PERFORMANCE AND PROPERTIES OF STRUCTURAL CONCRETE MADE WITH COREX SLAG

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DECLARATION

I, Hassen Jaufeerally, hereby declare that this dissertation is my own, unaided work. It is being submitted for the degree of Master of Science in Engineering in the University of Cape Town. It has not been submitted before for any degree or examination in any other University.

Signed by candidate

Dated this [illegible]th day of December 2001.

ABSTRACT

Slag has been used in concrete as a cementitious extender for about 50 years in South Africa. Traditionally, blastfurnace slag has been used in concrete but recently a new product called Ground Granulated Corex Slag (GGCS) has become available on the market in the Western Cape Province. The objective of this research is to characterise the properties of this new product in concrete. In this study, the properties of corex slag concrete were compared to normal blastfurnace slag and plain CEM I concretes. A series of mixes was undertaken, with water:binder ratios varying between 0.4 and 0.8, and slag replacement levels between 30 and 70 %.

The physical characterisation of corex slag revealed that the material is finer than blastfurnace slag, having more ultra-fine particles. The oxide analysis showed that the higher proportions of the calcium and magnesium oxides present in corex slag increase the potential for hydraulic activity of the binder compared with blastfurnace slag.

The investigation of the fresh concrete properties revealed that the consistence of concrete increases with the use of slag, especially at higher water:binder ratios. Blastfurnace slag performed marginally better than corex slag. The use of slag generally increased the setting time of the paste, with pastes containing corex slag having a shorter final setting time than those containing blastfurnace slag. The setting time was also found to increase with increasing slag replacement level. The increase in setting time caused the bleed time of slag concrete to increase but the total bleed volume was significantly reduced. The bleed properties of concrete were improved when corex slag was used.

It was found that the compressive strength of the new cementitious material lagged behind that of CEM I controls during early ages but after seven days, corex slag concrete showed higher strength. The strength was observed to decrease with increasing water:binder ratio From the compressive strength results, it was deduced that the optimum corex slag substitution rate varied with water:binder ratio, ranging from 45 to 60 %. The elastic modulus of corex slag concrete was found to be equal to or higher than CEM I concrete, especially at low water:binder ratios (w:b = 0.4).

Deformation experiments showed that corex slag concrete had the lowest creep and shrinkage strains of all the concretes at low water:binder ratios. At higher water:binder ratios, however, the shrinkage strains were in the same range as the other two materials. Prediction models were also assessed and it was found that no model was able to accurately predict both creep and shrinkage. Generally, the shrinkage predictions were more accurate.

Durability index tests showed that corex slag concrete has good to excellent potential durability, based on historical data. Marine exposure testing indicated that corex slag binds a substantial amount of chlorides, hence reducing the risk of corrosion in marine environments. Furthermore, the risk of carbonation induced corrosion is also decreased. Expansion associated with alkali- silica reaction is minimised with the use of corex slag and the efficiency of the material increases with replacement level.

It is concluded that corex slag is an excellent extender for use in concrete. Finally, recommendations are made on the need to further characterise the properties of the material

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CONTENTS

Page

6 DURABILITY PROPERTIES OF COREX SLAG CONCRETE 86

LIST OF FIGURES

LIST OF TABLES

Table **Page**

CHAPTER 1

INTRODUCTION

Slag is a by-product of the reduction of iron ores to metallic iron (pig iron) and has been used as a cementitious product in concrete for more than a century. The main reason for the use of slag is because of the derived economic benefits. The main cost associated with the material is the grinding process and transportation to the point of use (Philleo, 1989). Furthermore, the energy required to produce granulated slag is estimated at only 25 to 33 % of that of portland cement and consequently, replacing cement with slag in concrete should result in significant energy savings (Malhotra, 1987).

In addition to the economic advantages, slag also enhances the durability potential of concrete. The improved resistance to expansion due to alkali-silica reaction and ingress by chloride ions is well known. The need to build structures that last is more important today than ever, with a burgeoning population in a world of dwindling resources, and the use of slag concrete can help to achieve durable structures.

Moreover, the protection of the environment is also a crucial factor nowadays and significant environmental benefits are obtained from the use of slag in concrete. Not only is the problem of the disposal of slag eliminated but also the life of existing quarries at the cement plants is extended which postpones the development of future quarries. The protection of the environment is of particular concern to the Saldanha Steel Plant, where corex slag is produced, as it is located close to the sensitive ecological system of the Langebaan Lagoon and West Coast National Park.

1.1 MANUFACTURE OF SLAG

Slag is a by-product of the pig iron manufacturing process. In a blastfurnace, the iron oxide is reduced by means of coke to metallic iron, while the silica and alumina constituents combine with fluxing stones to form a molten slag which floats on top of the molten iron. The blastfurnace slag and iron are drawn off at regular intervals from the continuous-process furnace in the molten form. The molten slag is usually broken up by water jets and is then immediately immersed in water (Hooton, 1987). The water-quenched product is called granulated slag due to the sand-size particles. The product is then ground to the appropriate fineness and is called Ground Granulated Blastfurnace Slag (GGBS).

Ground Granulated Corex Slag (GGCS), on the other hand, is essentially the same as GGBS but the manufacturing process used to produce the iron differs from the traditional blastfurnace process. The Saldanha plant produces steel using the newly developed Corex Technology. This technology is based on the physical separation of reduction and melting processes, which are carried out in two reactors. In the melter gasifier, reduction gas is generated and liquid hot metal is produced. The reduction shaft, which is located above the melter gasifier, is designed for the reduction of iron oxides. All chemical and metallurgical processes in the melter gasifier are carried out at an elevated pressure level exceeding 300 kPa gauge. Unlike the traditional Blastfurnace Technology, the corex plant operates without coke oven and sinter plant, which provides a potential for cost savings. However, tapping and separation of hot metal and slag are performed in the same way.

The corex process can be operated with a wide variety of raw materials such as lump ore, sinter or pellets or any mixture thereof, using non-coking coal as reducing agent. Thus, corex technology offers increasing flexibility for hot metal production. The corex process produces hot metal of a quality similar to that of the blastfurnace technique and in order to achieve the desired results, the quality requirements of the raw material regarding stability and consistence are very important. Important raw material parameters include iron content and reducibility of iron oxides, the composition of coal and the grain size distribution of all solids. However, the requirements for the corex process are generally not as restrictive as applied in the blastfurnace technique.

Furthermore, Corex technology aims for complete and efficient recycling of all by-products generated during the process. Additionally, closed loop systems support economical resource management. From an emission point of view, no sulphur components and dust, generally generated by a coking plant, are released. Also, neither chemical treatment of the coal devolatilisation products nor excessive amounts of coke quenching water is required. Finally, considerably lower emissions of nitrogen dioxide, phenols, sulphides, ammonium and free cyanides can be observed in a corex plant.

1.2 HISTORY OF THE USE OF SLAG

The reactivity of blastfurnace slag was first discovered as long ago as 1862 in Germany by Emil Lagen and the addition of blastfurnace slag to portland cement was first done in Germany in 1892. Originally, the use of blastfurnace slag concrete was limited to seawater work, foundations and other structures where the concrete was not in direct contact with air. At that time, the strength development of blastfurnace slag was considered to be very good under wet conditions, but there were some doubts about the hardening process of slag in air. It was only in 1915-16, after a series of tests, that slag concrete was allowed for use under all curing conditions. Since then, slag concrete has gained in popularity in many European countries including France, Germany, Holland and Belgium for general building work, such as reinforced concrete, water-retaining structures and precast products. Nowadays, over 60 % of all concrete structures in Holland contain blastfurnace slag (Wainwright, 1986).

In South Africa, Stutterheim, in the 1950s, investigated the suitability of the local blastfurnace slag for manufacturing cement and for use in concrete. Field trials were undertaken using blastfurnace slag together with ordinary portland cement as an activator. Experimental construction of a variety of low-cost houses, industrial floors and an irrigation canal were undertaken and the trials proved successful. In the 1960s, 65 000 tons of blastfurnace slag were produced annually and this represented about 12 % of the country's cement requirements. Nowadays, more than 600 000 tons of slag are produced per annum.

1.3 AIM OF THIS INVESTIGATION

Research on the properties of slag has been carried-out for more than a century in Europe and for about 50 years in South Africa. However, all the published results pertain to the properties of blastfurnace slag in concrete. Little information is available concerning corex slag and this is because the material is a new product. Hence, engineers have to make assumptions about the behaviour of corex slag in concrete based on the properties of blastfurnace slag, but the extent to which the two materials are similar is unknown at this stage. Therefore, the properties of corex slag need to be found such that engineers can choose the best material for their structure. Consequently, it was critical that the behaviour of corex slag in concrete be investigated.

1.4 OBJECTIVES AND SCOPE OF THIS INVESTIGATION

The main objective of this investigation is to characterise the properties of corex slag in concrete and to compare the results with the properties of blastfurnace slag and CEM I concretes.

The specific objectives of the research are to:

- Provide a general literature review on the properties of blastfurnace slag concrete,
- Characterise the chemical and physical properties of corex slag,
- Evaluate the effect of different water:binder ratios and replacement levels on the properties of corex slag concrete,
- Assess the influence of corex slag on fresh concrete properties,
- Investigate the compressive strength development and deformation behaviour of corex slag concrete,
- Evaluate the durability potential of concrete containing corex slag.

The scope of this study is to investigate the above mentioned properties by using water:binder ratios varying between 0.4 and 0.8, and slag replacement levels between 30 and 70 %.

1.5 ORGANISATION OF THIS THESIS

The chemical composition and physical properties of corex slag are considered in Chapter 2. These include the oxide analysis, particle size distribution and fineness. Electron microscopy images and characteristics of the concrete mixes are also provided in this chapter.

Chapter 3 deals with the fresh properties of concrete which include consistence, setting time and bleeding.

The compressive strength development characteristics of the various mixes considered are presented in Chapter 4. The static moduli of elasticity of some of the mixes are also discussed in the same chapter.

Details of the creep and shrinkage behaviour of the different mixes investigated are provided in Chapter 5. Furthermore, the results of various creep and shrinkage prediction methods are compared with experimental results in the same chapter.

In chapter 6, the durability potential of corex slag concrete is investigated and the properties studied include permeation, sorption, expansion due to alkali-silica reaction and resistance to ingress by chloride ions and carbon dioxide gas.

Finally, the general conclusions of this research are summarised in Chapter 7 and specific recommendations are provided.

In this thesis, the relevant literature is reviewed at the beginning of each chapter, rather than in an overall literature review chapter.

1.6 REFERENCES

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CHAPTER 2

MATERIALS AND MIXES

In this chapter, the general properties of the materials used in the manufacture of concrete for this research are investigated. The chosen materials are in common use in the Cape Peninsula Region. Klipheuwel sand was used as the fine aggregate, Malmesbury shale as the coarse aggregate and Riebeeck CEM I as the cement.

Corex slag was obtained from Saldanha and its chemical and physical characteristics were compared to blastfurnace slag from Vanderbijlpark. The properties investigated included oxide analysis, particle size distribution and fineness. Furthermore, the two different slags were compared using electron microscopy.

The various mixes performed in this research programme are also discussed in this chapter.

2.1 MATERIALS

2.1.1 Fine Aggregate

Klipheuwel sand is a siliceous pit sand having a very good particle shape and a continuous grading. According to Grieve (1994), Klipheuwel sand has a high percentage of fines but has no apparent detrimental effect on shrinkage. The concrete water requirement is very low, hence making it an excellent sand for concrete. The grading curve for the Klipheuwel sand used in this research is shown in Figure 2.1 and the data are given in *Appendix A*. The grading analysis was performed according to SABS 829:1994. It was found that the material grading fell within the limits recommended by SABS 1083:1994. The fineness modulus was 2.50, indicating that Klipheuwel sand is a medium sand. A single batch of sand was used throughout this project.

2.1.2 Coarse Aggregate

Greywacke, also known as Malmesbury shale, is a hornfels that has developed by thermal metamorphism of argillaceous rocks of the Malmesbury Group (Brink, 1985). It is a fine-grained 'glassy' rock consisting of quartz, feldspar, mica and iron oxides. Greywacke does not crush to a good cubical particle shape and hence tends to be elongated and flaky. Consequently, the workability of concrete made with this aggregate is negatively affected. A typical grading curve for 19-mm greywacke stone is given in Figure 2.2 and Table 2.1 gives some of the typical characteristics of the coarse and fine aggregates. It must also be noted that greywacke is a highly reactive material with regard to alkali-silica reaction (Crosswell, 1992).

2.1.3 Cement

The cement used in this research was a CEM I 42.5 which, essentially, is an ordinary portland cement. Portland cement consists of a mixture of calcium silicates, calcium aluminates and other compounds which have hydraulic properties. The proportions of the compounds present in cement may vary from one plant to the next, and even at a specific factory the cement may vary from time to time The cement used for this work was obtained from one batch and stored in a cement silo. The cement did not deteriorate over the period of time it was used (10 months). A typical oxide composition of the cement is given in *Appendix A*.

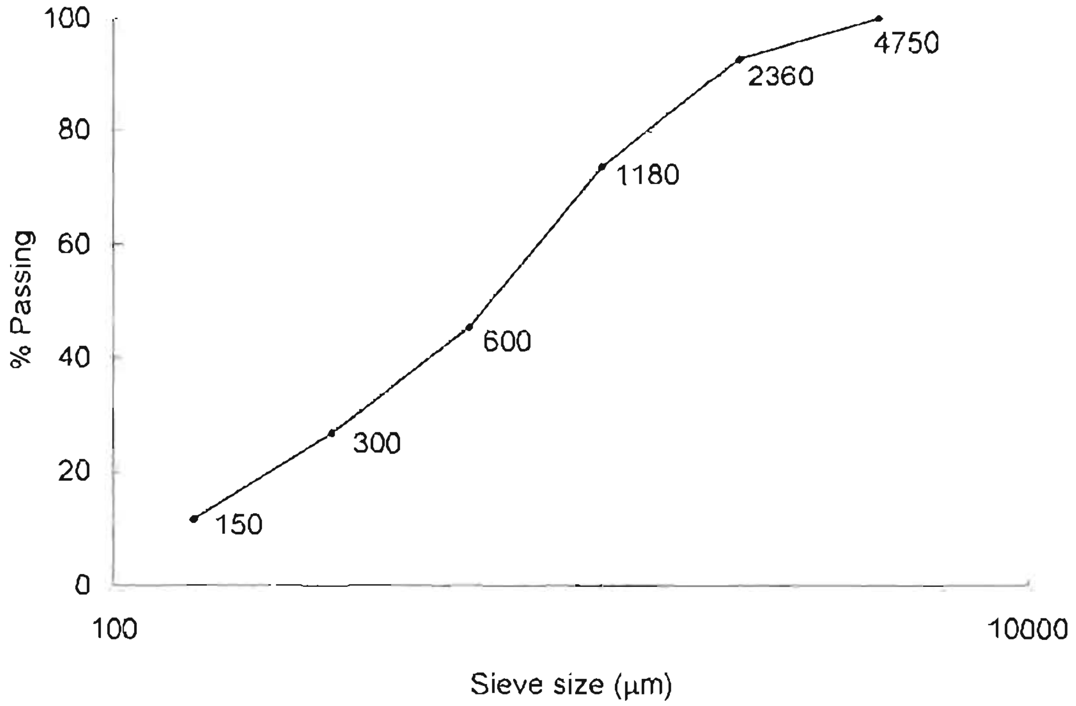

Fig. 2.1: Grading curve of fine aggregate

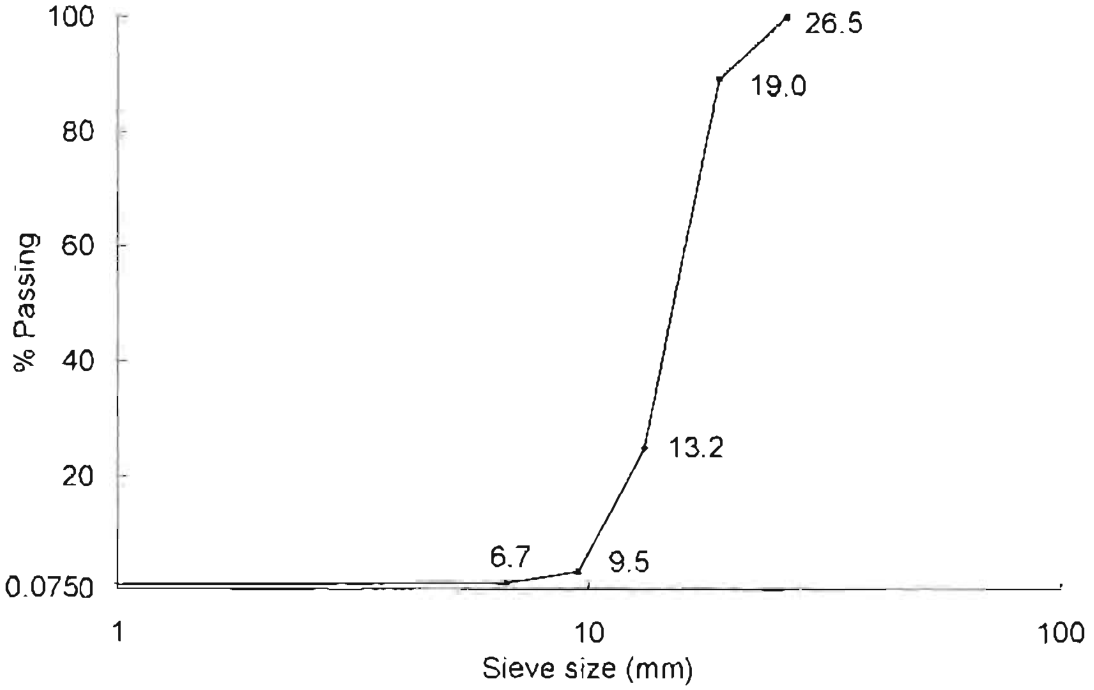

Fig 2 2· Grading curve of coarse aggregate

Table 2.1. Typical characteristics of the coarse and fine aggregates (Davis and Alexander, 1992)

Property	**Greywacke**	**Klipheuwel**
RD	2.72	2.71
10 % FACT (kN)	140-300	--
FM	--	2.50
Unconfined Compression (MPa)	297-308	--
Elastic Modulus (GPa)	68-77	--

2.1.4 Slag

Two types of slag were used in this work namely, ground granulated blastfurnace slag and ground granulated corex slag. Blastfurnace slag was obtained from Vanderbijlpark and corex slag from Saldanha. Corex slag is processed and marketed by PPC Cement in the Western Cape. The chemical composition of slag is close to that of ordinary portland cement, containing the same oxides but in different proportions. The properties of the materials will be thoroughly discussed in the next section.

