	376	398	420	340	332	323
STONE CONTENT	1121	1121	1121	1121	1121	1121	1121
SAND CONTENT	695	670	655	640	701	715	728
SLUMP	70	95	70	80	85	80	70

Note: EQ28 denotes mixes designed on the basis of equal 28 day compressive strength with same slump as opc mix.
DR denotes mixes with the opc content replaced with blended cement, and made to same slump as opc mix.

Table 7.2b
12 hour compressive strength (MPa)

CEMENT TYPE	C:W RATIO		CURED			UNCURED		
			OVEN	STANDARD	COLD	OVEN	STANDARD	COLD
OPC A	1,75		4,6	3,1	0,4	5,1	2,5	0,3
PC15FA A	1,87	EQ 28	4,1	1,6	0,4	4	1,2	0,3
PC22.5FA A	1,98	EQ 28	5,6	1,6	0,5	5,4	1,9	0,4
PC22.5FA A	1,99	EQ 28	5,2	3,1	0,4	5,4	2,9	0,3
PC30FA A	2,1	EQ 28	4,1	1,6	0,4	5,5	1,4	0,3
PC15FA A	1,75	DR	4,8	2,6	0,3	5,2	2,5	0,3
PC22.5FA A	1,75	DR	3,4	2,9	0,7	4,4	2,2	0,5
PC30FA A	1,75	DR	2,2	1,5	0,3	2,4	1,7	0,3
OPC B	1,67		2,7	1,9	0,3	3	1,5	0,3
PC15FA B	1,82	EQ 28	3,6	2,1	0,3	6,4	2,2	0,3
PC22.5FA B	1,93	EQ 28	2,6	1,7	0,3	2,8	1,8	0,3
PC22.5FA B	1,93	EQ 28	3,2	2,1	0,2	3	1,5	0,2
PC30FA B	2,06	EQ 28	2,7	1,8	0,3	2,9	1,6	0,4
PC15FA B	1,67	DR	2,2	1	0,2	2,4	1	0,2
PC22.5FA B	1,67	DR	2,8	1,5	0,3	3,6	1,6	0,2
PC30FA B	1,67	DR	2	1,3	0,3	2	1,3	0,3
OPC C	1,7		3,9	2	0,7	3,6	1,8	0,4
PC15FA C	1,86	EQ 28	2,9	2,6	0,4	3,3	1,9	0,3
PC22.5FA C	2,04	EQ 28	3,4	2,2	0,3	3,7	2,3	0,3
PC30FA C	2,21	EQ 28	3,1	1,7	0,4	2,9	1,8	0,4
PC15FA C	1,7	DR	2,2	1,2	0,3	2,6	1,4	0,2
PC22.5FA C	1,7	DR	2,2	1,9	0,4	2,7	1,8	0,3
PC30F C	1,7	DR	1,9	1,6	0,3	2	1,4	0,3

Note: Oven conditions were c. 30 °C and 38 % RH
Standard conditions were c. 23 °C and 45 % RH
Cold conditions were c. 7 °C and 95 % RH
All cured specimens were sealed in plastic bags.
All uncured specimens were unsealed.

Table 7.2n
24 hour compressive strength of Lethabo fly ash mixes (MPa)

CEMENT TYPE	C/W RATIO		CURED			UNCURED		
			OVEN	STANDARD	COLD	OVEN	STANDARD	COLD
OPC A	1.75		13,5	9,1	1,7	14	8,3	1,7
PC15FA A	1,67	EQ 28	13,3	7,7	1,7	12,6	6	1,4
PC22.5FA A	1,99	EQ 28	11,5	7,2	2,2	11,3	6,5	1,7
PC22.5FA A	1,99	EQ 28	10,9	6,4	1,7	10,8	6,2	1,6
PC30FA A	2,1	EQ 28	10,8	6,9	1,6	11,5	6,9	1,8
PC15FA A	1,75	DR	10,9	6,3	1,3	11	6,1	1,6
PC22.5FA A	1,75	DR	7,5	5	1,6	8,6	5,9	1,2
PC30FA A	1,75	DR	6,3	5,2	1,3	7,2	5,5	1
OPC B	1,67		7,9	5,8	1,5	8,2	5,9	1,5
PC15FA B	1,82	EQ 28	9,6	5,9	1,4	11,5	6,1	1,2
PC22.5FA B	1,93	EQ 28	7,4	5,9	1,2	8,6	6,3	1,2
PC22.5FA B	1,93	EQ 28	7,5	5,7	1,2	8,9	5,5	1,1
PC30FA B	2,08	EQ 28	7,3	5,5	1,5	7,3	6,3	1,3
PC15FA B	1,67	DR	6,2	4,3	1	6,3	5,2	0,8
PC22.5FA B	1,67	DR	6,5	4,4	1	5,9	5,1	0,9
PC22.5FA B	1,67	DR	6	4,1	0,9	5,7	4,1	1,3
PC30FA B	1,67	DR	4,6	4,2	1,3	5	4,2	1
OPC C	1,7		8,1	4,9	2,7	7,2	4,8	2,2
PC15FA C	1,88	EQ 28	6,5	5	1,8	6,4	5,3	1,3
PC22.5FA C	2,04	EQ 28	6	5	1,7	7,2	5,3	1,2
PC30FA C	2,21	EQ 28	6,1	4,6	1,5	5,5	5	1,2
PC15FA C	1,7	DR	5,2	3,5	1,2	5,8	3,8	1,1
PC22.5FA C	1,7	DR	5,2	4	1,4	5,3	3,9	1
PC30FA C	1,7	DR	4,3	3,3	1,2	4,4	3	1

Note: Oven conditions were c. 30 °C and 35 % RH
Standard conditions were c. 23 °C and 48 % RH
Cold conditions were c. 7 °C and 95 % RH
All cured specimens were sealed in plastic bags.
All uncured specimens were unsealed.

Table 7.2d
7 day compressive strength of Lethabo fly ash mixes (MPa)

CEMENT TYPE	C:W RATIO		CURED			UNCURED		
			OVEN	STANDARD	COLD	OVEN	STANDARD	COLD
OPC A	1,75		28,2	26,4	19,3	24,9	22,7	17,2
PC15FA A	1,67	EQ 28	29,7	28,2	18,4	23,5	21,6	16,6
PC22.5FA A	1,99	EQ 28	30	23,7	20	24,2	20,8	17
PC22.5FA A	1,99	EQ 28	30	25,2	17	23	23,5	18,6
PC30FA A	2,1	EQ 28	30,5	24,7	18,4	23,5	19,3	16,2
PC15FA A	1,75	DR	29	23,7	15,6	22,6	20,7	15,1
PC22.5FA A	1,75	DR	23,2	20,3	13,9	18,6	18	14,6
PC30FA A	1,75	DR	20,8	19,3	12,4	16,2	18	12,6
OPC B	1,67		28	23,6	15,4	18,4	17	20
PC15FA B	1,82	EQ 28	30,2	25,3	18	20,3	20,3	17,2
PC22.5FA B	1,93	EQ 28	28,6	24	16,9	18,6	19,3	17,2
PC22.5FA B	1,93	EQ 28	29,2	22,8	15,8	19	20,5	16
PC30FA B	2,06	EQ 28	28,8	23	17,4	18,5	18,6	17
PC15FA B	.67	DR	23,7	19,4	15,1	16,2	17,6	14,1
PC22.5FA B	1,67	DR	24,9	18,5	14,3	16,5	16,2	15,1
PC22.5FA B	1,67	DR	24,6	17,4	13,5	15,6	15,6	15
PC30FA B	1,67	DR	21,4	18	12,3	12,5	14,1	12,1
OPC C	1,7		26,9	21,8	16,9	16,5	15,2	15,8
PC15FA C	1,88	EQ 28	25,8	20,7	14	15,1	16	13,3
PC15FA C	1,88	EQ 28	24,5	22,1	13,5	17	19,7	15,3
PC22.5FA C	2,04	EQ 28	27,9	21,8	13,8	17,8	17	12,7
PC30FA C	2,21	EQ 28	25,9	21,1	12,9	18	15,6	12,2
PC15FA C	1,7	DR	21,4	17,4	11,1	14	14,1	11,1
PC22.5FA C	1,7	DR	20,2	16,4	10,3	13,2	12,1	9,9
PC30FA C	1,7	DR	17,8	13,8	8,9	10,8	11,8	8,4

Note: Oven conditions were c. 30 °C and 36 % RH
Standard conditions were c. 23 °C and 46 % RH
Cold conditions were c. 7 °C and 95 % RH
All cured specimens were sealed in plastic bags.
All uncured specimens were unsealed.