2.1.5 Water

Ordinary tap (potable) water was used in this research to make concrete.

2.2 CHEMICAL COMPOSITION OF SLAG

The chemical compositions of blastfurnace and corex slag are given, in terms of their oxides, in Table 2.2. X-ray fluorescence techniques were used to characterise the slags. The chemical and physical characterisations were performed at the University of Cape Town and checks were conducted by PPC Technical Services in Johannesburg. No major differences were observed in the two sets of results.

Table 2.2 Oxide analysis of slags

Oxides	Blastfurnace Slag	Corex Slag
CaO	34.0	37.2
SiO_2	35.5	30.8
Al_2O_3	15.4	16.0
MgO	9.4	13.7
TiO_2	1.20	0.51
Fe_2O_3	0.98	0.87
MnO	0.88	0.09
K_2O	0.87	0.35
Na_2O	0.16	<0.12
SO_3	2.49	3.19
Cr_2O_3	0.008	0.003
P_2O_5	0.017	0.017
NiO	<0.002	<0.002

From the above table, it can be seen that the proportions of CaO, MgO and Al_2O_3 are higher in corex slag while blastfurnace slag has higher levels of SiO_2 and MnO Hooton (1987) reported that the hydraulic activity of slags increases with increasing contents of CaO and Al_2O_3 and with decreasing contents of SiO_2 and MnO. Furthermore, based on the work of Kondo, Hooton also reported that higher levels of Al_2O_3 may result in higher strengths but require more calcium hydroxide to develop the strength.

Based on European research, Taylor (1992) reported that an increase in Al_2O_3 content above 13% tended to increase early strengths but to decrease later strengths. This was also reported by Moranville-Regourd (1998) and is illustrated in Figure 2.3. The figure shows the percentage increase in strength with increases in the percentage of Al_2O_3 It can be observed that a relatively small increase in the Al_2O_3 content from 15 to 16 % can have a significant effect on the initial strength increase of the material and this is of particular importance for corex slag.

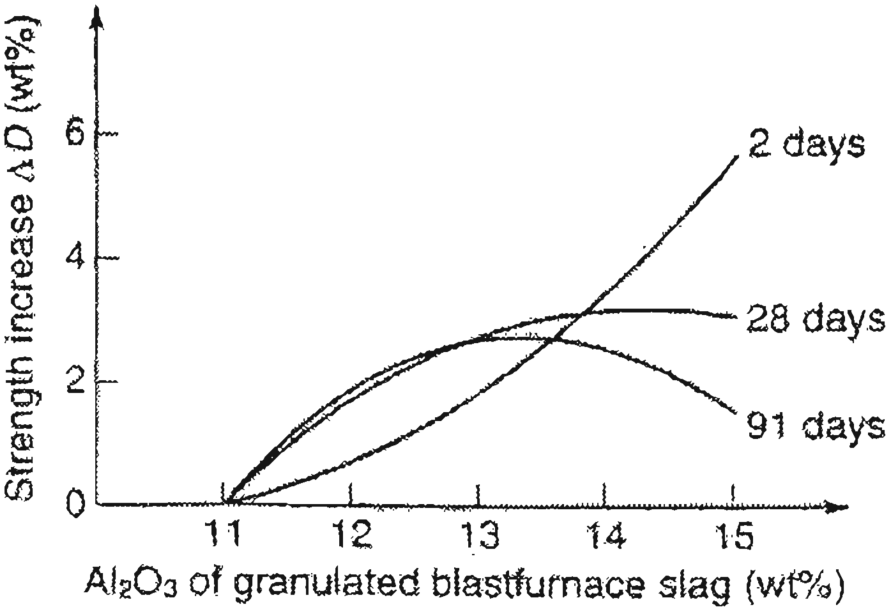

Fig 2.3: Effect of Al_2O_3 on strength development (Moranville-Regourd, 1998)

Concerning the MgO content, it was found that MgO was quantitatively equivalent to CaO in amounts up to 11% (Taylor, 1992 and Jolicoeur et al, 1994). South African slags are generally characterised by high proportions of MgO and this is due to the use of dolomite or dolomitic limestone as the fluxing agent in the production of iron in blastfurnaces. There was early concern that South African slag could result in unsoundness because of the magnesia content, but early research conducted by Stutterheim showed that the local slag could successfully be used as a cementitious material (Grieve, 1993).

2.3 HYDRAULIC ACTIVITY

Slag cement producers have no direct control over the chemical composition of the material but because the raw material burden is carefully controlled to give consistent iron production, the range of slag chemical compositions is fairly narrow for a specific ore and furnace operation. Much effort has been devoted to compositional effects on slag activity. Various hydraulicity formulae have been proposed to predict the hydraulic activity of blastfurnace slag and below are five common formulae for hydraulic moduli (Mantel, 1994).

$$\frac{CaO}{SiO_2} \qquad (1)$$

$$\frac{CaO + MgO}{SiO_2} \qquad (2)$$

$$\frac{CaO + MgO}{SiO_2 + Al_2O_3} \qquad (3)$$

$$\frac{CaO + 0.56Al_2O_3 + 1.4MgO}{SiO_2} \qquad (4)$$

$$\frac{CaO + MgO + Al_2O_3}{SiO_2} \qquad (5)$$

It can be noted that in some of the formulae Al_2O_3 appears in the numerator while in others it is in the denominator. Some of the formulae do not even include Al_2O_3. This implies that the exact contribution of Al_2O_3 is still unclear. Table 2.3 gives the requirement for good performance for each formula together with preferred values, as reported by Mantel (1994). The hydraulic activity of the two slags used in this research was then calculated based on the given formulae.

Table 2.3: Hydraulic activity of slags

Formula	Requirement for Good performance	Preference	GGBS	GGCS
1	1.3-1.4	1	1.0	1.2
2	> 1.4	1	1.2	1.7
3	1.0-1.3	1	0.9	1.1
4	≥ 1.65	2	1.57	2.12
5	≥ 1	3	1.7	2.2

It can be said from Table 2.3 that corex slag should show more hydraulic activity than blastfurnace slag, based on the different moduli alone. However, Hooton (1987), Glasser (1991) and Mantel (1994) pointed out that, in many cases, the proposed formulae did not adequately predict slag hydraulicity. Furthermore, hydraulic activity is also a function of slag fineness and hydraulic properties of the cement and, thus, low values of moduli do not necessarily imply low hydraulic activity and mechanical strength at different ages. It is believed that the mineralogical composition of slag and glass content rather than the chemical composition could have a more significant influence on its hydraulic properties.

The glass contents of blastfurnace and corex slags are typically 98 and 97 %, respectively (Crosswell, 2001), with the SABS 1491-1 standard requiring a minimum content of 95 %. According to Hooton (1987), a glassy structure is essential to reactivity but there is no exact correlation of glass content to hydraulicity.

2.4 PHYSICAL CHARACTERISTICS OF SLAG

2.4.1 Fineness

The fineness of blastfurnace and corex slag was determined by using both the Blaine and BET (Brunauer-Emmett-Teller) fineness methods. In the Blaine method, the specific surface of cement is determined directly by air permeability methods whereas the BET method uses gas adsorption techniques (Taylor, 1992). The results obtained from the BET method are two to three times higher than the air permeability method because it includes internal surfaces present in microcracks or in pores open at only one end (Taylor, 1992). Table 2.4 below gives the fineness of the two slags considered. One sample of each material was tested for each method. The BET fineness test was conducted at the University of Cape Town while the Blaine fineness was measured by PPC Technical Services. The fineness of a typical CEM I sample is also given as reference.

Table 2.4: Fineness of slags

Method	Fineness (m^2/kg)		
	GGBS	GGCS	CEM I
Blaine	390	467	319
BET	991	1145	-

It was found that, in this case, corex slag is a finer material than blastfurnace slag. It must be borne in mind that the two slags had different granulation processes, with the corex plant having a more efficient granulator. As pointed out by Jolicoeur et al (1994) and Roy (1989), the reactivity of slag generally increases with the fineness of the material. Hooton (1987), based on the work of Daimon, also reported that increasing the fineness of the slag component results in better strength development of the blend. Furthermore, the rheology of fresh concrete pastes is also dependent on the slag fineness.

Generally, the reactivity of slag is proportional to its fineness, with other considerations such as economics (cost of grinding), shrinkage and setting times limiting the surface area.

2.4.2 Particle Size Distribution (PSD)

The particle size distributions of blastfurnace and corex slags are shown in Figure 2.4. A Malvern particle sizer was used at the University of Cape Town to determine the PSD. The optical measurement unit of the machine consisted of an optical transmitter, a receiver and an optical bench. The equipment measures the sedimentation rates of particles dispersed in a liquid by means of a finely collimated He/Ne laser beam. The data are automatically interpreted to yield a cumulative mass per cent distribution in terms of equivalent spherical diameters. The PSD is presented in a logarithmic graph. One sample of each material was tested.

The particle size analysis data (Fig. 2.4) revealed that corex slag had a marginally finer distribution than blastfurnace slag. This is in accordance with the findings of Douglas et al (1990) who showed that there was a progressively finer distribution of particle sizes with increasing specific surface area. The typical CEM I sample had the coarsest particle size distribution.

Based on the work of Wada and Ikawa, Mehta (1983) reported that slag particles less than 10 µm contributed to early strength development in concrete whereas 10 to 40 µm particles continued to hydrated thereafter. In the case of the two slags considered, it was found that corex slag had around 4 and 7 % more 5 and 10 µm particles, respectively, than blastfurnace slag. This is of great significance in assessing the relative reactivity of the materials since the ultra fine particles, having high surface area, add greatly to the activity of the materials, especially in the early stages of hydration (Douglas et al, 1990).

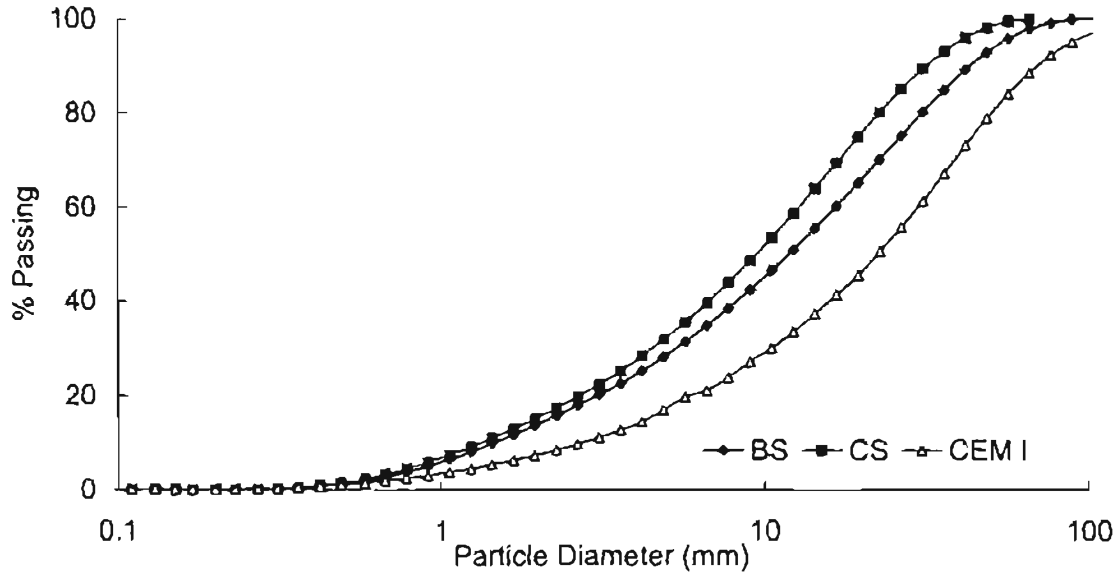

Fig. 2.4: Particle size distribution of slags

2.4.3 Scanning Electron Microscopy (SEM)

The microscopic study was conducted at the Electron Microscope Unit of the University of Cape Town. The instrument used was a Leo S440 analytical scanning electron microscope. The images of blastfurnace and corex slag were taken at magnifications of 2 500 and 10 000 times, and are given in Figures 2.5 and 2.6 respectively.

From Figures 2.5 and 2.6, it can be observed that corex slag is a finer material than blastfurnace slag as demonstrated by the Blaine and BET fineness values. Furthermore, it is also evident that the individual grains of both slags are markedly angular with conchoidal faces. This is because of the material being hard and glassy. Grieve (1989), St John et al (1998), Mehta (1983) and Taylor (1992) also report this characteristic shape of slag.

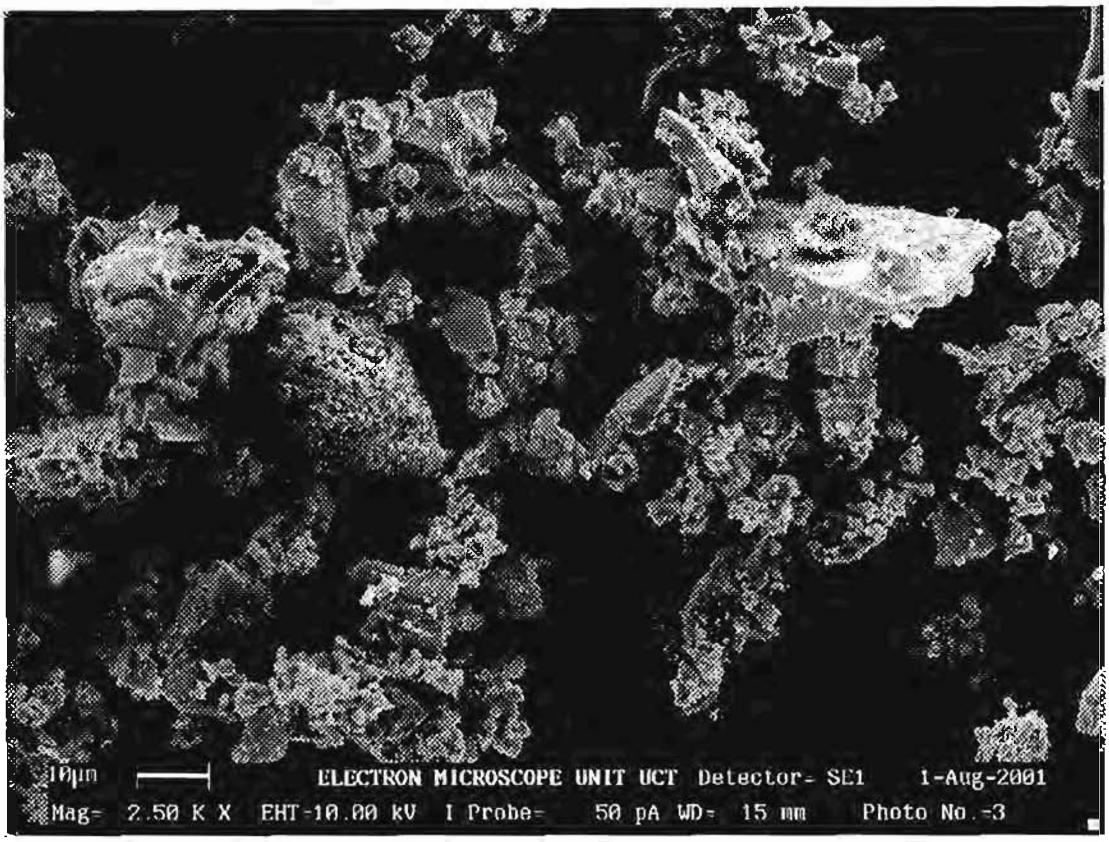

Fig. 2.5a: SEM image of blastfurnace slag (x2 500)

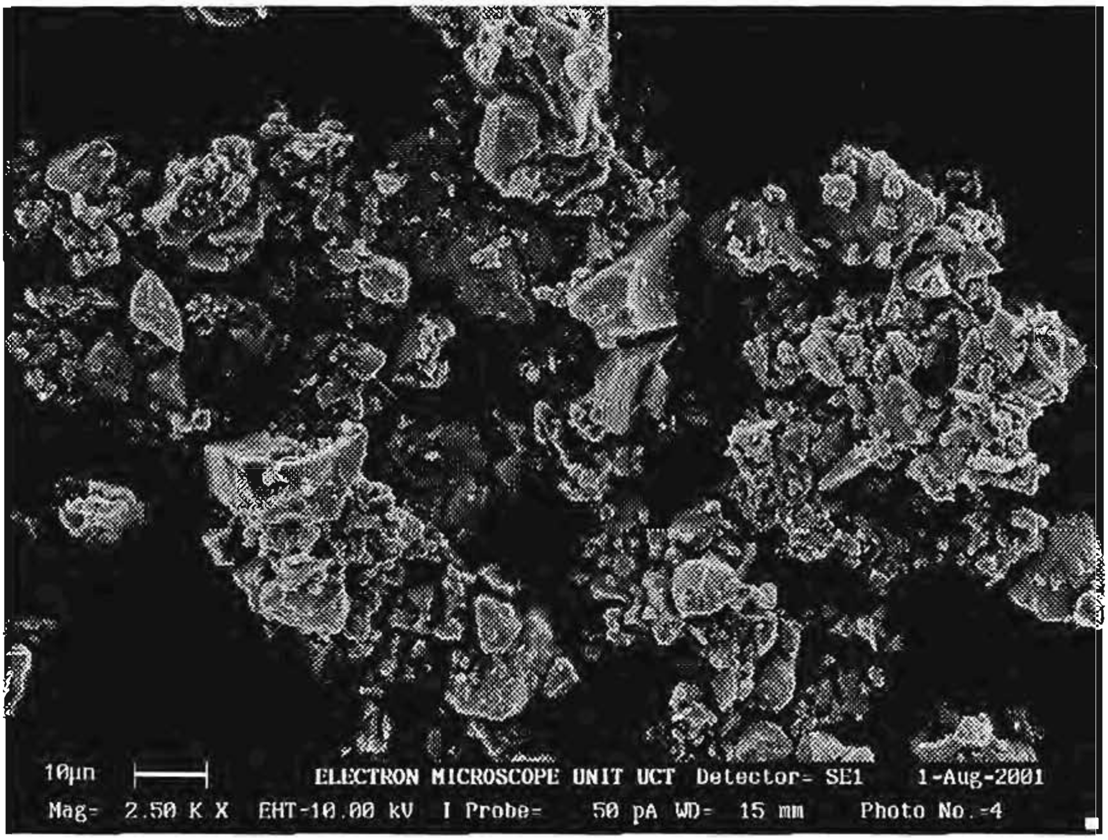

Fig. 2.5b: SEM image of corex slag (x2 500)

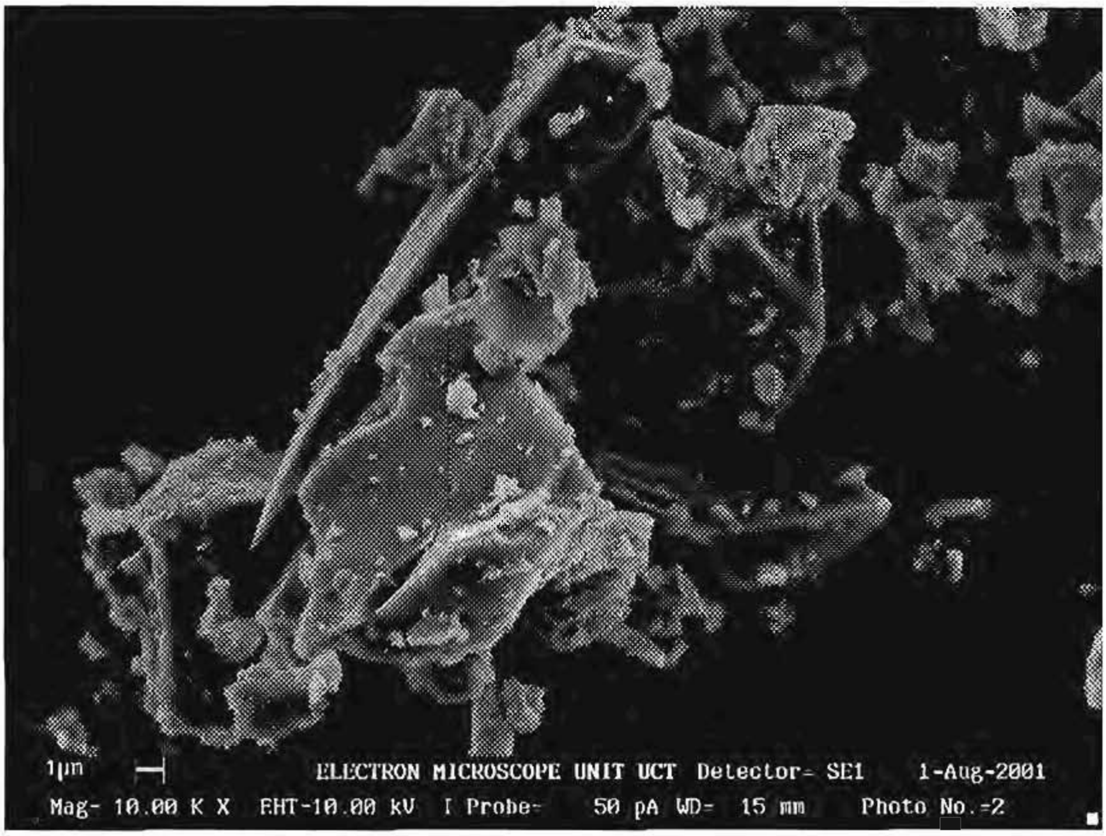

Fig. 2.6a: SEM image of blastfurnace slag (x10 000)

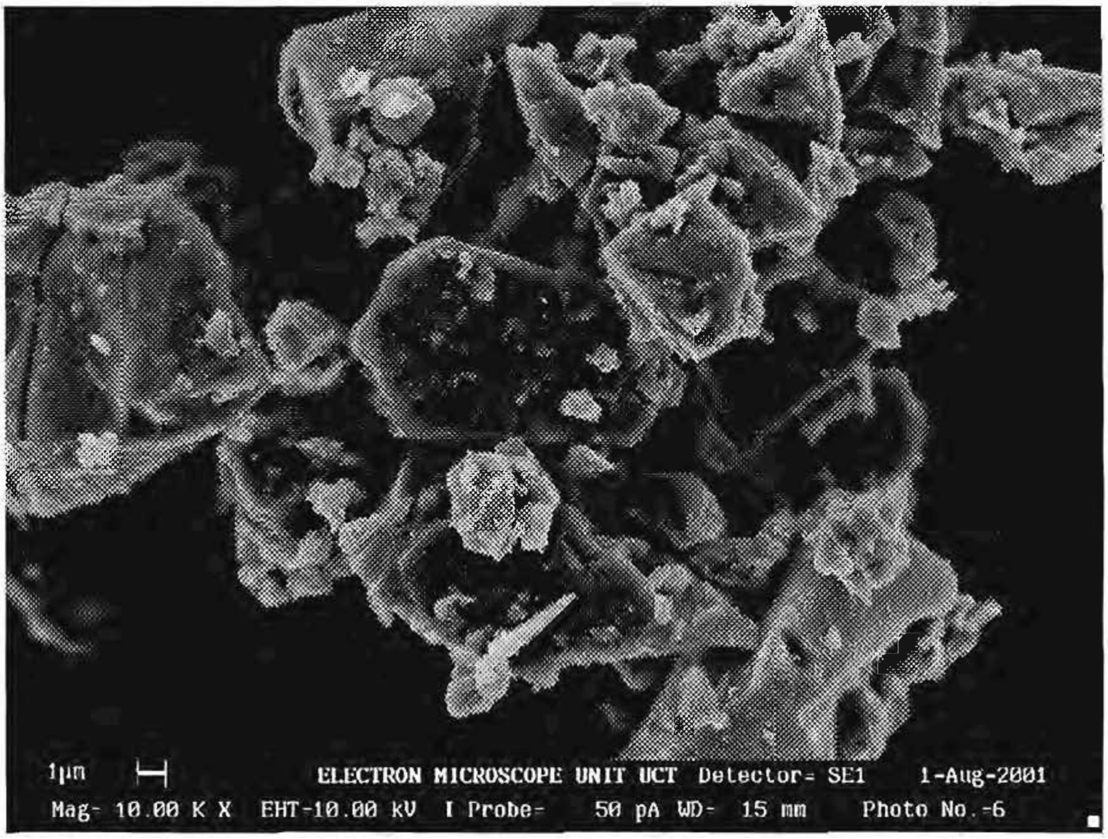

Fig. 2.6b: SEM image of corex slag (x10 000)

2.5 MIX DESIGN

In this research, no specific mix design method was used in preparing the different mixes. Instead, the masses (and hence volumes) of stone and water were decided at the beginning of the investigation and kept fixed in all the mixes. The fixed masses of stone and water were based on values utilised by the ready-mix industry in order to simulate as closely as possible the effect of corex slag in industrial mixes. Also, in so doing, the number of variables was limited. The stone and water contents used are indicated below.

Stone content : 1100 kg/m^3
Water content : 180 l/m^3

- For the different mixes considered, a minimum slump of 50 mm was aimed for. A medium-range water reducing admixture was used in cases where the required slump was not attained. The plasticizer was a ABE/Fosroc material and consisted of naphthalene based lignosulphonate.
- The slag used in the tests was replaced on an equal mass basis.
- The mass of sand was determined from the equation given by the C&CI mix design method (Addis, 1997).

The actual concrete mix designs are given in *Appendix A*.

2.5.1 Range of Mixes Developed

Three water:binder ratios were considered for each test. Also, the replacement level of cement by slag was varied according to the specific experiments. Below is a summary of the different mixes performed.

Experiments	Water:Binder ratio	Replacement Level %
Bleeding Workability Compressive Strength	0.4, 0.6, 0.8	0, 30, 50, 70
Creep Durability Index Tests Elastic Modulus Shrinkage	0.4, 0.5, 0.6	0, 50

In addition to the above, setting times and alkali-silica reaction tests were carried out, in which a fixed water:binder ratio was used as stipulated by the relevant standard.

Before starting with the proper mixes, trial mixes were performed to check the slump and strength characteristics. Throughout this thesis, the abbreviations CEM I, BS and CS refer to plain CEM I, blastfurnace slag and corex slag concretes or pastes respectively.

2.5.2 Mixing Procedure

Mixing of the concrete was done in a 50-litre pan mixer. The accurately weighed materials were added to the pan in the following order: stone, sand and binder. The materials were then dry-mixed for one minute followed by a standard wet mixing time of two minutes. The water was added over a period of one minute. A slump test was then performed according to SABS 862-1:1994. If the slump was found to be less than 50 mm, a plasticizer was added to the mix to get the required workability.

Once the desired slump was achieved, the concrete was placed in the required moulds and compacted. Compaction was done mechanically on a vibrating table until the concrete appeared to be fully compacted. The time taken for compaction varied from mix to mix. Generally, the 100 mm cubes took about 30 seconds to compact.

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CHAPTER 3

FRESH CONCRETE PROPERTIES

Fresh concrete properties play a vital role in the long-term properties of concrete structures. This is because the fresh concrete properties influence the ease with which concrete can be handled and compacted. Also, concrete having good compaction and handling characteristics is beneficial from a practical and economical viewpoint. Furthermore, good compactibility helps to uniformly distribute the different constituents within the concrete, hence avoiding regions of poor or weak concrete (Kellerman, 1994).

The effect of corex slag on the fresh properties of concrete will be discussed in this chapter and will be compared to the effects of blastfurnace slag and plain CEM I concretes. The fresh concrete properties considered include consistence, setting times and bleeding.

In this research, the workability of concrete will be characterised by its consistence, as measured by the slump test However, in the literature, slump is often regarded as directly related to the workability of the mix and in the literature review section the slump of concrete will be quoted as described by the researchers.

3.1 DEFINITION OF TERMS

Workability of concrete is defined as the characteristic governing the effort required to place, compact and finish fresh concrete with minimum loss of homogeneity. Workability is a composite property and the most common descriptive terms used are consistence and cohesiveness.

The *consistence* of a mix is a measure of the stiffness/sloppiness or fluidity of the mix. It is generally characterised by means of the slump value of the concrete.

Cohesiveness is the tendency of concrete to remain a homogeneous mass without separation of the constituents.

Setting time is defined as the start of solidification of cement paste or concrete. Two arbitrarily defined times are used to describe the onset of stiffening. They are the initial and final setting times According to Mehta and Monteiro (1993), the initial setting time represents approximately the period at which fresh concrete can no longer be properly mixed, placed and compacted, while the final set defines the elapsed time at which strength begins to develop at a significant rate, i.e. hardening.

Bleeding is the term used to describe the movement of water to the surface of freshly placed and compacted concrete. According to Powers (1968), bleeding is a form of settlement or sedimentation, the water being forced to the surface as the heavier solids in the concrete begin to settle. The reason for this phenomenon is that the solid constituents of the mix are unable to hold all the mixing water when they settle downwards.

3.2 ADVANTAGES AND DISADVANTAGES OF CONCRETE BLEEDING

One of the main advantages of bleeding is that it minimises the potential of plastic shrinkage cracking. The risk of plastic shrinkage cracking increases significantly when the rate of evaporation is faster than the rate of bleeding. Furthermore, the fact that water is removed from the fresh concrete results in the lowering of the effective water:binder ratio, hence giving rise to a possible strength increase of the concrete (Neville, 1975).

Unfortunately, the disadvantages associated with bleeding often exceed the beneficial effects First of all, there is a great potential for plastic shrinkage cracking to occur if the evaporation of water from the concrete surface is faster than the bleeding rate. Moreover, a significant amount of water gets trapped under coarse aggregates and horizontal reinforcing bars when the bleed water migrates upwards (Mehta and Monteiro, 1993). The upward movement of the water also gives rise to bleed channels which could possibly lead to durability problems.

Hoshino, as quoted by Olorunsogo (1997a), concluded that the upward movement of water could result in poor bond between concrete and steel, hence decreasing the amount of protection of the steel to corrosion. Moreover, bleeding gives rise to a variation in the effective water binder ratio throughout the depth of the concrete and this produces corresponding changes in the concrete properties. Excessive bleeding could result in the formation of a laitance layer having a high water:binder ratio at the surface. This, in turn, could possibly lead to durability problems.

3.3 LITERATURE REVIEW ON THE EFFECTS OF SLAG ON FRESH CONCRETE PROPERTIES

3.3.1 Consistence

Meusel and Rose (1983) have reported that concrete containing ground granulated slag usually exhibits superior workability characteristics compared with portland cement concrete. Based on the work of Fulton, they argued that this could be attributed to the thixotropic nature of cement paste containing slags. The same authors, from the research work of Wu and Roy, reported that blastfurnace slag exhibited different rheological properties compared to paste of portland cement alone. Furthermore, the results indicate a better particle dispersion and higher fluidity of the pastes and mortars for the blastfurnace specimens Experiments performed by Meusel and Rose (1983) found that the slump of slag concrete was greater than identical portland cement concrete mixtures with typical increases being 30 mm or more. This is illustrated in Figure 3.1.

Grieve (1993) and Mehta (1983) reported similar findings. However, it was also reported by Grieve (1989) and Wainwright (1992) that the beneficial effect of slag on concrete workability is not that apparent especially when relating workability to the standard slump test results. This is because the slump test is a measure of consistence rather than the actual workability of the mix

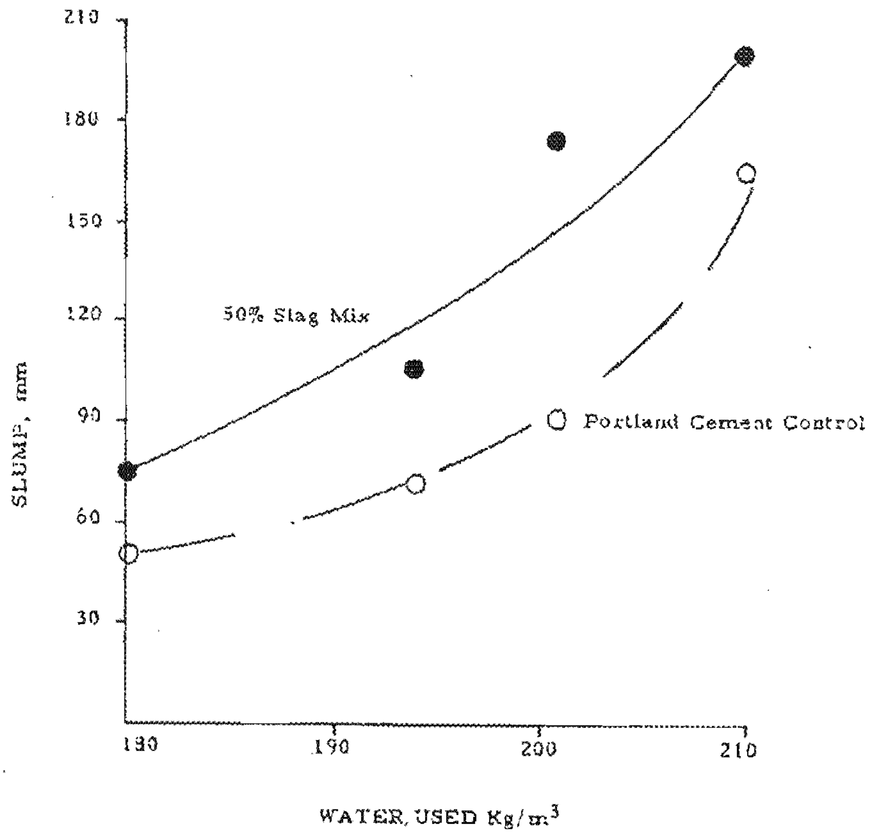

Fig. 3.1: Slump comparison of slag vs portland cement concrete (Meusel and Rose, 1983)

Another reason attributed to the better workability of slag concretes is due to the increased paste content of the concrete mixture when slag is replaced on an equal mass basis (Wainwright, 1986 and Malhotra, 1987). The increased workability of slag concretes is also associated with a reduction of water content or water reducing agent for similar cohesion, flow and compaction characteristics (Wainwright, 1986 and Nakamura et al, 1991).