Table 7.2e
28 day compressive strength of Lethabo fly ash mixes (MPa)

CEMENT TYPE	C:W RATIO		CURED			UNCURED		
			OVEN	STANDARD	COLD	OVEN	STANDARD	COLD
OPC A	1,75		38,5	37,5	29,5	25,2	26	28,2
PC15FA A	1,87	EQ 28	42,4	39,3	30,8	24,8	26,7	28,3
PC22.5FA A	1,99	EQ 28	42,3	37,6	30,8	28	24,9	33,5
PC22.5FA A	1,99	EQ 28	45,4	37,5	30,3	26,8	32,8	28,5
PC30FA A	2,1	EQ 28	45 8	36,8	31,1	24,5	25,5	26,5
PC15FA A	1,75	DR	37,6	36,8	26,1	23,8	24,3	25,1
PC22.5FA A	1,75	DR	38,8	33	24,2	20,3	23,1	22,9
PC30FA A	1,75	DR	32,4	32,2	20,8	17,3	19,8	20,2
OPC B	1,67		39	36,9	31,1	18,3	21,4	29,9
PC15FA B	1,82	EQ 28	44,1	39,5	28,9	21,7	23,7	28,8
PC22.5FA B	1,93	EQ 28	46	41,1	30,7	19,1	24,4	27,4
PC22.5FA B	1,93	EQ 28	45,9	36,7	26,8	20	28,2	24,1
PC30FA B	2,06	EQ 28	45,5	39,2	30	20	23,6	26,7
PC15FA B	1,67	DR	33,3	32,3	24	15,9	20,2	21,7
PC22.5FA B	1,67	DR	31,2	30,1	23,1	15,9	19	22,9
PC22.5FA B	1,67	DR	36,4	29,2	21,3	17,7	20,5	22,6
PC30FA B	1,67	DR	33	29,6	21,9	13,3	16,7	20,3
OPC C	1,7		33,3	34,1	26,5	17,1	17,8	25,8
PC15FA C	1,88	EQ 28	40	34,9	28,1	16,7	18,7	22,3
PC15FA C	1,88	EQ 28	40,2	36,9	24,4	18,7	27	22,8
PC22.5FA C	2,04	EQ 28	40,4	37,8	25,8	18,8	18,8	22,4
PC30FA C	2,21	EQ 28	28,2	37,3	24,9	17,4	20,1	23,3
PC15FA C	1,7	DR	30	29,7	19,4	14,6	18,1	18,9
PC22.5FA C	1,7	DR	33,1	28,9	20,6	14,6	15,7	19,4
PC30FA C	1,7	DR	32,6	25	15,8	11,8	18,3	15,2

Note:
Oven conditions were c. 30 °C and 38 % RH
Standard conditions were c. 22 °C and 46 % RH
Cold conditions were c. 7 °C and 95 % RH
All cured specimens were sealed in plastic bags.
All uncured specimens were unsealed.

Table 7.2f
56 day compressive strength of Lethabo fly ash mixes (MPa)

CEMENT TYPE	C:W RATIO		CURED			UNCURED		
			OVEN	STANDARD	COLD	OVEN	STANDARD	COLD
OPC A	1,75		38,6	45,4	37,5	25,7	27,5	28,9
PC15FA A	1,67	EQ 28	47,3	47,8	35,3	26,4	27,8	30
PC22.5FA A	1,99	EQ 28	48,7	44,6	37,5	27,2	28,2	32,1
PC30FA A	2,1	EQ 28	49,3	47,9	35,7	25,7	26,6	28,3
PC15FA A	1,75	DR	41,4	40,6	29,8	25,9	28	27,3
PC22.5FA A	1,75	DR	43,5	38,8	29,1	19,8	22,5	25,1
PC30FA A	1,75	DR	32,1	38,5	24,1	19	20,6	21,7
OPC B	1,67		41,4	44,3	36,4	20,1	21,2	32,1
PC15FA B	1,82	EQ 28	47,1	47,2	34,8	23,7	24,9	30,5
PC22.5FA B	1,93	EQ 28	48,8	47,2	35,4	21	24,1	29,9
PC30FA B	2,06	EQ28	40,1	47,5	33,6	21,4	21,9	30,9
PC15FA B	1,67	DR	34,4	40	29,9	15,9	20	26,2
PC22.5FA B	1,67	DR	30,1	36,2	29,4	18,7	19,7	28,1
PC30FA B	1,67	DR	32,5	36,5	24	16	17,2	23,2
OPC C	1,7							
PC15FA C	1,88	EQ 28	36,9	42,6	31,7	17,1	19,2	26,2
PC22.5FA C	2,04	EQ 28	41	47,6	31	19,9	20,7	19,9
PC30FA C	2,21	EQ 28	27	46,8	30,6	17,2	20,5	26,8
PC15FA C	1,7	DR	34,2	40	24,7	14,7	17,1	21,6
PC22.5FA C	1,7	DR	25,2	37,4	24,7	14,1	16,3	22,1
PC30FA C	1,7	DR	34	35,6	[illegible]	12,9	[illegible]	18,4

Note: Oven conditions were c. 30 °C and 38 % RH
Standard conditions were c. 23 °C and 45 % RH
Cold conditions were c. 7 °C and 95 % RH
All cured specimens were sealed in plastic bags.
All uncured specimens were unsealed.

Table 7.3a:
Mix proportions for concrete used in large blocks for evaluation of curing effects with extenders (quantities in kg/m^3)

Material	OPC mix	PC15FA mix	PC30FA mix	PC50SL mix
Cement (PPC Jup)	350	296	250	175
Fly ash (Matla)	–	54	111	–
Slag (VdBijl)	–	–	–	175
Granite Crusher sand	422	422	413	419
Kendal sand	422	422	413	419
19 mm Granite Stone	1050	1063	1072	1050
Water	210	201	194	208
C/W ratio	1,67	1,77	1,88	1,77
Slump (mm)	150	160	140	150

Table 7.3b:
Compressive strength test results for cubes and cores from large blocks in Winter 1987.

Cement blend used	7 day cube strength (MPa)	28 day cube strength (MPa)	Outside 28 day core strength (MPa)	Outside ratio to 28d cube strength (%)	Inside 28 day core strength (MPa)	Inside ratio to 28d cube strength (%)
OPC	22,0	29,0	22,4	77,2	21,4	73,8
PC15FA	20,5	32,0	28,5	89,1	25,0	78,1
PC30FA	18,0	30,5	25,0	82,0	22,3	73,1
PC50SL	18,0	34,5	27,1	78,6	23,5	68,1

Table 7.3c:
Characteristics of fresh concrete
(mixes for winter 1987)

Cement blend used	Approx duration of Bleeding (h)	Approx time to final finish (h)	Slump of concrete (mm)
OPC	3,75	5,75	150
PC15FA	4,25	8,00	160
PC30FA	4,50	9,50	140
PC50SL	3,75	7,50	150

Table 7.3d:
Compressive strength test results for cubes and cores from large blocks cast in Summer 1987/88

Cement blend used	28 day cube strength (MPa)	Outside 28 day core strength (MPa)	Outside ratio to 28d cube strength (%)	Inside 28 day core strength (MPa)	Inside ratio to 28d cube strength (%)
OPC	31,0	31,3	101,0	28,3	91,3
PC15FA	31,5	32,0	101,6	31,2	99,0
PC30FA	26,5	30,0	113,2	26,8	101,1
PC50SL	31,5	33,2	105,4	31,8	101,0

Table 7.3e:
Compressive strength results for cubes and cores from small blocks cast in Summer 1987/88.

Cement blend used	28 day cube strength (MPa)	North 28 day core strength (MPa)	North ratio to cube strength (%)	South 28 day core strength (MPa)	South ratio to cube strength (%)
OPC	31.0	32.0	103.2	31.7	102.3
PC15FA	31.5	30.2	95.9	30.5	96.8
PC30FA	26.5	28.8	108.7	27.7	104.5
PC50SL	31.5	29.2	92.7	29.5	93.7

Table 7.3f:
Characteristics of fresh concrete
(Summer 1987/88)

Cement blend used	Approx duration of Bleeding (h)	Approx time to final finish (h)	Slump of concrete (mm)
OPC	3,75	5,75	150
PC15FA	4,25	8,00	160
PC30FA	4,50	9,50	140
PC50SL	3,75	7,50	150

Table 7.3g:
Compressive strength test results for cubes and cores from large blocks cast in winter 1988.

Cement blend used	28 day cube strength (MPa)	Outside 28 day core strength (MPa)	Outside ratio to 28d cube strength (%)	Inside 28 day core strength (MPa)	Inside ratio to 28d cube strength (MPa)
OPC	35,5	27,7	78,0	27,8	78,4
PC15FA	34,5	28,8	83,5	30,3	87,8
PC30FA	33,5	29,8	89,0	30,4	90,9
PC50SL	34,3	26,8	78,1	26,5	77,1

Table 7.3h
Compressive strength results for cubes and cores from small blocks cast in Winter 1988.

Cement blend used	28 day cube strength (MPa)	North 28 day core strength (MPa)	North ratio to cube strength (%)	South 28 day core strength (MPa)	South ratio to cube strength (%)
OPC	35,5	33,3	93,8	34,7	97,7
PC15FA	34,5	29,8	86,4	29,8	86,4
PC30FA	33,5	26,7	79,7	28,7	85,7
PC50SL	34,5	27,3	79,1	26,7	77,4

Table 7.3i
Characteristics of fresh concrete (Winter 1988)

Cement blend used	Approx duration of Bleeding (h)	Approx time to final finish (h)	Slump of concrete (mm)
OPC	3,75	5,75	150
PC15FA	4,25	8,00	160
PC30FA	4,50	9,50	140
PC50SL	3,75	7,50	150

Table 7.4
Ambient temperature and humidity ranges for curing period of large and small blocks (Summer 1987–88, Winter 1988)

Season	Minimum temperature (°C)	Maximum temperature (°C)	Minimum humidity (%)	Maximum humidity (%)
Winter	3	32	10	78
Summer	12	33	20	80

Table 7.5a
Compressive strength of OPC, RHC, Slag and fly ash mixes under hot conditions (c. 30 °C) of mixes detailed in table 5.12c.

	Compressive strength (MPa) for				
Age (days)	Mix No. 9 OPC	Mix No. 10 PC50SL	Mix No. 11 RHC	Mix No. 13 PC15FA	Mix No. 14 PC30FA
0,33	2,5	0,9	3,8	0,6	0,4
0,5	4,6	2,0	8,9	3,4	1,7
1	10,9	5,2	15,7	10,1	6,6
3	20,3	11,5	26,0	17,4	14,2
7	26,3	18,7	35,9	26,2	19,7
28	36,3	31,5	44,9	37,3	31,2

Table 7.5b
Compressive strength of OPC, RHC, Slag and fly ash mixes under standard conditions (c. 23 °C) of mixes detailed in table 5.12c.

Compressive strength (MPa) for					
Age (days)	Mix No. 9 OPC	Mix No. 10 PC50SL	Mix No. 11 RHC	Mix No. 13 PC15FA	Mix No. 14 PC30FA
0,33	1,5	0,5	2,6	0,3	0,2
0,5	3,8	1,1	6,2	1,6	1,2
1	8,9	3,6	11,8	7,6	5,5
3	18,2	8,4	22,2	17,1	13,0
7	23,7	14,9	33,6	23,6	18,1
28	31,5	31,9	46,9	35,9	29,2

Table 7.5c
Compressive strength of OPC, RHC, Slag and fly ash mixes under cold conditions (c. 7 °C) for mixes detailed in table 5.12c

Compressive strength (MPa) for					
Age (days)	Mix No. 9 OPC	Mix No. 10 PC50SL	Mix No. 10 RHC	Mix No. 13 PC15FA	Mix No. 14 PC30FA
0,33	0,5	0,2	0,5	0,0	0,0
0,5	1,0	0,4	0,9	0,2	0,0
1	2,9	1,0	3,5	0,8	0,6
3	11,4	4,6	7,4	10,3	6,7
7	19,3	9,4	27,5	18,1	12,9
28	30,6	18,1	41,7	31,2	22,4

Table 7.6
Effect of temperature matched curing on compressive strength of OPC and OPC/fly ash blend mixes detailed in table 6.2

Age (days)	Standard curing			Temperature matched curing		
	OPC Mix 1	PC30FA Mix 2	Ratio 2/1	OPC Mix 1	PC30FA Mix 2	Ratio 2/1
1	9,0	4,5	50,0	13,5	6,0	44,4
3	15,5	9,5	61,3	22,0	13,0	59,1
7	23,5	12,0	51,1	31,0	26,0	83,9
28	32,5	20,0	61,5			
Note: The data for the PC30FA mixes were derived from 2 tests on mixes 2 and 3 in table 6.2						

Table 7.7a
Flexural strength at 28 days of concrete with and without fly ash

% fly ash	Cement source	Cement/water ratio			
		C/W 1,0	C/W 1,5	C/W 2,0	C/W 2,5
0	PPC Jup	2,50	4,50	5,60	7,30
	BC Licht	2,80	5,20	5,60	7,35
	A–A Rood	3,10	5,40	5,60	6,90
5	PPC Jup	2,65	3,65	4,85	6,65
	BC Licht	3,50	4,90	6,10	7,05
	A–A Rood	3,10	4,80	5,65	6,70
	PPC Blend	2,80	4,75	5,85	6,90
	PPC Grind	2,85	4,55	5,65	6,45
10	PPC Jup	2,85	4,55	5,80	6,15
	BC Licht	2,80	4,60	5,85	6,90
	A–A Rood	3,10	4,80	5,85	5,90
15	PPC Jup	2,35	3,60	5,00	6,40
	BC Licht	2,70	4,65	6,35	6,80
	A–A Rood	2,45	4,20	5,35	6,25
	PPC Blend	2,65	4,40	5,15	5,65
	PPC Grind	2,50	4,40	4,90	6,40
30	PPC Jup	2,10	3,70	4,50	5,60
	BC Licht	2,50	4,20	5,40	6,40
	A–A Rood	2,25	3,80	4,80	6,00
50	PPC Jup	1,50	2,95	3,55	4,35
	BC Licht	1,65	3,40	4,50	5,25
	A–A Rood	1,70	3,15	4,30	4,65

Table 7.7b
Ratio (%) of 28 day flexural to compressive strength

% fly ash	Cement source	Cement/water ratio			
		C/W 1,0	C/W 1,5	C/W 2,0	C/W 2,5
0	PPC Jup	18,2	15,0	12,7	13,2
	BC Licht	17,5	14,6	10,1	11,0
	A–A Rood	20,0	15,4	10,3	10,5
5	PPC Jup	20,0	12,4	11,1	11,9
	BC Licht	23,3	14,6	11,6	10,7
	A–A Rood	21,4	14,1	10,9	10,7
	PPC Blend	19,3	15,8	12,6	11,9
	PPC Grind	19,7	14,4	12,4	11,0
10	PPC Jup	21,9	16,3	13,8	11,4
	BC Licht	18,7	13,9	11,5	10,5
	A–A Rood	23,0	15,2	12,2	9,6
15	PPC Jup	20,4	14,0	12,5	12,0
	BC Licht	19,3	14,3	13,4	10,7
	A–A Rood	19,6	13,5	11,3	10,0
	PPC Blend	20,4	15,2	11,8	10,0
	PPC Grind	20,0	15,2	11,1	10,1
30	PPC Jup	22,7	16,8	12,4	11,7
	BC Licht	23,8	16,5	12,4	11,1
	A–A Rood	30,0	15,8	13,3	11,0
50	PPC Jup	23,1	23,1	13,7	11,6
	BC Licht	22,0	19,4	14,3	12,4
	A–A Rood	37,8	24,2	17,6	12,4

CHAPTER 8

8. ELASTIC AND TIME DEPENDENT MOVEMENT PROPERTIES

In structural applications concrete is required to have an acceptably predictable degree of elastic behaviour and dimensional stability, acceptably close to the design assumptions that have been made. This will ensure that the concrete structure will perform as expected by the designer and that it will not show unacceptable levels of deflection, cracking, creep or shrinkage.

The design assumptions are generally based on the observed behaviour of concrete, most of which has been made using ordinary portland cement as the binder. If the use of fly ash is likely to influence the elastic or movement properties and dimensional stability of the concrete then the effect of this should be understood, and taken into consideration by the designer.

The following paragraphs give a brief, essentially introductory indication of the influence of fly ash on these properties. All the work covered in the following paragraphs refers to tests done on Matla fly ash only; no work has been done on the Lethabo fly ash.

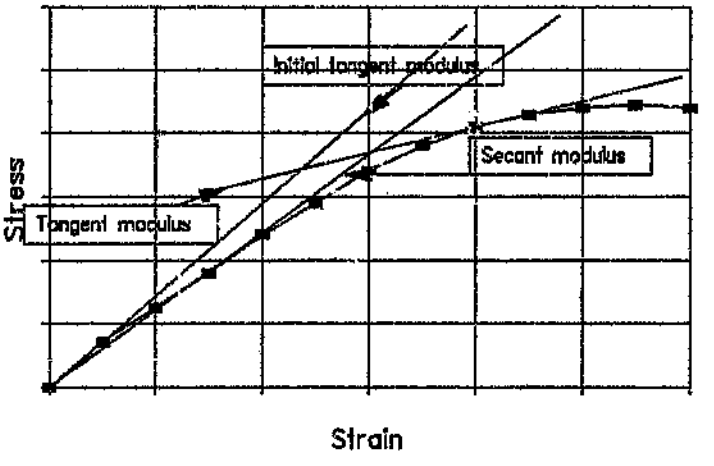
8.1 Elastic modulus

An elastic material is one which will recover completely from a load–induced deformation once the load is removed. Concrete, however, is not an elastic material as the recovery from the load–induced deformation will generally not be complete. Nor is the stress–strain relationship for concrete a linear relationship. As the relationship is not linear it is impossible to talk of a unique value for the elastic modulus (i.e. the ratio of applied compressive stress to longitudinal strain, otherwise known as the Young's modulus) without defining the point on the curve at which it is measured.

Fulton[294] lists three forms of static elastic modulus, namely the secant, the initial tangent and the tangent moduli. The different moduli are shown in figure 8.1. In the research covered here the value provided is the secant modulus, although the initial tangent modulus in this case has the same value since over the range of stress tested at age 28 days the tests generally provided straight line relationships with the tangent and secant moduli coinciding.

Table 8.1 gives the details of the mixes used in making the concrete specimens on which the elastic modulus tests were done. PPC Jupiter OPC was used in all these mixes.

Figure 8.1
Forms of elastic modulus



The elastic modulus tests were done in accordance with PCI method 7.6[1] which is based on the BS 1881 part 121[2] for the method, and on ASTM C469–87a[3] for the apparatus.

Tables 8.2a to 8.2d give the values measured at 28 days for the different cements used in this investigation at the various levels of fly ash replacement adopted. It should be noted that as for the compressive strength results the fly ash has been used as a straight replacement and no adjustment has been made for the difference in 28 day compressive strength.

Figure 8.2a shows the comparative values of elastic modulus against compressive strength for the three cement sources tested. It should be noted that in the case of the PPC Jupiter cement the compressive strength results are an average of 2 sets of

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[1] Portland Cement Institute, **Laboratory Manual**, The static modulus of elasticity of concrete and mortar, Halfway House: PCI, 1986, Chapter 6, 5 pp.

[2] British Standards Institution, **Method for Determination of Static Modulus of Elasticity in Compression**, London, BSI., (1983). (BS 1881 Part 121).

[3] American Society for Testing and Materials, **Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression**, Philadelphia: ASTM., (1987). (C469-87a).

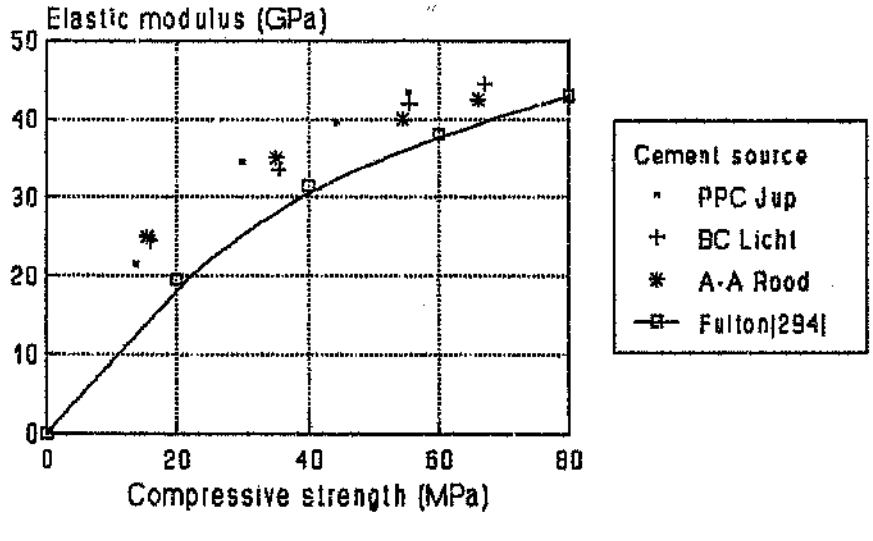
results from tables 7.1a and 7.1d. but there was only one equivalent set of elastic modulus test results for the PPC Jupiter control cement from the PCI silo. Also shown on this graph is the curve for elastic modulus against compressive strength given in Figure 7.17 in Fulton[294].