Concerning the effect of slag fineness on workability, Meusel and Rose (1983) found that the higher the slag fineness the lower the measured slump. However, they concluded that this effect was only marginal (Fig. 3.2) and would be insignificant for slag fineness of 5200 ± 500 cm^2/g.

Olorunsogo (1997b) also found that increasing slag fineness resulted in no significant change in workability. However, in his research, based on 70% replacement level, he observed that higher slag fineness marginally increased the flow diameters. An increase in the percentage of voids was also recorded which normally should result in lower workability. The researcher then concluded that it was possible for the slag grains to act as a kind of lubricant but this effect was masked by the increasing fineness and voidage, hence resulting in no apparent change in workability.

Nakamura et al (1991) discovered that slag having finenesses of 450 and 790 m^2/kg required the same level of water reducing agent while for ultra fine slag (1160 m^2/kg), the dosage had to be increased by 20 to 30 %.

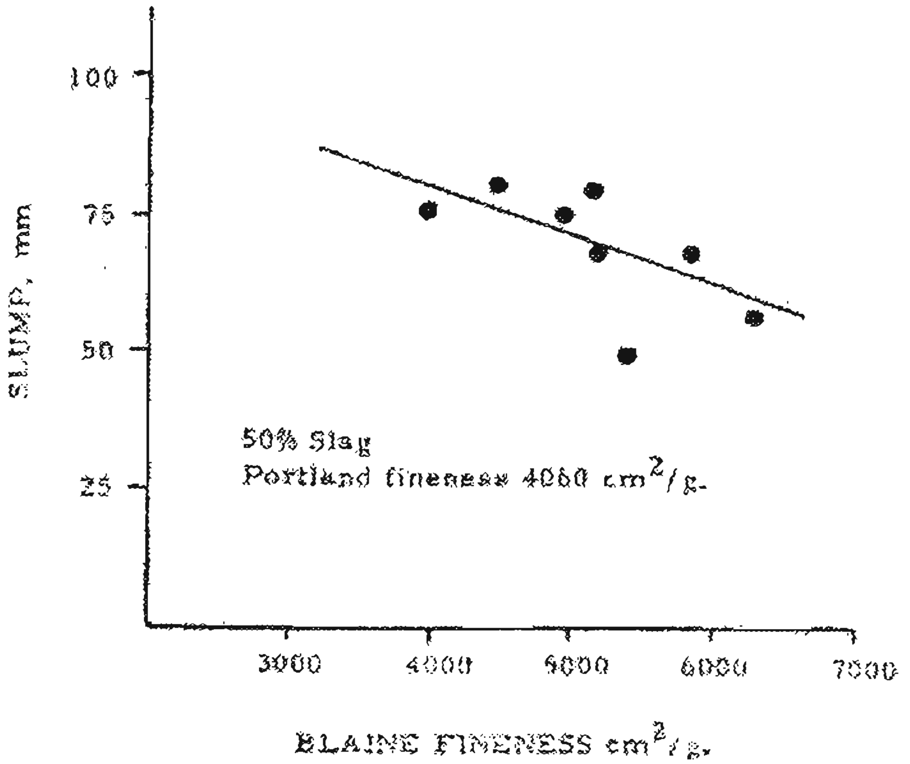

Fig. 3.2: Effect of slag fineness on workability of concrete (Meusel and Rose, 1983)

For the effect of different blends on workability, Meusel and Rose (1983) noted that the slumps tend to slightly increase with an increase in the slag replacement level. This was also observed by Osborne (1989) who showed that the water:binder ratio had to be reduced as the replacement level of slag was increased to maintain similar workability to the concrete mix without any slag. However, at low water:binder ratios (below 0 3), Sivasundaram and Malhotra (1992) found that the workability of high-volume slag concretes decreases substantially.

3.3.2 Setting Times

It is a well-documented fact that the use of slag in concrete results in an increase in the setting time (Grieve, 1987, 1989 and Malhotra, 1987). This is because the initial rate of reaction between slag and water is slower than that of cement and water (Wainwright, 1986). Experiments performed by Woodrow, at various temperatures and with slag replacement levels of 0 and 50%, indicated that low temperatures (5 °C) lead to a marginal increase in setting time of the slag specimen but no major difference was observed at higher temperatures (15 & 25 °C) (Wainwright, 1986). Malhotra (1987) reported similar findings

Sivasundaram and Malhotra (1992) found that the setting times of slag and control mixes were generally close at similar binder contents. However, the difference between the initial and final set was less for the control concretes. Nakamura et al (1991) observed that the higher the replacement level of slag, the greater the initial and final setting times. However regarding the effect of slag fineness, they found that high fineness slag had a less significant effect on setting time.

3.3.3 Bleeding

The bleeding characteristics of concrete containing slag are influenced by many factors including the physical properties of the binder, water:binder ratio and replacement level

Olorunsogo (1997b) performed bleeding experiments on slag having different fineness and noted that increasing the fineness from 432 to 750 m^2/kg resulted in reductions of 74 % and 43 % in bleeding rate and capacity respectively. This is illustrated in Figure 3.3. Bleeding capacity refers to the amount of water which can rise to the surface and, in this case, is expressed as a percentage of the total mix water

Bensted and Bye, as quoted by Olorunsogo (1997b), attributed the results to finer particles requiring more water for both physical and chemical reasons. The physical reasons relate to the initial wetting of the surface of the particles, and the chemical reason refer to the greater demand for water for early hydration for larger surface areas. Nakamura et al (1991) also found that high fineness slag produced lower bleeding rates and observed that no bleeding occurred for a mix having a slag fineness of 1160 m^2/kg and a water:binder ratio of 0.4

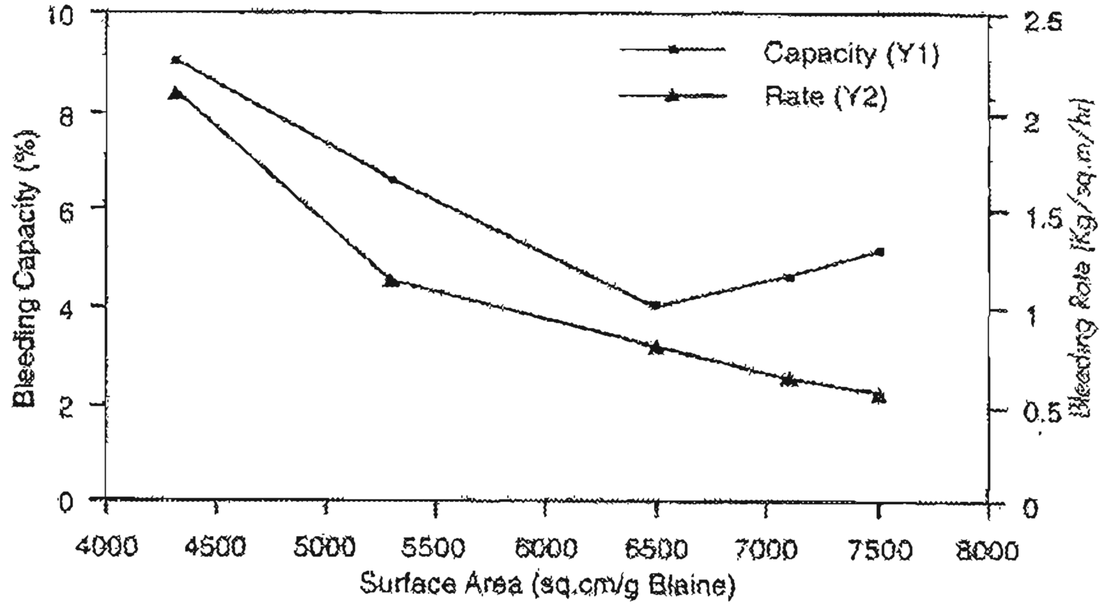

Fig. 3.3: Effect of slag fineness on bleeding (Olorunsogo, 1997b)

Using American and Canadian slags, Malhotra (1987) reached similar conclusions about the effect of the fineness of slag on bleeding, and reported that bleeding of concrete is governed by the ratio of the surface area of the binder to the volume of water. From cements of different fineness, Neville (1975) and Powers (1968) arrived at identical conclusions.

Based on South African research, Grieve (1993) reported that the use of slag in concrete results in higher bleed rate and capacity but attributed it to the relative coarseness of the material. The results, however, refer to the local blastfurnace slag which has been used in South Africa for several decades.

Another factor affecting the bleeding characteristic of slag concrete is replacement level. Wainwright and Ait-Aider (1995) observed that replacing portland cement with slag resulted in an increase in bleeding rate, capacity and time and this was more significant at higher replacement levels (Fig. 3.4).

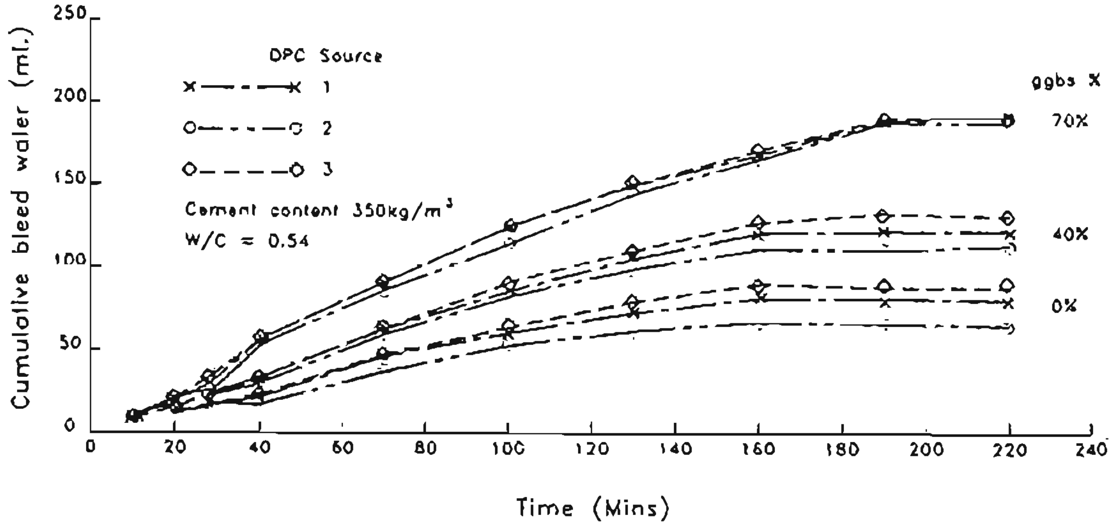

Fig. 3.4: Effect of replacement level on bleeding (Wainwright and Ait-Aider, 1995)

This observation was explained by the fact that slag reacts slower than portland cement and the reactivity is further diminished as the percentage of slag is increased. The extended bleeding time is significant because of delay in the formation of hydration products which help to physically restrict the movement of water to the surface (Wainwright, 1986). Similar effects of replacement level on bleeding were reported by Nakamura et al (1991), Grieve (1987) and Mehta (1983).

Concerning the effect of water:binder ratio on bleeding, Olorunsogo (1997a) reported, based on the works of Powers and Steinour, that at higher water:binder ratios, the average distance between the particles increases hence leading to a lower number of points of near-contact and weaker cohesive attractive forces. Consequently, the settlement potential is increased, thus resulting in higher bleeding rate and volume.

In summary, the literature indicates that the use of slag increases slightly the consistence of concrete. The setting time of slag concrete is also increased, with the effect being greater at higher replacement level. On the other hand, the bleeding of concrete is decreased with the use of finely ground slag as an extender.

3.4 TEST METHODS

3.4.1 Consistence

The standard slump test was performed in order to determine the consistence of the concrete. This was done according to SABS 862-1:1994. A modified lignosulphonate plasticizer was added to the mix if the slump value was less than 50 mm. The initial and final slump values were both recorded and are referred to as the values before and after the addition of the plasticizer. The maximum dosage of the plasticizer was 0.35 % by mass of the binder. For each mix, one slump test was performed and the slump reading was taken to the nearest 5 mm

3.4.2 Setting Times

The setting times of the different slag blends in paste form were determined in accordance with SABS-EN 196-3.1994. The Vicat apparatus was used to find the setting time of the paste (Fig. 3.5).

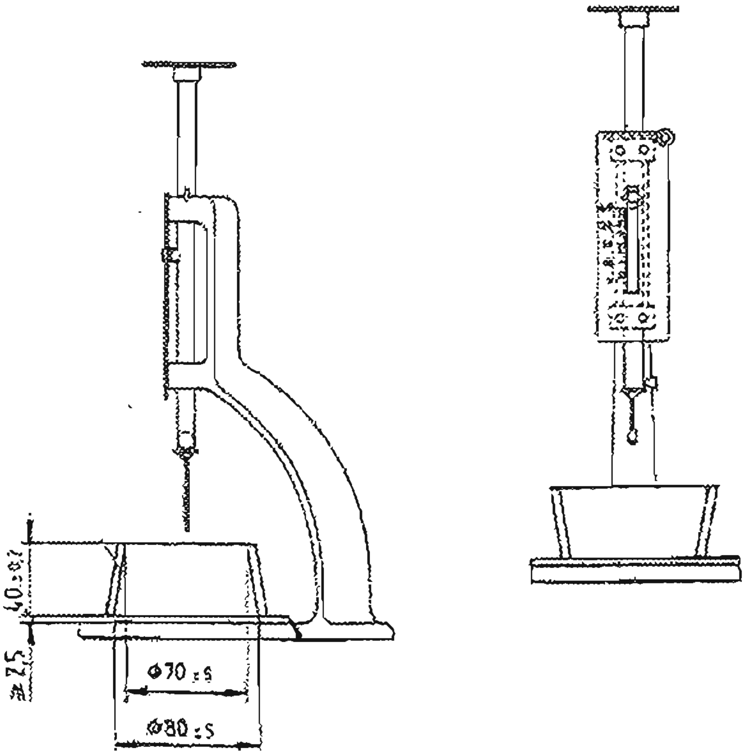

Fig 3.5: Vicat apparatus for determining setting time of cement

The setting time is determined by observing the penetration of a needle into cement paste of standard consistence until it reaches a specified value. In order to produce paste of standard consistency, different water contents were used until one was found to produce a distance between the plunger and base plate of 6 ± 1 mm. One setting time test was performed for each mix.

3.4.3 Bleeding

A modified version of the ASTM standard C 232-92 was used to determine the bleeding potential of concrete. In the experiment, a rigid steel cylindrical container having an inside diameter of 155 mm and an inside height of 165 mm was used instead of the prescribed container (inside diameter of 254 ± 6.4 mm and inside height of 279 ± 6.4 mm). It was decided to take the measurements at 30-minute intervals throughout the period of bleeding and a pipette was used to draw off the bleed water. The bleed cylinders were kept at a constant temperature of 22 ± 1 °C and were covered to prevent evaporation. One bleeding experiment was performed for each mix.

3.5 RESULTS AND DISCUSSION

3.5.1 Consistence

The slump results are given in Table 3 1 For all the results for the fresh concretes, CEM I, BS and CS refer to CEM I cement, blastfurnace slag and corex slag respectively and the percentage refers to amount of the material in the specific mix

Table 3.1: Slump of mixes (water content of all mixes = 180 l/m^3)

Mix	Initial Slump (mm)	Final Slump (mm)	% of plasticizer
W/B = 0.4			
100% CEM I	20	30	0.35
30% BS	15	90	0.35
50% BS	20	60	0.35
70% BS	20	65	0.35
30% CS	15	50	0.27
50% CS	15	35	0.35
70% CS	15	40	0.25
W/B = 0.6			
100% CEM I	50		
30% BS	65		
50% BS	65		
70% BS	60		
30% CS	80		
50% CS	75		
70% CS	60		
W/B = 0.8			
100% CEM I	50		
30% BS	60		
50% BS	50		
70% BS	100		
30% CS	60		
50% CS	65		
70% CS	65		

From the above results, it can be seen that plasticizer was added only to the mixes having a water:binder ratio of 0.4, since for water:binder ratios of 0.6 and 0.8 the slump values were 50 mm and above. For the lowest water:binder ratio considered, the initial slump values were all around 20 mm. However, an increase of the water:binder ratio to 0.6 had a significant increase in the slump values but no further change was observed at a water:binder ratio of 0.8. In the case of the water:binder ratios of 0.6 and 0.8, it can be observed, from the slump values, that the slag mixes had better consistence than the corresponding CEM I mixes. However, the slump values were only about 10-15 mm greater than the CEM I mixes, and not 30 mm as claimed by Meusel and Rose (1983). In this case, the slight increase in slump can be attributed to the greater paste content associated with slag concretes as the other components such as stone and water were kept fixed.

Concerning the effect of slag fineness on consistence, no apparent negative effect was observed even though corex slag is a finer material than blastfurnace slag. This is in accordance with published data which showed that slags having finenesses of ~500 m^2/kg have no significant effect on the consistence of concrete Also when the slag replacement level was increased from 30 to 70 %, there was no visible improvement in slump values. However, it must be borne in mind that the slump test is only a reflection of the consistence of concrete. It is well known that slag improves the concrete workability, and hence the ease of placing and compacting.

3.5.2 Setting Times

The initial and final setting times are given in Table 3.2 and also shown diagrammatically in Figure 3.6.

Table 3 2: Setting times of pastes

Mix	Initial Set	Final Set
	Min	Min
CEM I	170	255
30% BS	220	315
50% BS	230	405
70% BS	245	440
30% CS	240	325
50% CS	270	355
70% CS	265	420

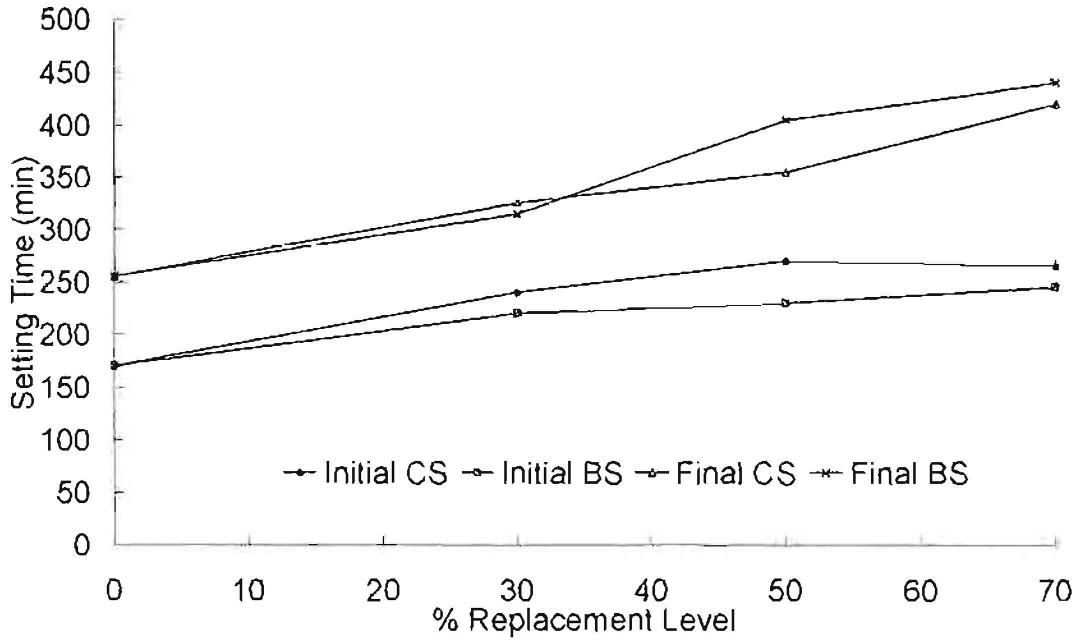

Fig. 3.6: Effect of replacement level on setting time

It can be noted that the control mix had the lowest setting times When comparing the results for corex and blastfurnace slags it can be observed that corex slag had slightly longer initial setting times but shorter final set times for most replacement levels.

Also, the higher the slag replacement levels, the longer the setting times. Figure 3.6 shows that the initial setting time increases with slag replacement level up to about 30 %. However, for higher blastfurnace and corex slag substitution rates, the initial setting time appeared to be independent of the replacement level. The final setting time, on the other hand, seemed to be proportional to the replacement level. Furthermore, the time lag between the initial and final setting was shorter for the control mixes than the slag mixes, as also observed by Sivasundaram and Malhotra (1992). Also the time lag increased with increasing replacement level.

The fact that slag mixes had prolonged setting times can be attributed to a slower rate of reaction between slag and water. As the replacement level increases, the rate of reaction decreases further, hence giving even longer setting times. This is because at early ages, it is the amount of cement available which is the critical factor controlling the reaction rate, and at higher replacement level, the dilution effect is greater. The longer initial setting times of corex slag could possibly be attributed to a long inactivity period. However, the shorter final set time of corex slag concrete is most probably due to its higher fineness resulting in a greater rate of reaction.

3.5.3 Bleeding

The bleeding results are given in Figures 3.7 to 3.9 while Table 3.3 gives the bleed volume as a percentage of the original mix water for the different mixes. The detailed bleed data are given in *Appendix B*.

It can be observed from the figures that the bleed rate and total bleed volume of the slag mixes were less than the corresponding control mixes. For water:binder ratios of 0.4 and 0.6, the blastfurnace slag mixes produced greater bleed volumes than the corresponding corex slag mixes but, for a water:binder ratio of 0.8 an inverse trend was observed. A greater bleed time can also be expected, especially at water:binder ratio of 0.4. From the graphs and Table 3.3, it can be noted that, generally, an increase in the replacement level results in a greater bleed volume, especially at lower water:binder ratios. From Figure 3.10, it can be noted that, at higher water:binder ratios, the percentage of bleed volume is almost independent of the slag replacement level in the range of 30 to 70 %. This can be directly related to the similar effect of substitution rate on the initial setting time.

The main reason for the extended bleeding time of concrete containing slag is due to the longer setting time of the material as discussed previously. This delays the formation of hydration products which help to prevent the upward migration of the water. The higher the slag replacement level, the longer the delay.

Furthermore, the fact that slag concretes produced less bleed volumes than CEM I concretes can be attributed to their fineness. Being finer, the slag particles required more water for the initial wetting of their surface and for early hydration purposes (Olorunsogo, 1997b). The same reasons apply for the superior bleeding characteristics of corex slag compared to blastfurnace slag and reductions of up to 33 % in bleed volume were observed.

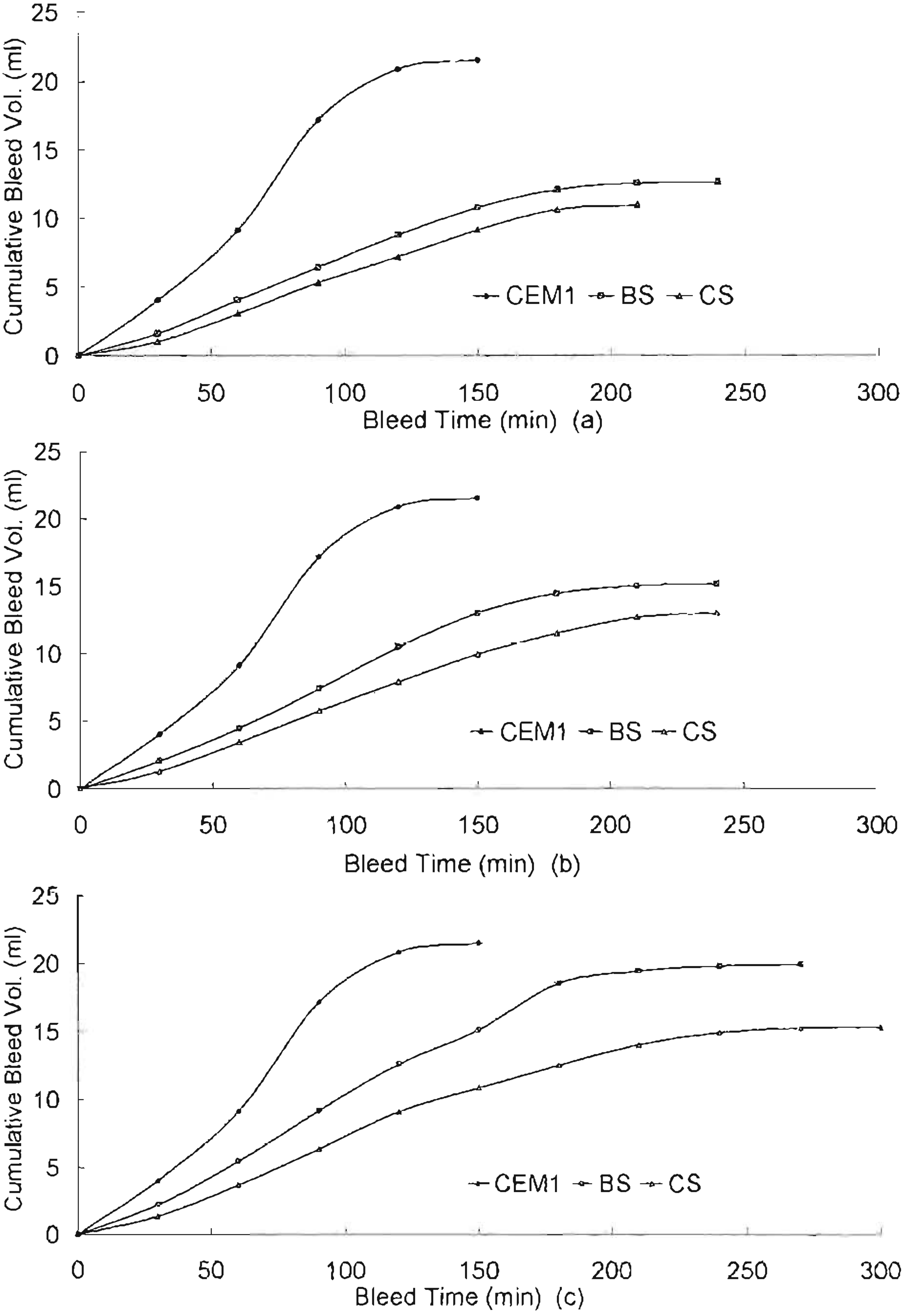

Fig. 3.7: Bleeding characteristics for concrete having water:binder ratio of 0.4 and slag replacement levels of (a) 30 % (b) 50 % (c) 70 %

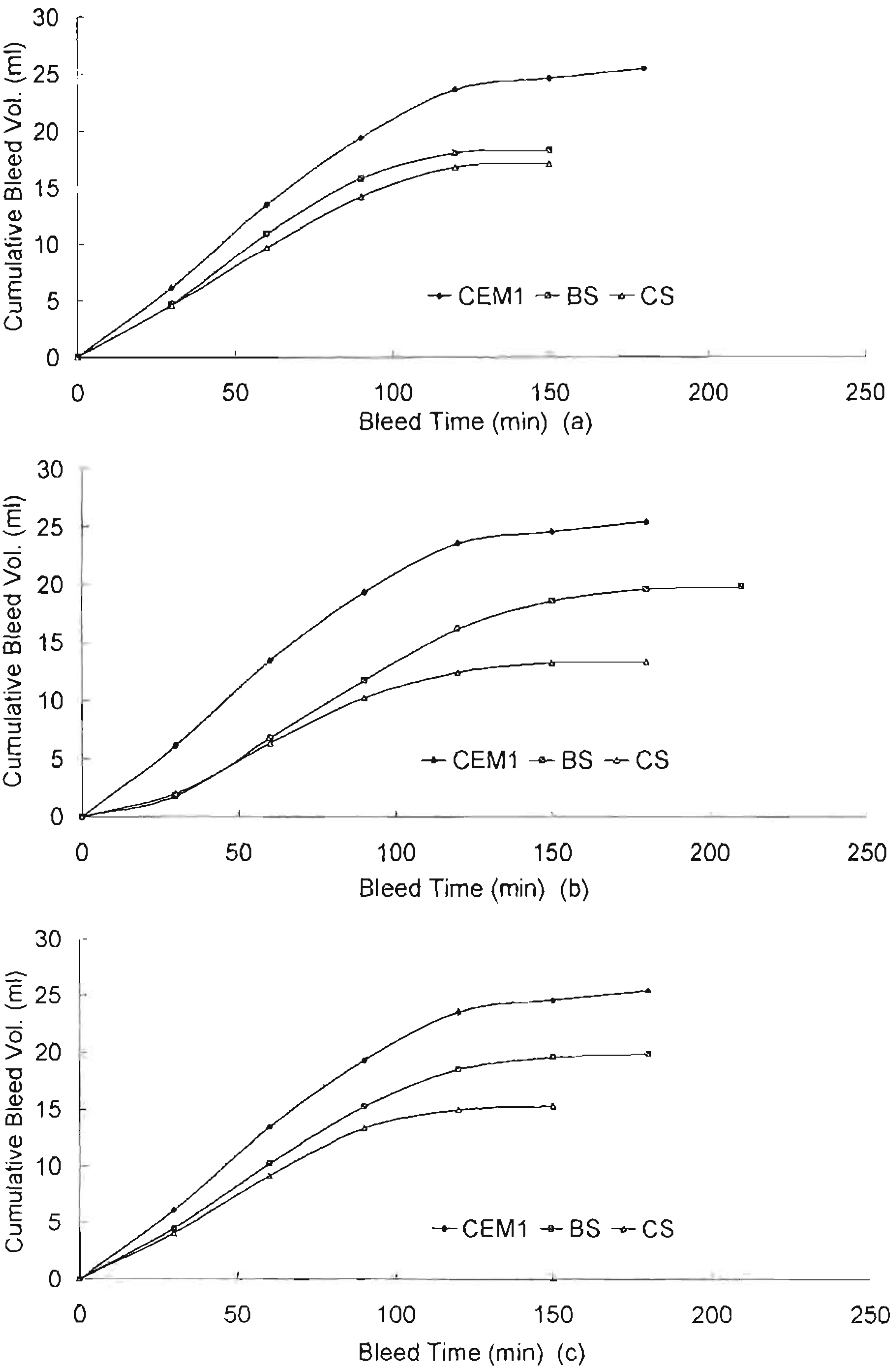

Fig. 3.8: Bleeding characteristics for concrete having water:binder ratio of 0.6 and slag replacement level of (a) 30 % (b) 50 % (c) 70 %

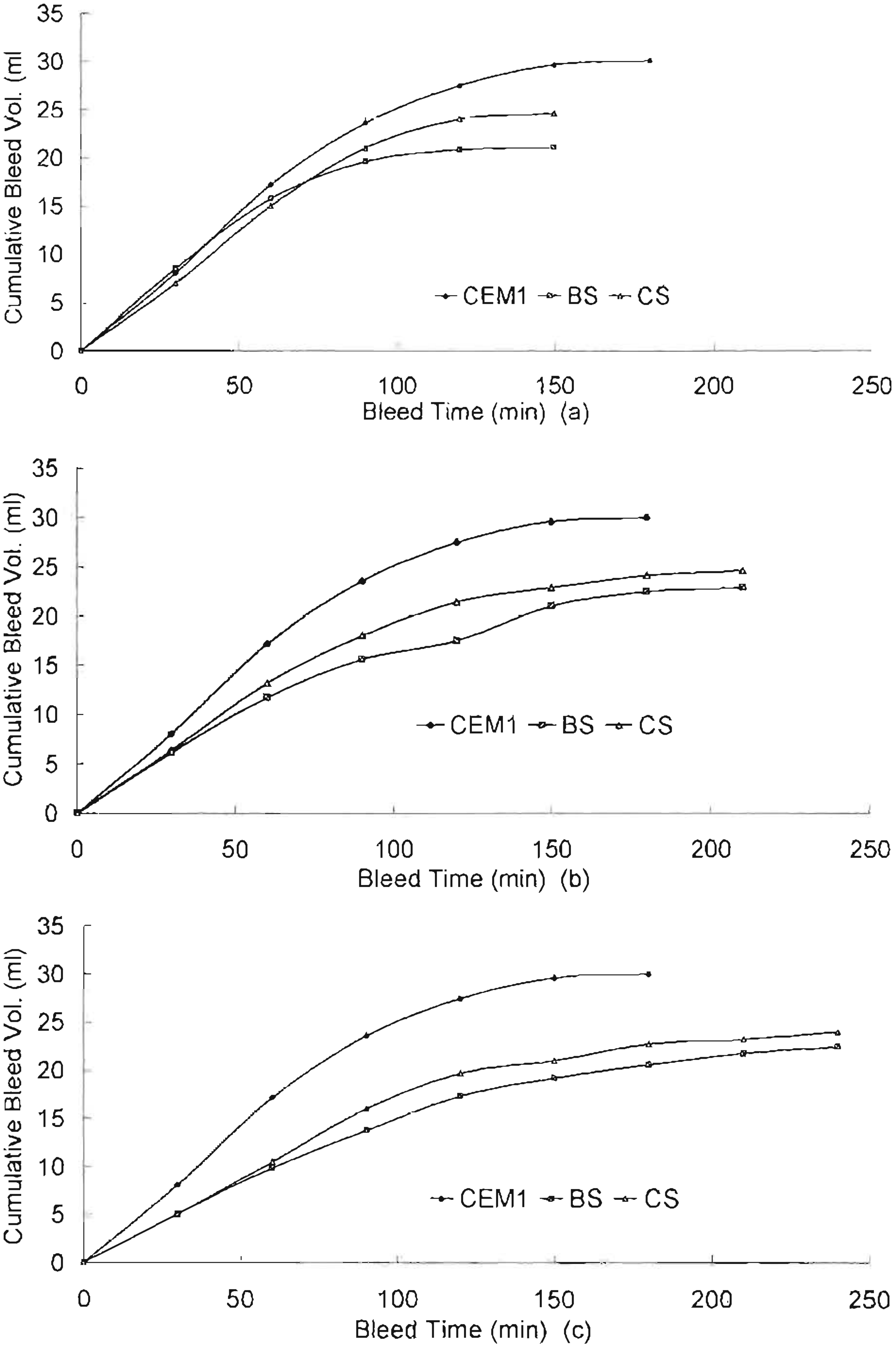

Fig. 3 9: Bleeding characteristics for concrete having water binder ratio of 0.8 and slag replacement level of (a) 30 % (b) 50 % (c) 70 %