It is clear that all the results shown here lie above the Fulton curve, i.e. all the mixes made have higher moduli at any chosen level of compressive strength than shown on the Fulton curve for other South African cements and are therefore stiffer.

The type of aggregate and the aggregate content of the mix are significant factors that influence the elastic modulus of the concrete. The dolerite coarse aggregate used in the mixes tested in this work is one of the stiffer aggregate types available in South Africa, and according to Davis and Alexander[295] its use results in concretes with higher than average elastic moduli. It is therefore not surprising that the overall impression for the ordinary portland cement concretes made here is that they are stiffer than is the case for many of the mixes tested and shown in the Fulton curve.

Although there are not many data in Figure 8.2a from which an assessment can be made it appears that there is not much difference between the elastic moduli for the different sources of ordinary portland cement tested in this work.

Figure 8.2a
Elastic modulus vs compressive strength
for all opc's tested



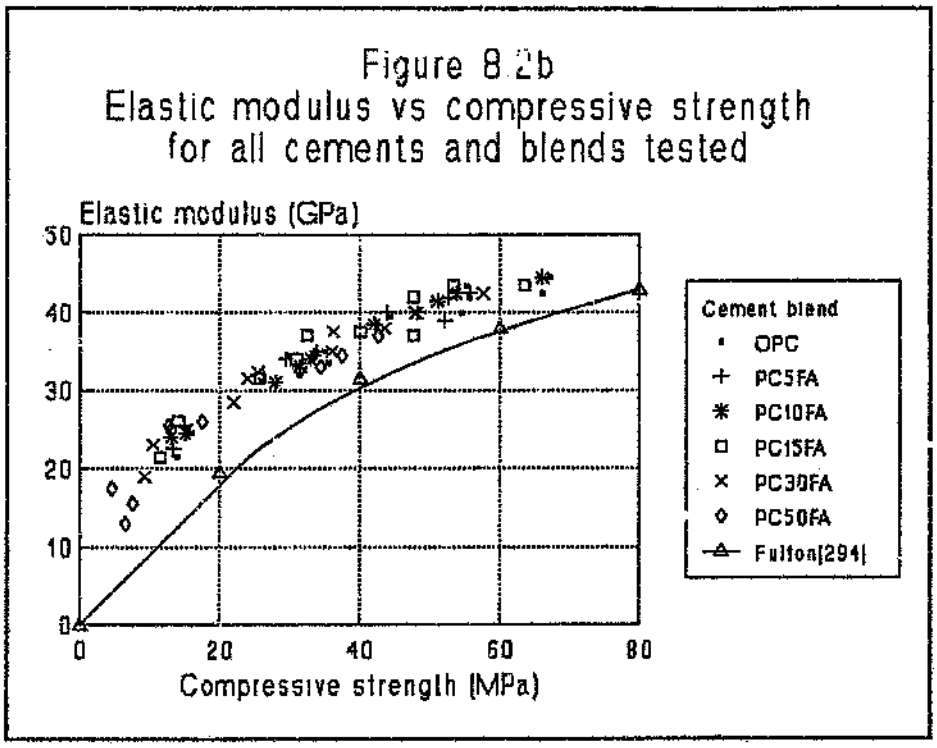


Figure 8.2b shows all the data for ordinary portland cement and the full range of fly ash blends tested. In this case it would seem that there is little difference between the ratio of elastic modulus to compressive strength for an ordinary portland cement mix and that for a blended cement mix, even with fly ash contents up to 50%. These findings therefore confirm the opinion of the majority of authors consulted[44,109,111,116,134,147,149,153,185] i.e. that the use of fly ash does not have a significant impact on the elastic modulus of the concrete.

This trend is also confirmed by Mukheibir[296] for concretes made with classified Lethabo fly ash. The work done by Mukheibir[296] included both static and dynamic methods of elastic modulus determination

Other elastic modulus data from creep tests (to be discussed in paragraph 8.2.3 of this chapter) are given in table 8.2e. These values have been determined from short term elastic deformations that occurred under initial load for the creep tests in different apparatus from that used for the above test results. If these data are plotted on figure 8.2b they fall within the scatter of the other points plotted on the graph, and therefore can be taken as confirmation of the above findings.

It is also apparent from the data shown on figure 8.2b that the magnitude of the influence of fly ash on the elastic modulus of concrete is insignificant relative to the effect of a change in aggregate type or concentration in the mix. This is shown by picturing best fit lines through the various sets of points for the different fly ash contents; there is little apparent difference in slope of the different lines.

No work has been done in this study to evaluate the effect of the use of fly ash on Poisson's ratio. It is expected that the same trend will be found as for the elastic modulus, i.e. the effect of the fly ash will be negligible, especially in comparison with the effect the aggregate type and concentration can have.

8.1.1 Summary of findings on elastic modulus

The use of fly ash seems to have little significant impact on either the elastic modulus, or the relationship between the elastic modulus and the compressive strength of the mix.

8.2 Movement properties

Shrinkage and creep are the movement characteristics of greatest interest and concern to the designer of concrete structures. The influence of fly ash on these properties is covered in the following paragraphs.

8.2.1 Shrinkage

Volumetric change of concrete or mortar will occur if the moisture content changes, with swelling occurring when the moisture content increases (as for example on submersion) and drying shrinkage occurring when the concrete or mortar is allowed to lose moisture to the environment. Although this phenomenon is a volumetric one the linear strain is probably of most concern. Shrinkage is a time-dependent, non-load-induced strain.[297]

Both concrete and mortar will generally contain more water in their plastic states than can be chemically bound by the cement. After hardening there is therefore a tendency for the concrete or mortar to lose water to the atmosphere resulting in drying shrinkage. The magnitude of the shrinkage that occurs is proportional to the water content of the mix. As the incorporation of fly ash allows a reduction of the water content of the mix the expected effect of fly ash on shrinkage would be to reduce the magnitude of shrinkage.

The tests in this study to evaluate this effect were done using a modification of SABS method 836[298]. In this test, normally done to evaluate the shrinkage potential of an aggregate specimen, mortar specimens measuring 50x50x280 mm were made with a single source of cement, i.e. PPC Jupiter, and the Ecca grit sand. The mix proportions used are detailed in table 5.14a. No control specimens were made, nor was use made of a control or standard sand. In contrast to the standard method, mixes were made to the same range of cement/water ratios as for the compressive strength tests. Another deviation from the standard method was that fly ash was used in the mixes. The curing regime used was that required by SABS method, with 24 hours in the mould at 22 to 25 °C, 6 days in water at the same temperature, and then exposure in an oven at 55 °C and 18 % RH for about 14 days.

The full range of fly ash contents was used in making the specimens which were then exposed to the normal curing and drying regime specified by SABS method 836. The

results of these tests are shown in table 8.3 and depicted graphically in figure 8.3a.

Figure 8.3a
Drying shrinkage of mortars with different fly ash contents

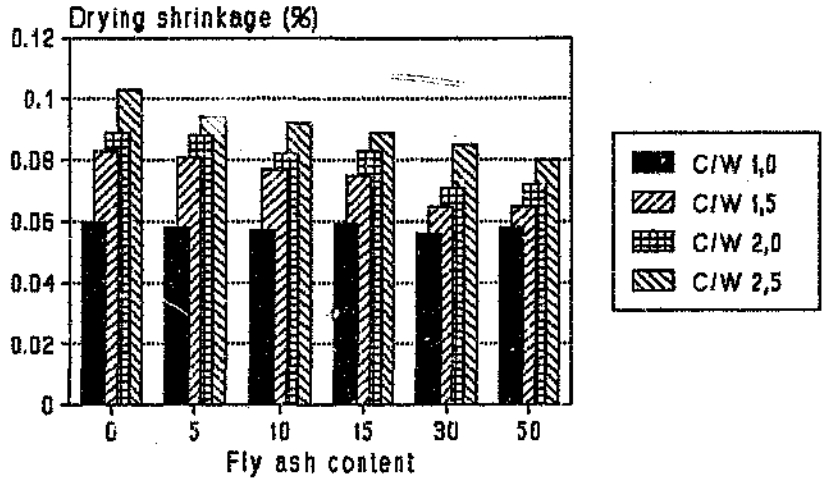


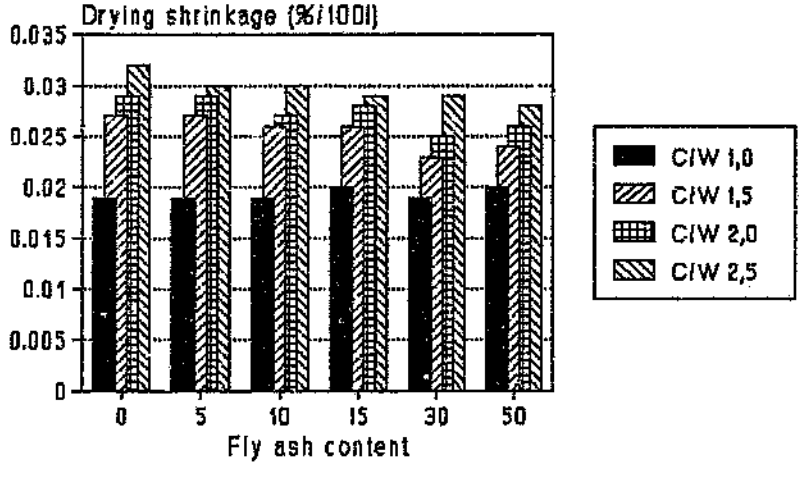
Table 8.4 gives the equivalent information for the interground and interblended cements from Jupiter.