Table 3.3: Total bleed volume expressed as percentage of bleed water

Mixes	Bleed vol. as % of original mix water
Water:Binder = 0.4	
100% CEM I	4.2
30% BS	2.5
50% BS	3.0
70% BS	3.9
30% CS	2.2
50% CS	2.6
70% CS	3.0
Water/Binder = 0.6	
100% CEM I	5.0
30% BS	3.6
50% BS	3.9
70% BS	3.9
30% CS	3.4
50% CS	2.6
70% CS	3.0
Water/Binder = 0.8	
100% CEM I	5.9
30% BS	4.1
50% BS	4.5
70% BS	4.4
30% CS	4.8
50% CS	4.8
70% CS	4.7

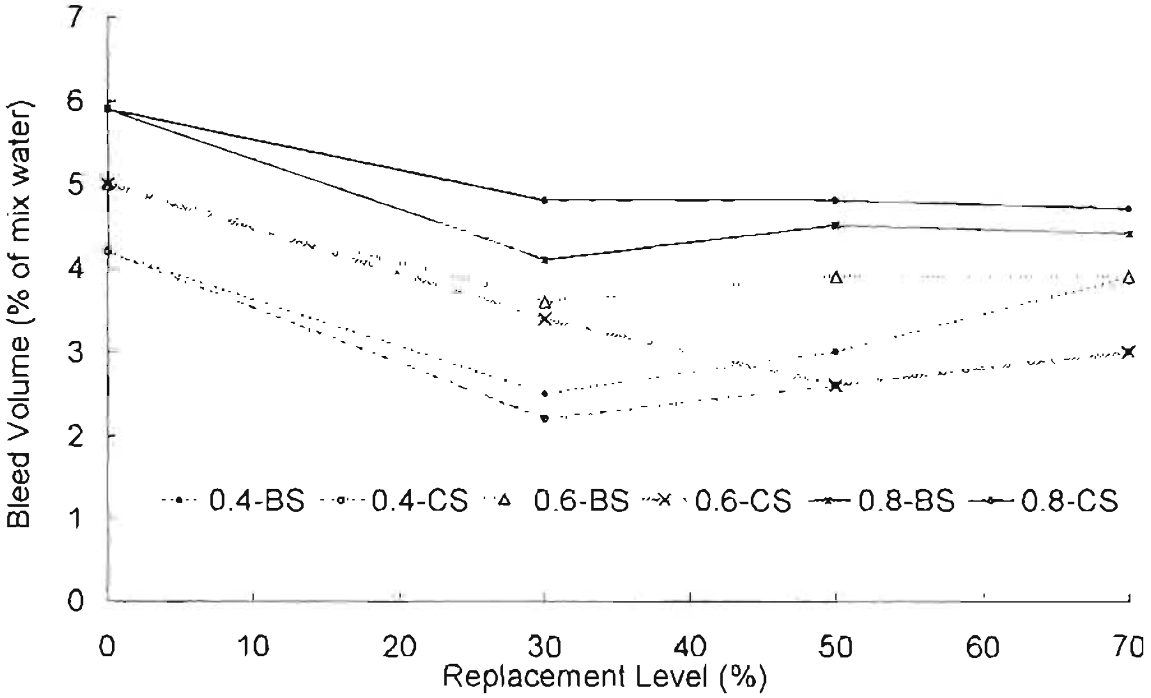

Fig. 3.10: Effect of replacement level on bleed volume

At a water:binder ratio of 0.8, however, the reverse trend for corex slag can be explained possibly by its smaller average particle size. This has the effect of increasing the inter-particle distance, thus leading to smaller cohesive forces. As a result, higher bleeding rates and volumes are obtained.

In this research, the bleeding trends for slag concretes were different from the ones observed by Grieve (1993) and Wainwright and Ait-Aider (1995). This is probably because different slag finenesses were used in the various experimental works.

3.6 CONCLUSIONS

After investigating the consistence, setting times and bleeding properties of slag concretes, the following conclusions can be drawn.

- The use of slag in concrete results in slightly higher concrete consistence, with the slump values for slag concretes generally 10-15 mm greater than CEM I controls Blastfurnace slag marginally out-performed corex slag.
- The effect of replacement level on concrete consistence was not visible, since mixes with 30 and 70 % substitution rates had almost similar slump values. This was the case for both corex and blastfurnace slag mixes. The increased fineness of corex slag was also found not to be a detrimental factor in respect of concrete consistence.
- Slag pastes, in general, led to an extension in the setting times, with the increase ranging between 50-100 minutes for the initial set and 60-185 minutes for the final set. The final set time was lower for corex slag than for blastfurnace slag. CEM I controls had the shortest setting times
- Generally, the higher the slag replacement level, the longer the setting time. For substitution rates of between 30 and 70 %, the initial setting time appeared to be independent of the replacement level.
- The bleed volume is significantly reduced when slag is added to concrete, with corex and blastfurnace slags causing reductions of up to 50 and 40 % respectively Corex slag was found to have lower bleeding properties.
- The higher the replacement level, the greater the amount of bleed water, especially at low water:binder ratios. However, at higher water:binder ratios, the bleed volume was almost independent of replacement level.

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CHAPTER 4

COMPRESSIVE STRENGTH AND ELASTIC MODULUS OF COREX SLAG CONCRETE

The compressive strength of concrete is traditionally the property which is most commonly specified in design. This is because the overall safety and stability, which are the first requirements for any structure, are crucially affected by the compressive strength. Also, the strength of concrete can be easily determined compared to other properties. Compressive strength is still regarded by many engineers as the most important property of hardened concrete. Furthermore, the compressive strength of concrete is related to other properties such as elastic modulus, and therefore they are discussed together in this chapter. This relationship has been reported by many authors, including Neville (1975) and Mehta and Monteiro (1993).

Being a new product, a wide range of compressive strength data of corex slag concrete is required by engineers. In this research the effects of water:binder ratio and slag replacement level on strength development were investigated. Moreover, the impact of corex slag on the elastic modulus of concrete was also studied.

A qualitative analysis of the effect of slag, in general, on the interfacial transition zone is also provided.

4.1 EFFECT OF SLAG ON THE INTERFACIAL TRANSITION ZONE

The interfacial transition zone (ITZ) between coarse aggregate and cement paste influences many concrete properties, including permeability, durability and strength (Mehta and Monteiro, 1988). The formation of the ITZ is mainly due to the creation of water-filled spaces around aggregates in fresh concrete and during the initial hydration period (Lagerblad and Kjellsen, 1999). The ITZ is characterised by a weaker and more porous zone having a higher water:binder ratio than the bulk of the paste. The complex structure of the ITZ is governed by hydration, nucleation and precipitation phenomena.

According to Bentur and Odler (1996), the high water:binder ratio in the ITZ is due to the effects of bleeding as well as to the so-called wall effect. The wall effect, in turn, prevents the proper filling of the space close to the aggregate with cement grains having a size of 10 μm or more, resulting in the hydration products less effectively filling the spaces.

The influence of slag on the interfacial transition zone is mainly through its impact on the bleeding characteristic of concrete. Moreover, being finer than the cement grains in many cases, slag also has a microfiller effect thereby improving the packing efficiency of the binder particles against aggregate grains and densifying the ITZ (Lagerblad and Kjellsen, 1999).

Experiments performed by Kobayashi et al (1998) showed that the hardness of the ITZ in mixtures containing blastfurnace slag was higher than that in plain cement mixes. This was attributed by Monteiro et al, as quoted by Kobayashi et al (1998), to the fact that slag consumes calcium hydroxide through hydration and fills the large pores in the ITZ with hydrates. It was also found in the same experiments that slag having higher specific area resulted in a narrower ITZ of greater hardness, even though the hardness of the bulk region was the same.

The properties of the ITZ are also enhanced by an increase in the replacement level of slag. Mehta and Monteiro (1988) and Detwiler et al (1987) observed that a 30 % replacement level of slag was quite effective in reducing the thickness of the transition zone as compared to a 10 % level of replacement. This improvement was due essentially to the nucleation of randomly oriented calcium hydroxide crystals on the fine slag particles as 30 % slag is not enough to combine with all of the calcium hydroxide present. On the other hand, Nilsen et al (1992) deduced that the addition of 30 % of slag had no major effect on the thickness of the transition zone.

4.2 EFFECT OF SLAG ON COMPRESSIVE STRENGTH

4.2.1 Fineness

Experiments performed by Nakamura et al (1991) on concrete with blastfurnace slag having finenesses between 450 and 1160 m^2/kg (Blaine) have shown that the higher the fineness of the extender the greater the compressive strength. This is illustrated in Figure 4.1. The high fineness of slag played an important role in the high early compressive strength of the concrete and for a water:binder ratio of 0.4 and a slag fineness of 1160 m^2/kg, the 3-day strength was almost equal to that of plain concrete.

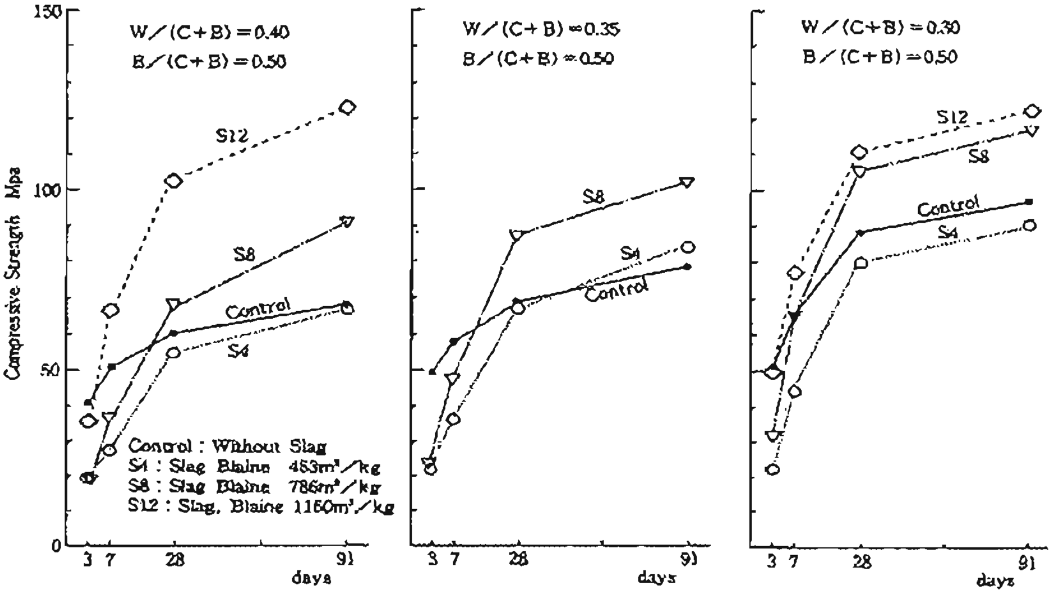


Fig. 4.1: Effect of slag fineness on compressive strength (Nakamura et al, 1991)

Madej et al (1995) also observed similar compressive strength characteristics for mortars incorporating blastfurnace slags of different fineness. The slag replacement level of the mortars was 40 % and finenesses of 400 (S4), 800 (S8) and 1500 (S15) m^2/kg were investigated (Fig. 4.2). The researchers argued that using suitable mix proportions and curing conditions, very finely ground blastfurnace slag could be used to make high-performance concrete since it is a highly efficient material, especially regarding compressive strength. This is because a decrease in the volume of micropores occurs with hydration time hence leading to greater compressive strength.

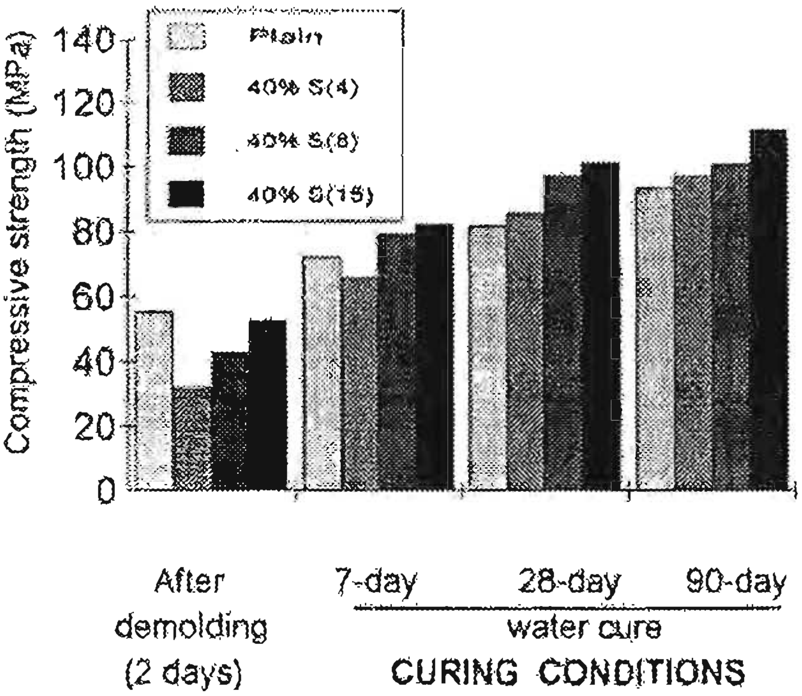


Fig. 4.2: Effect of fineness and curing on compressive strength (Madej et al, 1995)

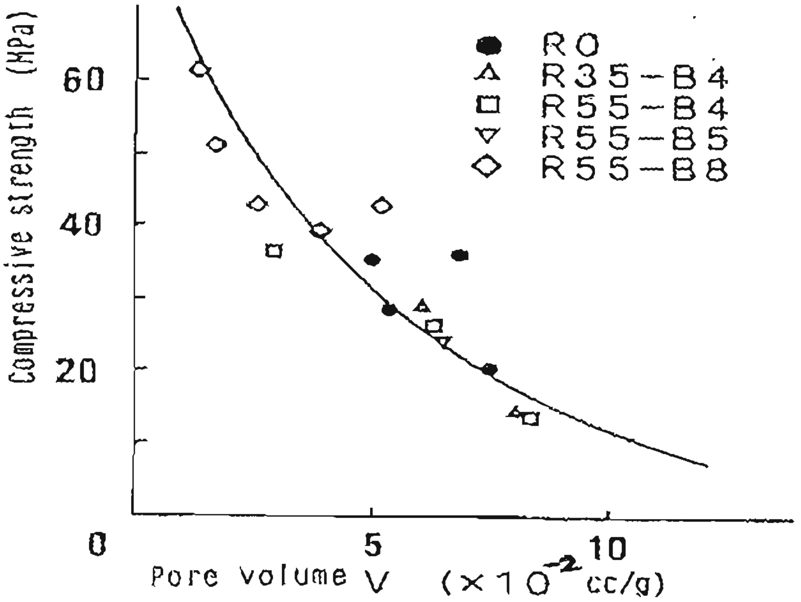


Fig 4.3: Relationship between strength and pore volume (Tazawa et al, 1989)

Tazawa et al (1989) showed that there is a trend indicating concrete containing finer slag results in smaller pore volume (Fig. 4.3). A slag replacement level of 55 % (R55) was used with finenesses of 440 (B4), 560 (B5) and 790 (B8) m^2/kg.

The effects of slag fineness on compressive strength discussed above are consistent with other studies which showed that finely ground slag had a higher activity (Tazawa et al, 1989, Tan and Pu, 1998, Douglas et al, 1990 and Olorunsogo, 1997).

4.2.2 Replacement Level and Strength Development

The effect of slag replacement level on the compressive strength of concrete has been investigated by many researchers. Generally, up to 75 % of slag is used in concrete. It has been found that the use of slag results in the suppression of the early strength of the concrete (Hwang and Lin, 1986, Alexander, 1994, Madej et al, 1995 and Lang and Geiseler, 1996). According to Swamy and Bouikni (1990) and Jolicoeur et al (1994), this is because the hydration of slag-cement blends is generally a two-stage process and the slag hydration tends to lag behind the hydration of portland cement. Consequently, the higher the replacement level of slag, the lower the early compressive strength of the concrete (Sivasundaram and Malhotra, 1992 and Mantel, 1994).

Clear (1994) pointed out that in the case of 70 % replacement level, an extended formwork striking time should be allowed such that the concrete can meet the required compressive strength prescribed by the codes. This was also reported by Grieve (1993) and Wainwright (1986).

Concerning the later- age strength development of slag concrete, many research works have shown that blastfurnace slag concrete continues to gain in strength with time compared to portland cement concrete. Wainwright (1986) argued that slag cement concrete required a higher binder content in order to achieve the same 28-day strength as portland cement concrete. However, the compressive strength at one year will be significantly higher Meusel and Rose (1983), on the other hand, found that for a 50 % blend of granulated slag concrete, an equal strength was achieved with portland cement after 4-5 days, and after 7 days greater strengths were obtained. However, they pointed out that the slag fineness and glass content are important factors to consider when comparing the initial activity of different slags. Numata et al (1986), Douglas et al (1990) and Swamy and Bouikni (1990) came to similar conclusions.

The compressive strength of slag concrete is also significantly affected by the replacement level (Ellis and Wimpenny, 1989). Based on the work of Hogan and Meusel, Malhotra (1987) reported that later-age compressive strength of slag concrete increases with the replacement level up to an optimum value of 40 % (Fig. 4.4). For higher replacement level, lower strength is obtained. Nakamura et al (1986) also deduced an optimum substitution rate of about 40 % for slag concrete.

Nakamura et al (1991) found that at all substitution levels the early age strength was less than concrete with no slag but at 28 days, mixtures containing up to 50 % slag achieved similar compressive strength as the portland cement control. However, at 91 days, even concretes containing 70 % replacement level of slag were able to reach equal strength as portland cement concrete (Fig. 4.5).

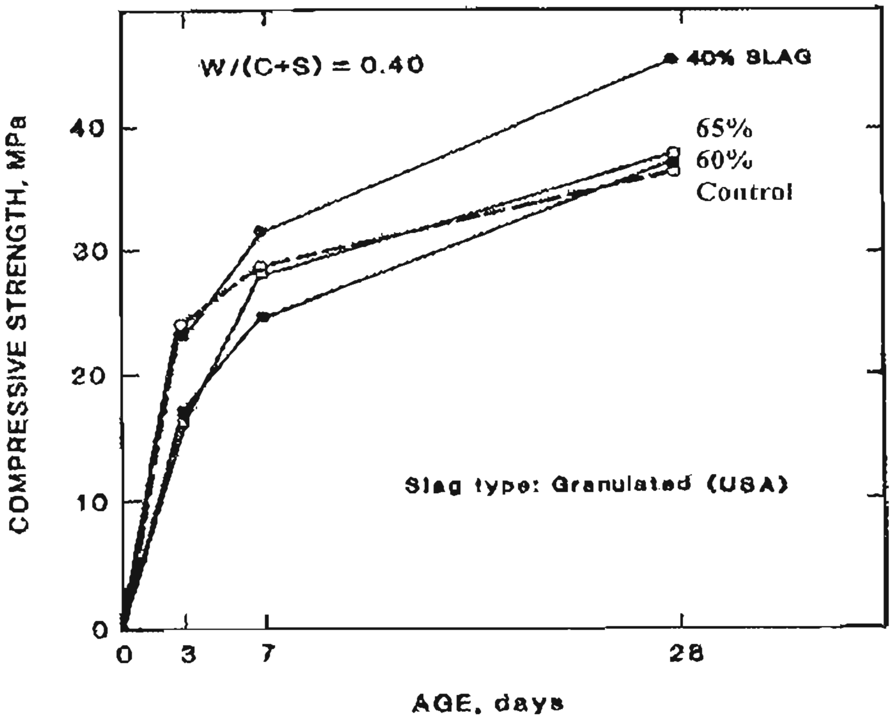


Fig 4.4: Effect of age and replacement level on compressive strength (Malhotra, 1987)

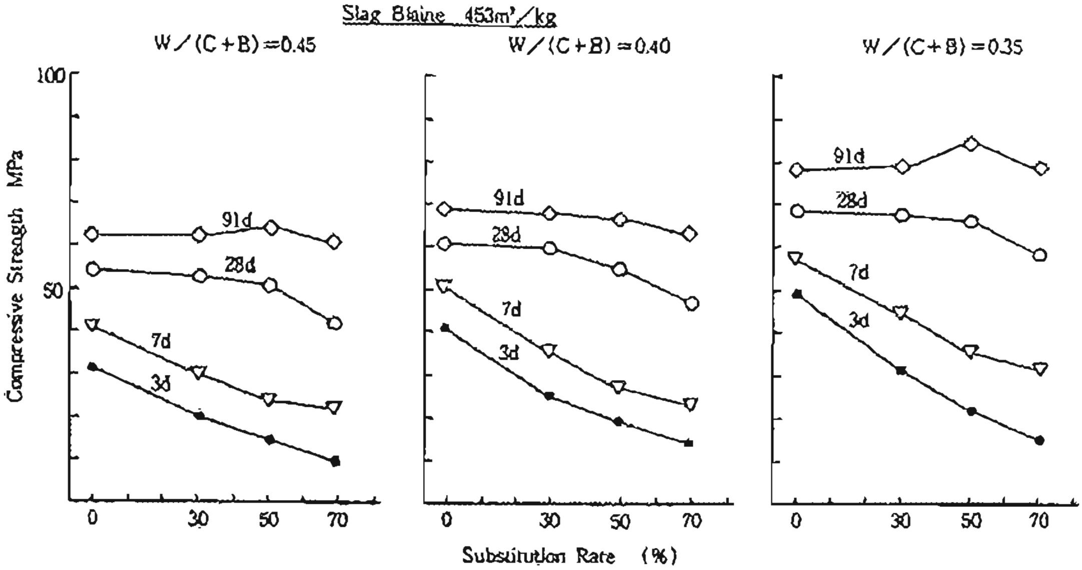


Fig. 4.5: Effect of curing period and substitution rate on strength (Nakamura et al, 1991)

Chern and Chan (1989), using slag replacement levels between 4.5 % and 68 %, showed that early rate of strength gain is inversely proportional to the slag content. This is illustrated in Figure 4.6. However, at later ages, there was an increase in strength for the 4.5 % and 35 % substitution level but concrete made with 68 % slag resulted in reduced strength at all ages. In this experiment, the optimum replacement level was 35 %. However, it should be borne in mind that not all slags are similar, and hence the optimum replacement level refers to the specific slag considered.

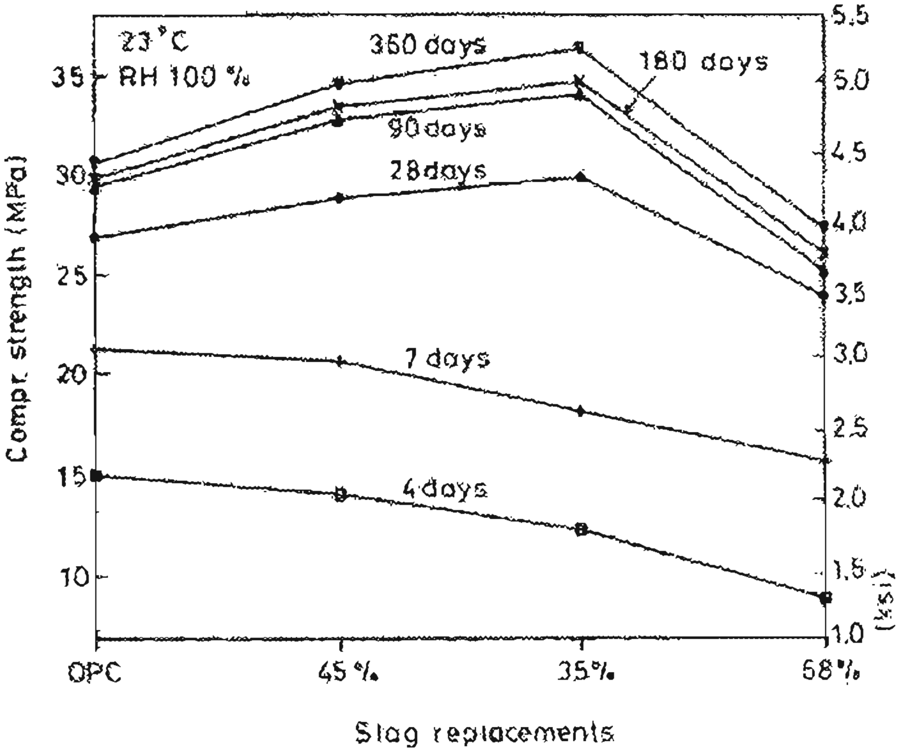


Fig. 4.6: Optimum slag replacement level (Chern and Chan, 1989) (Note: 45 % should read as 4.5 %)

4.3 EFFECT OF SLAG ON MODULUS OF ELASTICITY

Wainwright (1986) reported that slag concretes usually have a higher modulus of elasticity than portland cement controls of equal strength, with the difference being normally less than 6 GPa. This was also observed by Sivasundaram and Malhotra (1992) who performed tests on high volume slags. This was attributed to a change in the properties of the slag hydrates compared to the control concretes.

Wainwright and Tolloczko (1986) found that for Grade 45 concretes, there is virtually no difference in elastic modulus values between slag concretes and the controls. These researchers also found that for lower grade concretes, the addition of slag results in a slightly lower modulus than portland cement concretes. Nakamura et al (1986), Mak (2000) and Swamy and Bouikni (1990) also showed that there was no major difference between the elastic modulus of slag concretes and that of the controls.

Furthermore, Nakamura et al (1986) pointed out that the elastic modulus increases with compressive strength, but Chern and Chan (1989b) argue that this relationship only holds for results at early test ages

Based on South African research, Addis (1987) reported that there was almost no difference in modulus of elasticity between slag concretes and portland cement controls. Moreover, Alexander and Milne (1995), using aggregates from the Witwatersrand area of South Africa, showed that at very early ages (first 7 days) and for any given water:binder ratio the stiffness of slag concretes was lower than the corresponding portland cement controls However, over the period of 28 to 90 days, the rate of increase in elastic modulus for slag concretes was greater than for the controls. In the same study, it was found that, for a 50 % slag replacement level, the optimum water:binder ratio was about 0.5 with respect to the highest value of elastic modulus.

4.4 TEST METHODS

4.4.1 Compressive Strength

100 mm cubes were cast for compressive strength testing and were tested in accordance with SABS 863:1994. Concrete compressive strength was determined at ages of 3, 7, 14, 28 and 56 days after casting and curing in water at 23 °C. At 28 days, three cubes were tested, whereas at the other ages, two cubes were tested.

After completion of each test, the cubes were crushed into parts. The inner portions of the slag specimens revealed a characteristic bluish-green colour, with corex slag samples showing a darker colouration. After sufficient exposure to air, the colour disappeared. The colour is attributed to the presence of calcium sulphide in the slag which on oxidation causes the slow disappearance of the colour (Swamy and Bouikni, 1990). This is also reported by Malhotra (1987), Taylor (1992), Hwang and Lin (1986), ACI (1996) and St John et al (1998).

4.4.2 Elastic Modulus

Concrete prisms of 200 x 100 x 100 mm were tested according to the principles of BS 1881:Part 121:1983. The samples were fitted with a mechanical compressometer which had an LVDT mounted in it. This device transformed the displacement into a voltage which was used to produce a graph on an XY plotter. One-third of the ultimate load (based on the cube compressive strength) was applied and the corresponding displacements were recorded on the graph. The outputs were then used to determine the static elastic modulus of the specimens. The moduli of elasticity of the specimens were measured at 28 and 90 days after casting.

4.5 RESULTS

4.5.1 Compressive Strength

The compressive strength results for the mixes having a water:binder ratio of 0.4, 0.6 and 0.8 are shown in Figures 4.7 to 4.9 for slag replacement levels of 30 %, 50 % and 70 %. Refer to *Appendix C* for detailed results.

It can be observed that an increase in the water:binder ratio results in a decrease in the compressive strength of the mix (see Fig. 4.10). Furthermore, the compressive strength is also affected by an increase in the slag substitution level with the most significant effect being noticed at the 70 % replacement level. At the 70 % replacement level, the 3-day strength of blastfurnace slag concrete was up to 65% lower compared to the plain cement control concrete. The coefficient of variation of the samples tested at 28 days varied between 1 and 5 %, and the range/mean ratio was less than 15 % as required by SABS 0100.

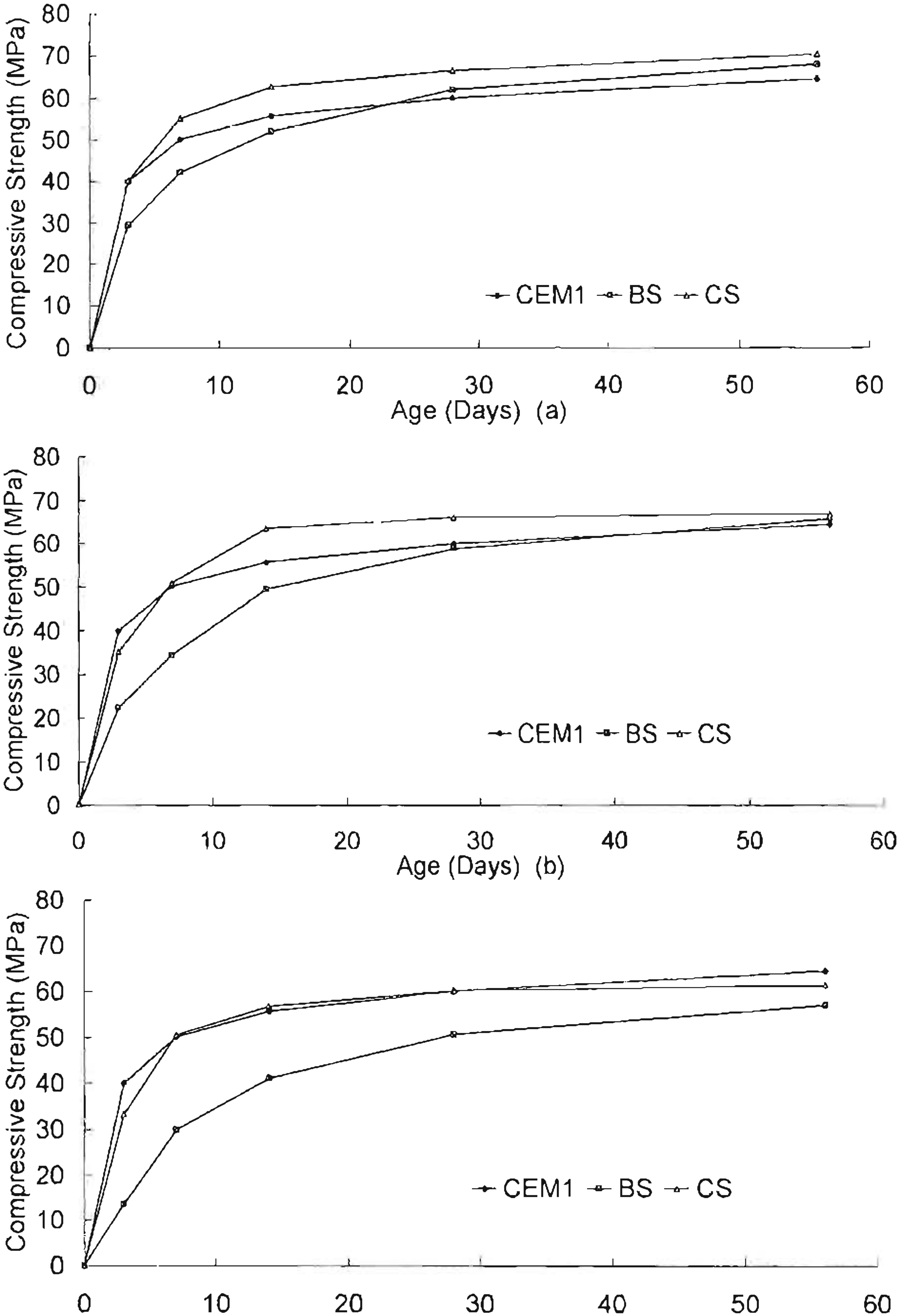


Fig. 4 7: Compressive strength of concrete having water:binder ratio of 0.4 and slag replacement level of (a) 30 % (b) 50 % (c) 70 %