Although there is some scatter of results it is clear from figure 8.3a that the incorporation of fly ash in a mortar has the effect of decreasing the magnitude of the drying shrinkage that occurs under the standard conditions to which it is exposed during the test. It is also evident that the drying shrinkage of these mortars increases as the cementitious/water ratio increases, although this is less marked for the high fly ash mixes.

Table 8.3b gives the data from table 8.3a as a proportion of the mixing water used. These data are shown in figure 8.3b. From figure 8.3b it appears that the reduction in the drying shrinkage that occurs when fly ash is incorporated in a mix is largely due to the reduction in water content permitted by the fly ash as the drying shrinkage results are more uniform than is the case in figure 8.3a.

Nevertheless it does seem that as the fly ash content gets to about 30 % or more there is a further reduction in drying shrinkage which must be attributable to the physical presence of the fly ash particles.

Figure 8.3b
Proportion of drying shrinkage to water content of mortars with/out fly ash



The fly ash mixes used in these tests, having the same cementitious/water ratio, will probably not give equivalent 28 day compressive strengths to the ordinary portland cement mix. The modification required by chapter 5 to give similar 28 day strengths is to increase the cementitious/water ratio. Doing this could result in the negation of any reduction in the magnitude of drying shrinkage that might occur. This calculation has been done using figure 7.1g to determine the required cementitious/water ratios for equivalent strength. The revised drying shrinkage as proportions of the water contents are shown in table 8.3c. This table indicates that while for lean mixes (c/w of opc mix = 1,0) there is a moderate increase in the proportion of shrinkage as the fly ash content increases, this is in contrast to the values for "structural" grades of concrete (ie the other two columns shown). The magnitudes of the shrinkages of all the comparable mortars are however very similar.

A further characteristic to be studied is the creep of concretes made with and without fly ash. In order to properly assess the creep of concretes it is necessary to measure the drying shrinkage that occurs simultaneously with the creep under the same conditions of exposure. The shrinkage results from creep studies done at the University of the Witwatersrand laboratories are given in tables 8.5a and 8.5b. Table 8.5a gives the drying shrinkage results for an initial set of tests with exposed specimens, and table 8.5b shows the results of the second set of tests with sealed specimens. The reason for covering two series of tests was that it was felt that some understanding was needed of the shrinkage potential of OPC and fly ash concretes in both thin sections with a high degree of possible moisture movement, and thick sections where the degree of moisture movement was limited. It should be noted that the shrinkage tests performed in the University facility were long term tests on concrete specimens which were exposed to a more realistic environment of 22 to 25 °C and about 50 % RH.

The results of the concrete shrinkage tests are depicted on figures 8.4a to 8.4f, and 8.6a to 8.6d in the section on creep later in this chapter (shown as the difference between the elastic+shrinkage and the elastic curves).

In Table 8.5a it can be seen that the fly ash seems to result in a small increase in the magnitude of the drying shrinkage of these concretes; it should be noted that even here where suitable adjustments have been made the compressive strengths of the fly ash mixes are not identical to those of the opc control. The fly ash mixes have slightly higher compressive strengths. Should the mixes be adjusted to have equal strength at 28 days then the drying shrinkage results could be expected to be even closer to those of the opc mixes.

A further point to note is that there is a considerable difference between the drying shrinkage results for the two opc mixes with the Blue Circle mix having about 15% higher shrinkage than that for the PPC Jupiter cement. The difference between the two opc's drying shrinkage far exceeds the effect that the fly ash has on the drying shrinkage.

These tests were done on 150 mm diameter cylinder specimens. The surface area to volume ratio of such a specimen (i.e. 33.33) is rather high and is roughly equivalent in its degree of exposure to a slab of concrete only 70 mm thick. This degree of exposure is unlikely to be reflected in actual section thicknesses in site concrete.

Table 8.5b shows how sealing the specimens from the environment affects the drying shrinkage. Sealing the specimens is done in an attempt to simulate the shielding effect of the outer layers of concrete on the moisture movement and drying shrinkage of the concrete and thus overcome the specimen geometry problem mentioned in the previous paragraph.

The magnitude of the drying shrinkage is dramatically reduced for sealed specimens. Obviously not all concrete on site can be regarded as sealed and it is likely that the actual magnitude of drying shrinkage of site concrete made with these materials and exposed to similar drying conditions would lie somewhere between the exposed and sealed values given in table 8.5b.

In table 8.5b it can be seen that under both curing conditions the fly ash mixes have slightly lower values for drying shrinkage than the opc mixes, but the compressive strengths are also lower.

8.2.2 Summary of findings on drying shrinkage

The results discussed above therefore indicate that for similar degrees of exposure the drying shrinkage of Matla fly ash concretes will be very similar to that for mixes which have similar compressive strength when made with ordinary portland cement. This confirms the reported findings of most of the references consulted.[33,44,68,110,134,147,164,165,187]

Mukheibir[296] found that the incorporation of Lethabo fly ash in concrete mixes had little impact on the drying shrinkage of the concrete.

8.2.3 Creep

Fulton[190] defines creep as "the time-dependent increase in strain of a solid body under a constant or controlled stress. Creep in concrete occurs at all stress levels and the creep strain can be several times larger than the initial strain on loading." Creep can be regarded as a desirable property as it lends a degree of ductility to what would otherwise be a rather brittle material. There are however negative aspects to creep including deflection and buckling of elements and loss of prestress.

In this study work has been done to evaluate the effect of fly ash on the magnitude of the creep that occurs under a given stress/compressive strength ratio of the concrete. This has been done in two ways as follows

- a drying cycle where the temperature is kept in the range 22 to 25 °C and the relative humidity in the range 50 to 70 %. In this case the specimens were cured under water for the first 28 days.

- a dual exposure cycle with some of the specimens exposed to the above environment, and others sealed so that no moisture loss could occur. In these cases the "dry" specimens were cured in air in the laboratory at a relative humidity of about 50% after curing under water for the first two days. The sealed specimens were cured under water as for the first set.

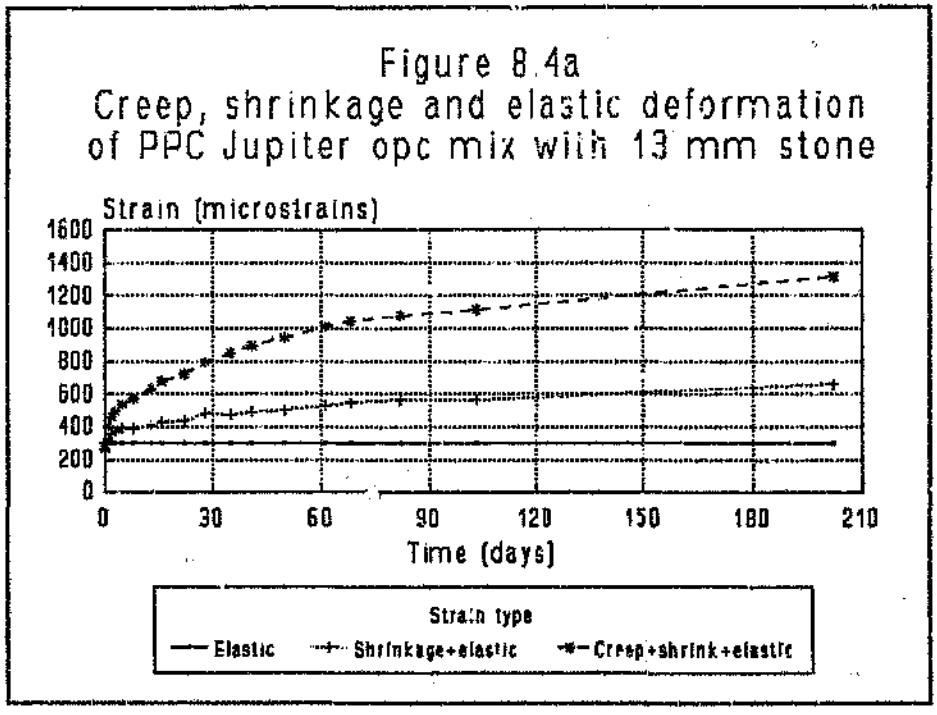
The specimens tested were, as mentioned in section 8.2.1, 150 mm diameter cylinders. The age at loading was 28 days.

The creep is measured by subjecting specimens to a fixed load and monitoring the change in strain with time. Other strains that occur are the elastic and shrinkage strains, and in order to isolate the creep strains the other two strains should be determined separately. The elastic strain is that which occurs immediately the load is imposed and which will be approximately recovered once the load is removed. The shrinkage is determined from companion specimens that are unloaded but exposed to the same environment.

The mixes used to make the specimens used for the first series of creep tests are given in table 8.6. The mixes used for the second series of tests in which pairs of sealed and exposed specimens were loaded were those for mixes 1 and 6 from table 8.6.

The compressive strength at 28 days for these mixes are as shown in table 8.2e. It can be seen that while the mixes were designed for the same target strength of 30 MPa at 28 days, there was some small difference between the opc and fly ash mix compressive strengths. All the specimens were however loaded to the same level of 10,1 MPa +– 0,07 MPa. (Note that the variance of +– 0,07 MPa is the drift in load that occurred during the duration of the test.) Readings were taken at regular intervals during the test period.

The results of Series 1 are given in tables 8.7a to 8.7f and illustrated graphically in figures 8.4a to 8.4f. The specific creep values for all the tests on these sets of specimens are given in table 8.8 and shown graphically in figure 8.5. From figure 8.5 it can be seen that the two opc mixes using 13,2 mm stone (mixes 1 and 3) have quite different specific creep values, with mix 3 having the higher values throughout. The opc mix with 19,0 mm stone has, as would be expected with a lower paste content and lower water content, a lower level of creep than the same mix with 13,2 mm stone.



Mix 4 (opc ex PPC Jupiter with 15% fly ash) has a very similar curve of specific creep

to that of the opc mix with the same aggregate after 60 days but the fly ash mix has slightly higher creep up to 60 days. Mix 5 on the other hand (opc ex. PPC Lichtenburg with 15% fly ash) shows a decrease in specific creep relative to its opc mix. Mix 6 with PPC Jupiter cement and 30% fly ash has the lowest level of specific creep of the mixes tested in this series,up to 200 days. However, the differences between the specific creep levels of the opc and fly ash mixes is small at early ages and only starts showing substantial differences beyond 28 days of exposure.

The creep curves for the series II tests are shown in figures 8.6a to 8.6d with the test results given in tables 8.9a to 8.9d. The data for the specific creep of this series of tests is given in table 8.10 with the corresponding curves shown in figure 8.7. In figure 8.7 it can be seen that, as would be expected where the degree of moisture movement is limited, the specific creep of the sealed specimens is substantially lower than that for the exposed specimens; in both cases the fly ash mixes have lower specific creep than for the opc mixes.

Figure 8.4b
Creep, shrinkage and elastic deformation of PPC Jupiter opc mix with 19 mm stone

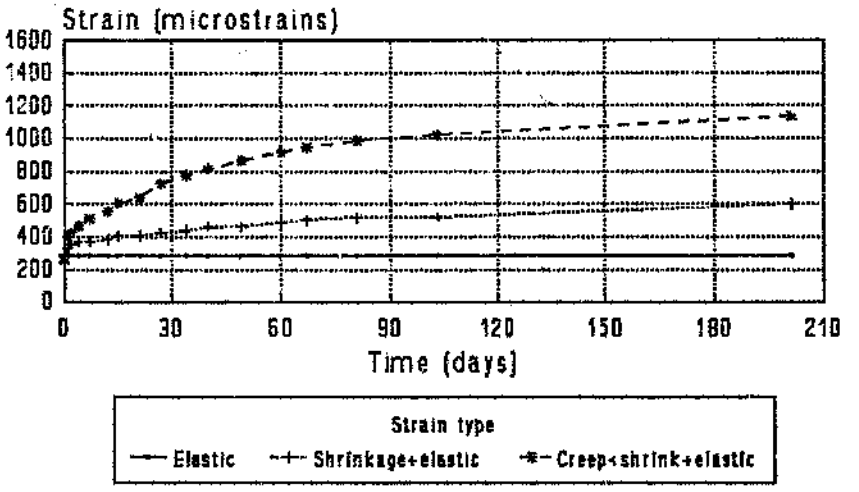


Figure 8.4c
Creep, shrinkage and elastic deformation of BC Licht. opc mix with 13 mm stone

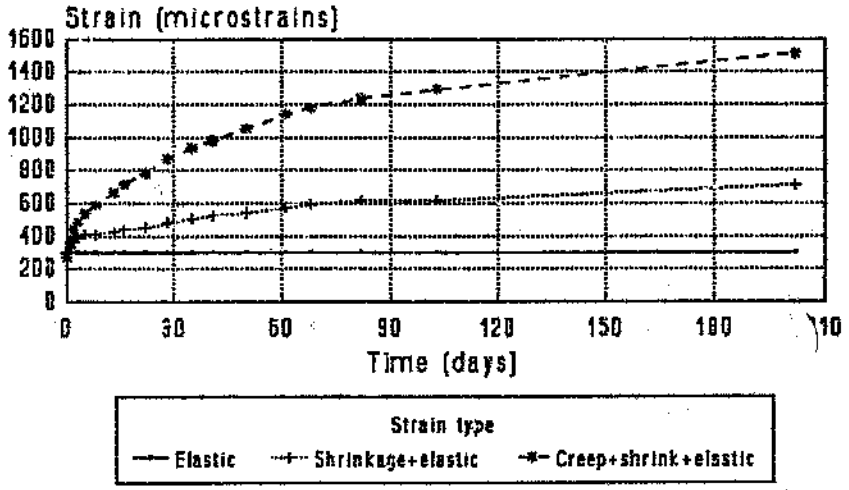


Figure 8.4d
Creep, shrinkage and elastic deformation of PPC Jup opc 15% fa mix with 13 stone

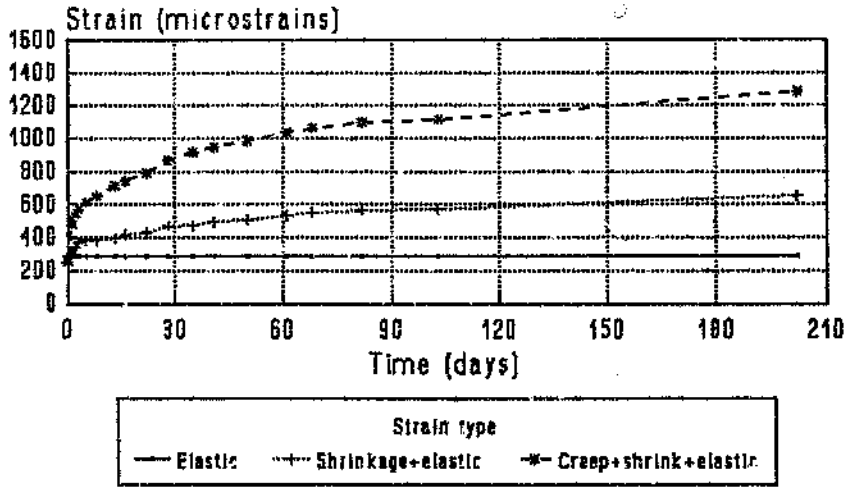


Figure 8.4e
Creep, shrinkage and elastic deformation of BC Licht opc 15% fa mix with 13 stone

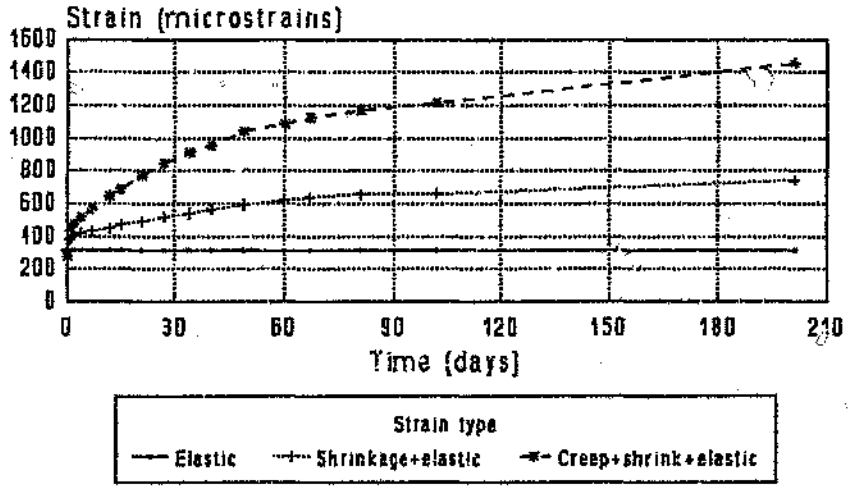


Figure 8.4f
Creep, shrinkage and elastic deformation of PPC Jup. opc 30% fa mix with 13 stone

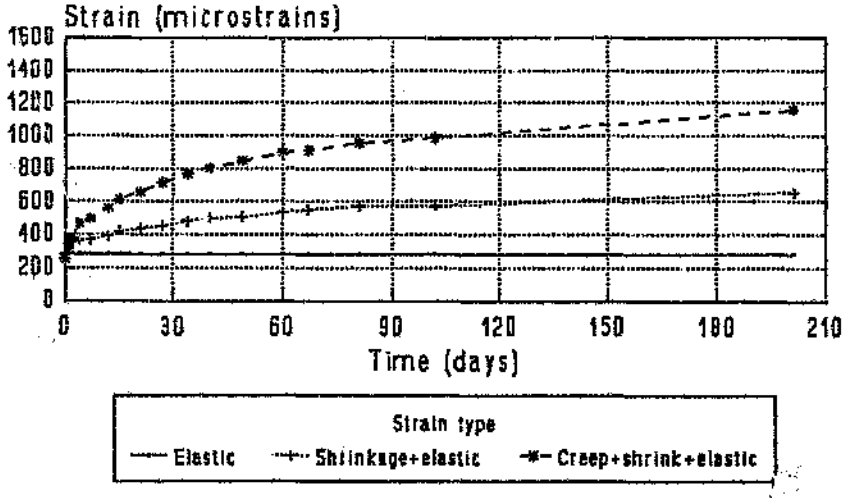


Figure 8.5
Specific creep : Series I
for opc and fly ash mixes

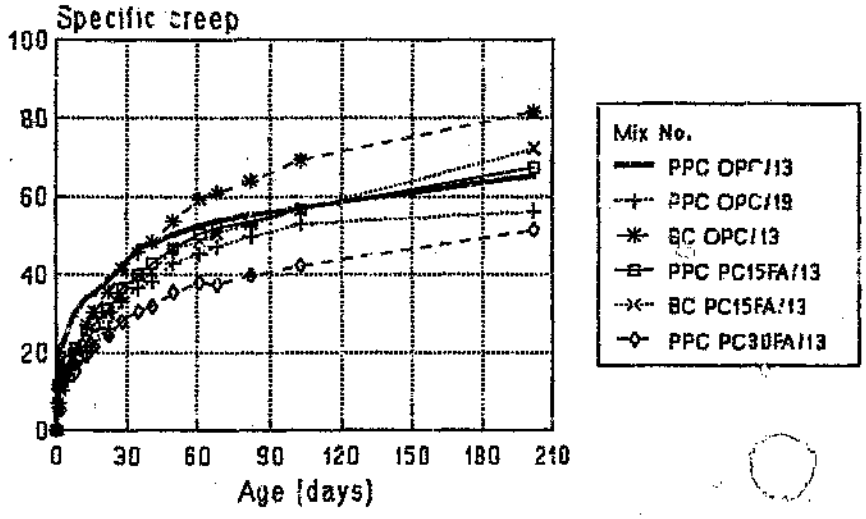


Figure 8.6a
Creep, shrinkage and elastic deformation
of PPC Jup opc mix (13 mm stone, sealed)

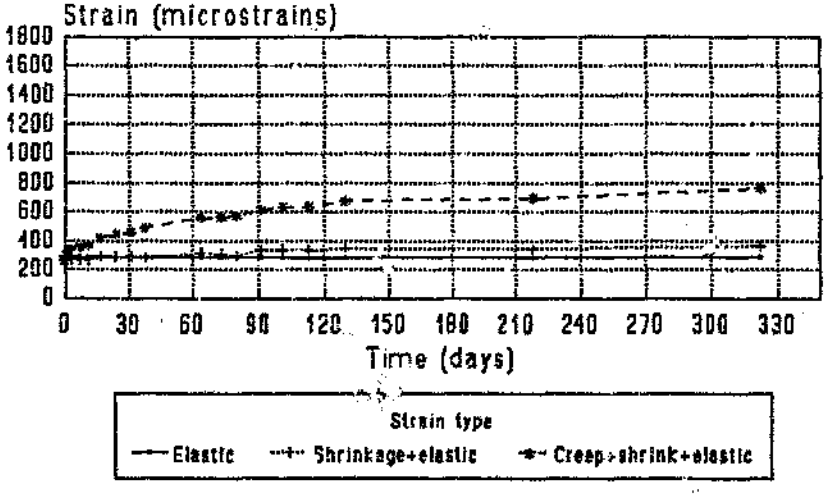


Figure 8.6b
Creep, shrinkage and elastic deformation
PPC Jup cpc (13 mm stone, unsealed)

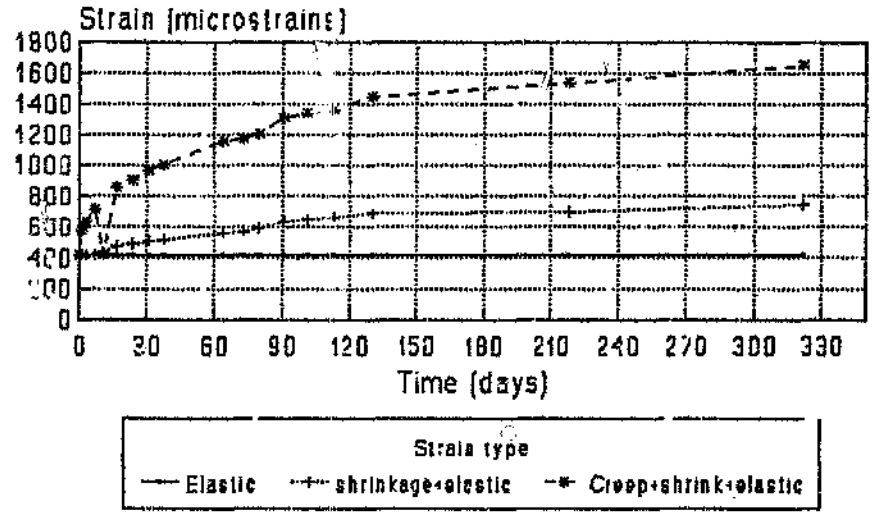


Figure 8.6c
Creep, shrinkage and elastic deformation
of PC30FA mix (13 mm stone, sealed)

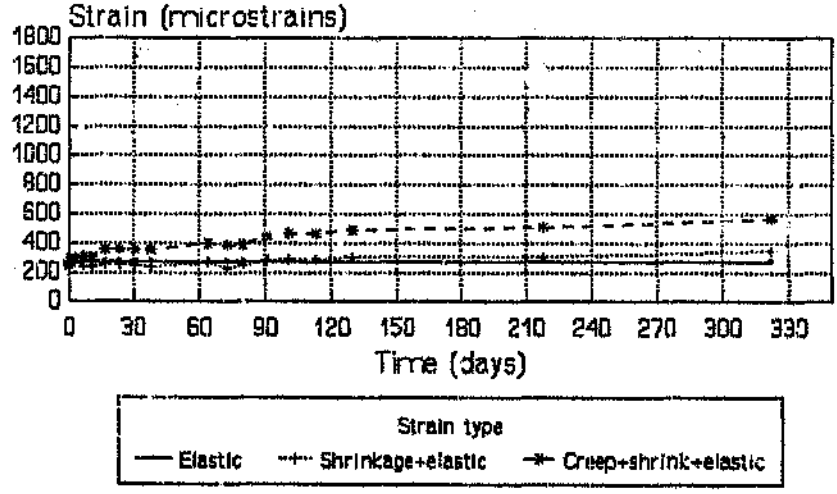


Figure 8.6d
Creep, shrinkage and elastic deformation of PC30FA mix (13 mm stone, unsealed)

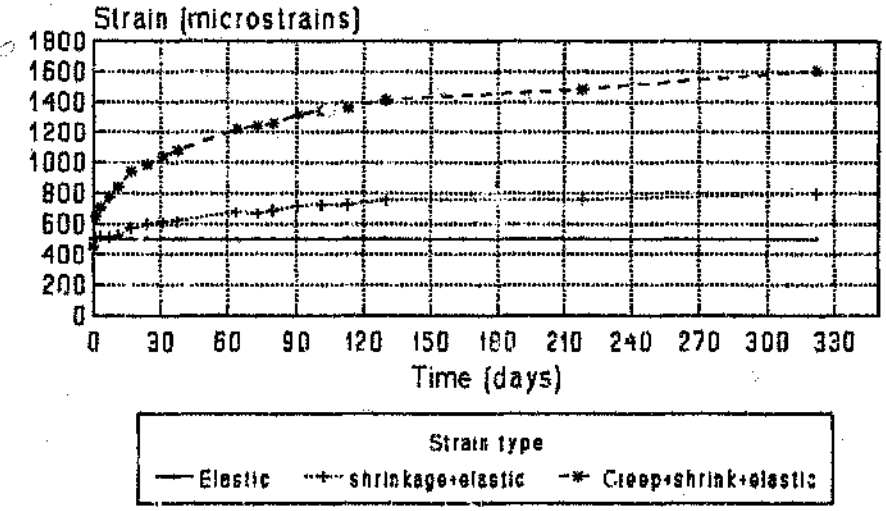
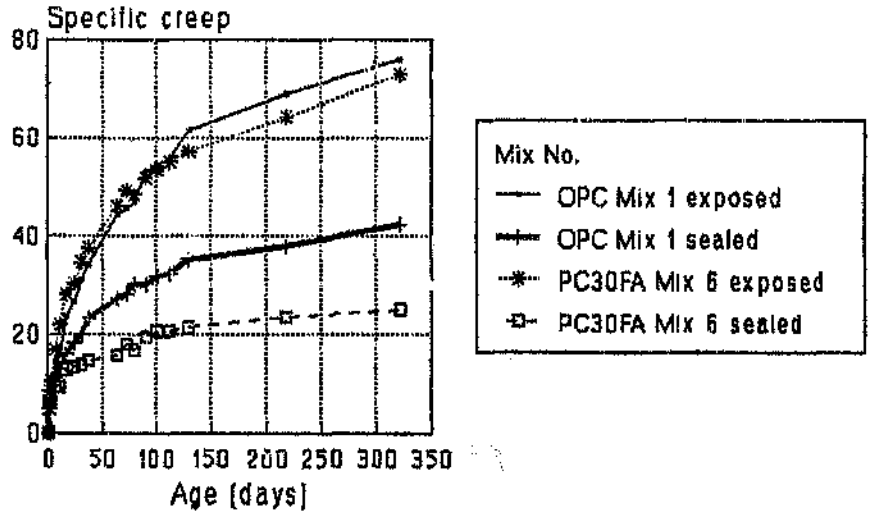


Figure 8.7
Specific creep : Series II
for opc, fa mixes (sealed and exposed)



A further point to note is that the exposed specimens were exposed to "dry" ambient conditions in the laboratory after only 2 days of curing under water. The "dry" conditions to which the specimens were exposed consisted of a controlled temperature of 22 to 25 °C and an uncontrolled relative humidity of about 50 %. Comparing the curve in figure 8.5 for mix 6 against the curve for mix 6 exposed it can be seen that the exposed specimens exhibited a substantially higher degree of creep than those which were wet cured for 28 days prior to being loaded. This change in creep is not evident for the two opc mixes where the level of creep is rather similar for both methods of curing.

Looking at the shrinkage deformations that occurred in series I (tables 8.7a and 8.7f) compared with the similar data from series II (tables 8.9b and 8.9d) it can be seen that under the severe dry curing regime of series II the shrinkage of both opc and PC 30 FA mixes increases by a similar order of magnitude of 200 to 300 microstrains, although the fly ash mix showed a slightly bigger increase than the opc mix.

It would therefore seem that the creep of the fly ash mix is more sensitive to poor curing than is the case for the opc mix, with a similar increase in sensitivity in the drying shrinkage behaviour of the fly ash mix. As this conclusion is arrived at after only studying the results of one set of mixes it is advisable that further tests should be done to confirm this finding.

Note should also be taken of the surface area to volume ratio of the cylinder specimens used for these series of tests as discussed under section 8.2.1. It is unlikely that this degree of poor curing would be matched in structural concrete elements on a construction site, although the skin concrete might have a similar degree of exposure.

Under ideal curing conditions the fly ash mix seems to benefit more than the opc mix, showing a far greater decrease in specific creep under sealed conditions than is the case for the opc mix. Thick structural elements would tend to exhibit this type of performance.

Several authors have postulated theories about the mechanism of creep.[190] Most of these theories hold that moisture movement in the concrete plays an important role in the phenomenon. With the reduced water content of fly ash mixes a reduction in the magnitude of the actual creep and the specific creep is to be expected. The magnitude of the decrease is probably bigger than can be ascribed to the reduced water content however; pore refinement resulting in decreased permeability with a consequent reduction in the rate of moisture movement may contribute to the low creep under sealed conditions.

8.2.4 Summary of findings on creep

The trend is for Matla fly ash to reduce the specific creep of concretes with similar levels of compressive strength at 28 days. This confirms the findings of a majority of the research reports consulted.[33,44,68,90,109,111,116,153,167,185,187,191]

Mukheibir[296] came to a similar conclusion from his research findings on concretes made using classified Lethabo fly ash.

There is an apparent trend for the Matla fly ash mixes to show a greater increase in specific creep when poorly cured than is the case for opc mixes. Mukheiber[296] noted similar degrees of sensitivity to poor curing for ordinary portland cement and mixes using classified Lethabo fly ash. Confirmation of the finding for the Matla fly ash would therefore seem to be required.

Table 8.1a

Mix proportions of concrete mixes (kg/m^3) for elastic modulus tests

Materials	% Fly ash	c/w 1,0	c/w 1,5	c/w 2,0	c/w 2,5	% Fly ash	c/w 1,0	c/w 1,5	c/w 2,0	c/w 2,5
Water	0	209	205	203	207	15	200	194	193	194
Cement		209	308	406	518		170	247	328	412
Fly ash		–	–	–	–		30	44	58	73
Stone		1065	1090	1110	1120		1085	1110	1130	1140
Sand		979	884	789	675		985	898	800	701
Water	5	206	201	199	203	30	193	188	185	188
Cement		196	286	376	482		135	197	258	329
Fly ash		10	15	20	25		58	85	111	141
Stone		1070	1095	1115	1125		1110	1130	1150	1160
Sand		982	892	797	684		990	894	803	694
Water	10	203	198	196	199	50	186	179	176	179
Cement		183	267	353	448		93	134	176	224
Fly ash		20	30	39	50		93	134	176	224
Stone		1075	1100	1120	1130		1135	1160	1180	1190
Sand		986	895	800	691		973	890	798	688

Table 8.2a

Elastic modulus using PPC Jupiter cement

% fly ash	28 day elastic modulus (GPa) at cement/water ratio			
	C/W 1,0	C/W 1,5	C/W 2,0	C/W 2,5
0	21,5	34,5	39,5	43,5
5	22,5	34,0	40,0	42,5
10	24,0	31,0	38,5	42,5
15	21,5	31,5	37,5	43,5
30	19,0	28,5	37,5	40,0
50	13,0	25,5	32,0	34,5

Table 8.2b

Elastic modulus using BC Lichtenburg cement

% fly ash	28 day elastic modulus (GPa) at cement/water ratio			
	C/W 1,0	C/W 1,5	C/W 2,0	C/W 2,5
0	24,5	33,5	42,0	44,5
5	25,5	34,5	42,0	44,5
10	24,5	34,0	41,5	44,5
15	26,0	37,0	42,0	43,5
30	23,0	32,5	38,0	42,5
50	15,5	26,0	32,5	37,0

Table 8.2c

Elastic modulus using Anglo–Alpha Roodepoort cement

% fly ash	28 day elastic modulus (GPa) at cement/water ratio			
	C/W 1,0	C/W 1,5	C/W 2,0	C/W 2,5
0	25,0	35,0	40,0	42,5
5	–	35,0	39,0	–
10	–	33,0	40,0	–
15	–	34,0	37,0	–
30	–	31,5	35,0	–
50	17,5	25,0	33,0	–

Table 8.2d

Elastic modulus using PPC Factory blended or interground cements

Type	% fly ash	28 day elastic modulus (GPa) at cement/water ratio			
		C/W 1,0	C/W 1,5	C/W 2,0	C/W 2,5
Blend	5	26,0	28,0	42,5	45,5
Blend	15	25,0	34,0	41,5	46,5
Grind	5	26,5	37,5	42,5	45,0
Grind	15	25,5	35,5	40,0	47,5

Table 8.2e

Elastic modulus of OPC and fly ash concretes
Additional data from creep tests

Cement source	Fly ash content (%)	Stone size (mm)	28d comp. strength (MPa)	Elastic modulus (GPa)
PPC Jup	0	13,2	28,5	33,70
PPC Jup	0	19,0	29,0	35,42
PPC Jup	0	13,2	30,0	33,70
BC Licht	15	13,2	31,0	35,12
PPC Jup	15	13,2	31,0	32,85
BC Licht	30	13,2	32,0	36,68
PPC Jup	0	13,2	30,0	35,21
PPC Jup	30	13,2	27,5	36,43

Table 8.3a

Drying shrinkage of PPC Jupiter mortar specimens with and without fly ash. Mix proportions detailed in table 5.14a

% fly ash	Drying shrinkage (%) at cement/water ratio			
	c/w 1,0	c/w 1,5	c/w 2,0	c/w 2,5
0	0,060	0,083	0,089	0,103
5	0,058	0,081	0,088	0,094
10	0,057	0,077	0,082	0,092
15	0,059	0,075	0,083	0,089
30	0,056	0,065	0,071	0,085
50	0,058	0,065	0,072	0,080

Table 8.3b

Drying shrinkage of mortars shown in table 8.3a as a proportion of the mixing water figures shown in table 5.14a

% fly ash	Drying shrinkage as proportion of mixing water (%/100l) at cement/water ratio			
	c/w 1,0	c/w 1,5	c/w 2,0	c/w 2,5
0	0,019	0,027	0,029	0,032
5	0,019	0,027	0,029	0,030
10	0,019	0,026	0,027	0,030
15	0,020	0,026	0,028	0,029
30	0,019	0,023	0,025	0,029
50	0,020	0,024	0,026	0,028

Table 8.3c

Calculated drying shrinkage values for equivalent compressive strength mortar mixes from table 8.3b adjusted using figure 7.1g

% fly ash	Circa 10 MPa		Circa 20 MPa		Circa 30 Mpa	
	C/W	shrinkage (%/100l)	C/W	shrinkage (%/100l)	C/W	shrinkage (%/100l)
0	1,00	0,019	1,50	0,027	2,00	0,029
15	1,08	0,021	1,65	0,026	2,20	0,028
30	1,20	0,021	1,85	0,024	2,43	0,027
50	1,51	0,024	2,25	0,027	–	–

Table 8.4

Drying shrinkage results (%) for PPC Jupiter factory blended or interground cements

Blend type	Drying shrinkage at cement/water ratio			
	c/w 1,0	c/w 1,5	c/w 2,0	c/w 2,5
5% blend	0,034	0,039	0,039	0,044
5% grind	0,039	0,040	0,042	0,044
15% blend	0,032	0,038	0,040	0,042
15% grind	0,037	0,043	0,043	0,043

Table 8.5a

Drying shrinkage of OPC and fly ash concretes (Series I)

Cement source	Cement Blend	Stone size (mm)	28d compressive strength (MPa)	Drying shrinkage (%)	Age tested (days)
PPC Jup	OPC	13,2	28,5	0,0357	202
PPC Jup	PC15FA	13,2	31,0	0,0365	202
PPC Jup	PC30FA	13,2	32,0	0,0368	201
PPC Jup	OPC	19,0	29,0	0,0317	201
BC Licht	OPC	13,2	30,0	0,0408	202
BC Licht	PC15FA	13,2	31,0	0,0427	201
Note: specimens exposed after 28 day submerged curing					

Table 8.4

Drying shrinkage results (%) for PPC Jupiter factory blended or interground cements

Blend type	Drying shrinkage at cement/water ratio			
	c/w 1,0	c/w 1,5	c/w 2,0	c/w 2,5
5% blend	0,034	0,039	0,039	0,044
5% grind	0,039	0,040	0,042	0,044
15% blend	0,032	0,038	0,040	0,042
15% grind	0,037	0,043	0,043	0,043

Table 8.5a

Drying shrinkage of OPC and fly ash concretes (Series I)

Cement source	Cement Blend	Stone size (mm)	28d compressive strength (MPa)	Drying shrinkage (%)	Age tested (days)
PPC Jup	OPC	13,2	28,5	0,0357	202
PPC Jup	PC15FA	13,2	31,0	0,0365	202
PPC Jup	PC30FA	13,2	32,0	0,0368	201
PPC Jup	OPC	19,0	29,0	0,0317	201
BC Licht	OPC	13,2	30,0	0,0408	202
BC Licht	PC15FA	13,2	31,0	0,0427	201
Note: specimens exposed after 28 day submerged curing					

Table 8.5b

Drying shrinkage of OPC and fly ash concretes (Series II)

Cement source	Cement blend	Stone size (mm)	Curing condition	28d compressive strength (MPa)	Drying shrinkage (%)	Age tested (days)
PPC Jup	OPC	13,2	sealed	30,0	0,0078	322
PPC Jup	OPC	13,2	exposed	28,0	0,0470	322
PPC Jup	PC30FA	13,2	sealed	27,5	0,0070	322
PPC Jup	PC30FA	13,2	exposed	25,0	0,0440	322

Note: Sealed specimens were cured submerged in water, then after the specimens were prepared for testing they were coated to prevent moisture loss. The exposed specimens were removed from the water at about 2 days and exposed to the laboratory environment. No coating was provided to these specimens. In the case of the exposed specimens the shrinkage values shown are from the time they were exposed to the laboratory environment. In the case of the sealed specimens the shrinkage values are from the time of loading of the specimens; as the specimens were submerged prior to this little shrinkage was likely.

Table 8.6

Concrete mix proportions used in creep specimens (kg/m^3) (Matla fly ash)

Mix No.	Cement source	Stone size (mm)	Fly ash (%)	c/w ratio	Water (l)	OPC (kg)	Fly ash (kg)	13,2 mm stone (kg)	19 mm stone (kg)	Sand (kg)
1	PPC Jup	13,2	0	1,5	205	308	0	1090	0	884
2	PPC Jup	19	0	1,5	195	294	0	236	944	843
3	BC Licht	13,2	0	1,3	207	269	0	1080	0	921
4	PPC Jup	13,2	15	1,6	197	268	47	1100	0	878
5	BC Licht	13,2	15	1,4	198	236	42	1090	0	868
6	PPC Jup	13,2	30	1,7	189	225	96	1115	0	917