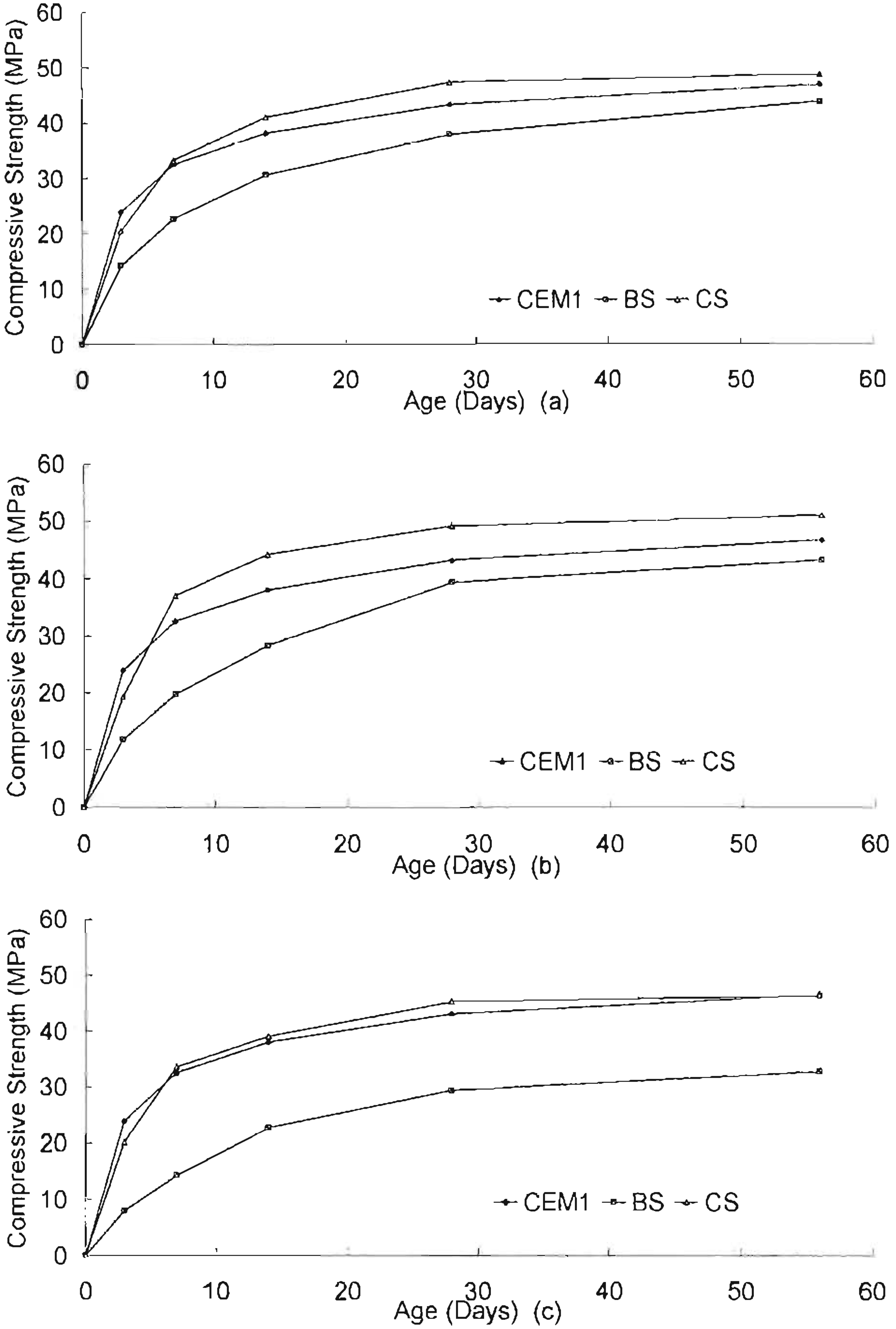
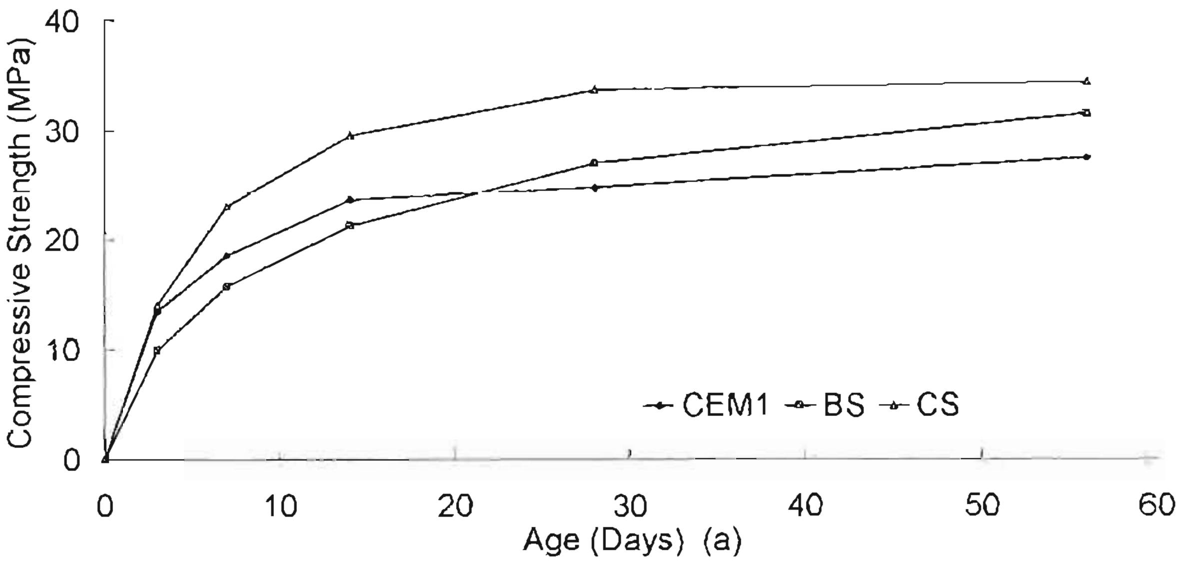
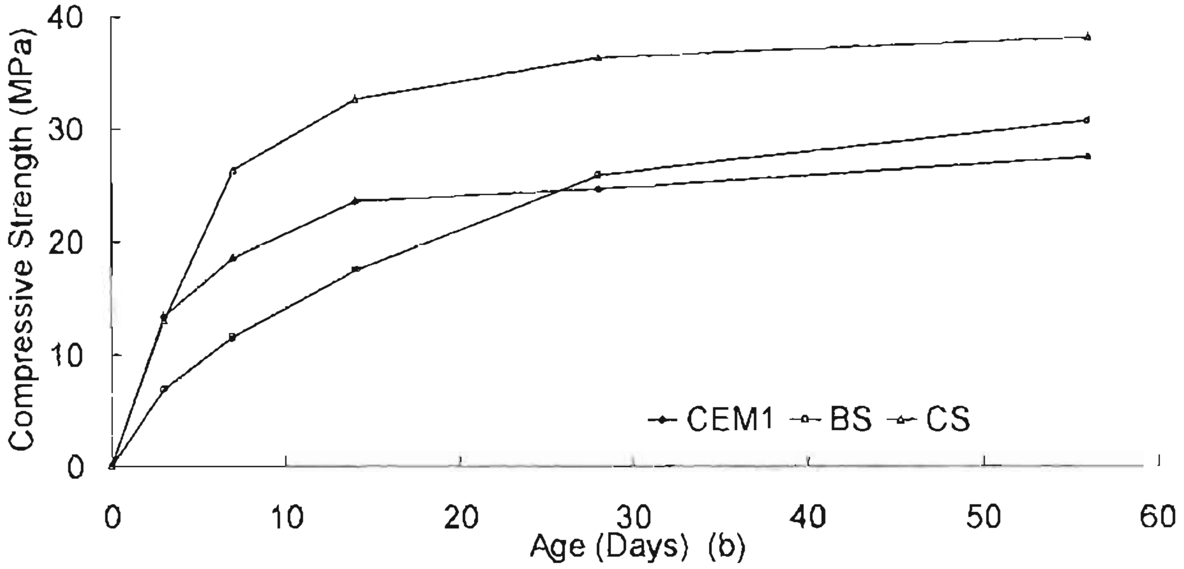


Fig. 4.8: Compressive strength of concrete having water:binder ratio of 0.6 and slag replacement level of (a) 30 % (b) 50 % (c) 70 %





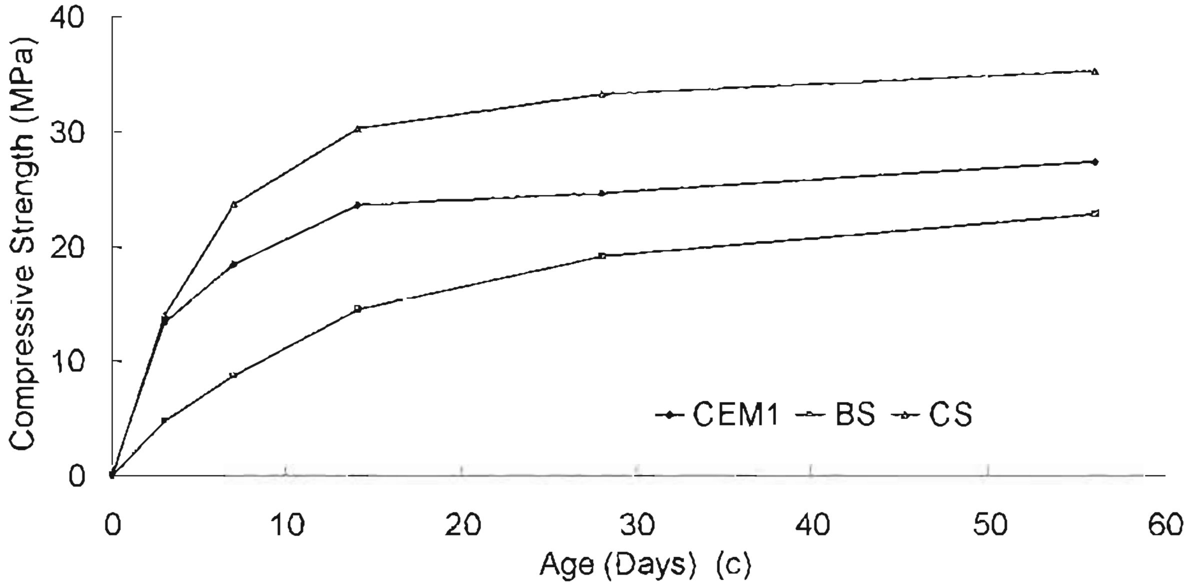


Fig. 4.9: Compressive strength of concrete having water:binder ratio of 0.8 and slag replacement level of (a) 30 % (b) 50 % (c) 70 %

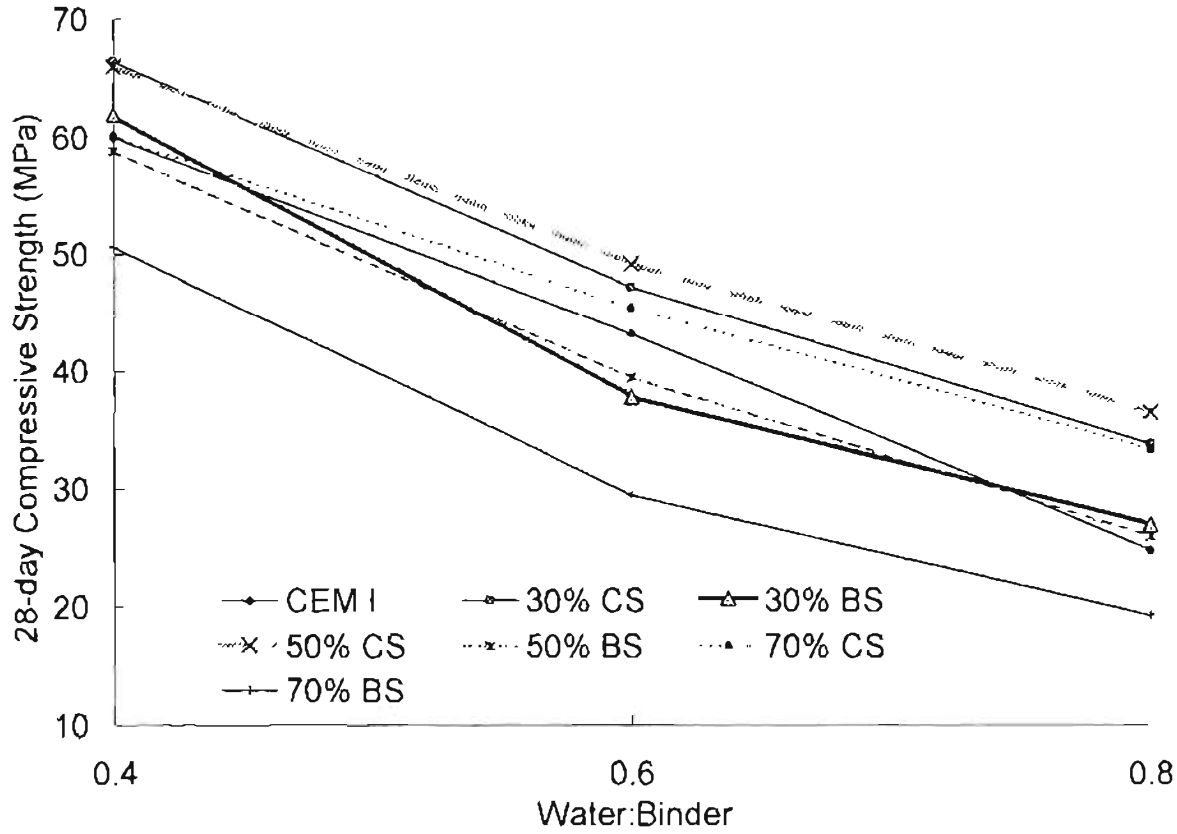


Fig. 4.10: Effect of water:binder ratio on 28-day compressive strength

On the other hand, corex slag concrete had almost the same early strength as the CEM I controls. However, it must be noted that the rate of strength gain for corex and CEM I concretes decreased significantly after 28 days while the blastfurnace slag samples continued to gain in strength. The one-year strength for blastfurnace slag concrete could even be higher than the other two materials.

4.5.2 Elastic Modulus

The static elastic modulus results of the mixes are given in Table 4.1. From the table, it can be observed that the elastic modulus for water:binder ratio of 0.4 and 0.5 were about the same at 41 GPa and 47 GPa respectively at both time intervals considered while the modulus of elasticity for the 0.6 water:binder ratio sample was lower by about 5 GPa at both ages.

At 28 days, blastfurnace slag had lower elastic modulus values than corex slag, but at 90 days, the values were similar. Furthermore, the 90-day elastic modulus values of CEM I concretes having water:binder ratios of 0.5 and 0.6 were lower than expected and it is believed that there is an instrumental error associated with the results. The coefficient of variation of the elastic modulus results varied between 1 and 6 % at both ages.

Table 4.1: Elastic modulus results (GPa)

Mix	**28-day**	**90-day**
	Water:Binder = 0.4	
CEM I	40.6	45.8
BS	38.4	47.2
CS	42.2	47.8
	Water:Binder = 0.5	
CEM I	41.9	41.0
BS	39.0	45.1
CS	41.2	46.9
	Water:Binder = 0.6	
CEM I	41.0	39.3
BS	34.1	42.4
CS	37.6	42.9

4.6 DISCUSSION

4.6.1 Compressive Strength

The high early compressive strength of corex slag concrete compared to blastfurnace slag concrete can probably be attributed to its higher fineness. This is because an increase in the surface area of the particles leads to an increase in reactivity (Olorunsogo, 1997) This would explain why the 3-day strength of corex slag concretes is about the same as the CEM I controls while blastfurnace slag concrete samples still lagged behind. The fact that corex slag concrete showed a higher rate of strength gain which then decreased rapidly with time is because most of the hydration processes, which are enhanced by the increasing surface area, are expected to have taken place at an early age (first 14 days).

The high compressive strength of corex slag concrete can also be partly attributed to a higher percentage of smaller sized particles (less than 10 μm), as small particles greatly contribute to the initial activity of the material. Moreover, the chemical composition of corex slag also impacts on the compressive strength, having greater percentages of CaO, MgO and Al_2O_3. The beneficial effects were argued in Chapter 2. As discussed previously, slag modifies the interfacial transition zone in concrete and the use of the finer slag results in the further enhancement of the ITZ. This could, in turn, translate into greater concrete strength.

Concerning the effect of replacement level on compressive strength, it was found that the higher the amount of slag used, the lower was the initial strength. This is because the hydration products of the portland cement component are responsible for the early strength of the concrete and, hence, the lower the amount of cement available for hydration, the lower the initial strength. This is illustrated by blastfurnace slag concretes having water:binder ratios of 0.4 and 0.8. At 30 % replacement level, blastfurnace slag concrete reached similar strength as the CEM I controls after about 25 days while at 70 % substitution rate, the compressive strength was still lower after 56 days of curing. The corresponding compressive strengths for corex slag concretes were higher in all cases.

Regarding the influence of water:binder ratio on compressive strength, an increase in the water.binder ratio resulted in a decrease in the strength of all the different mixes (Fig. 4.10). This is to be expected and is related to a decrease in the amount of binder available for hydration. Furthermore, the same linear decrease in compressive strength was observed for the various replacement levels At a water:binder ratio of 0.8 and a slag replacement level of 70 %, corex slag concrete was still able to achieve a strength of 33 MPa at 28 days compared to 19 and 25 MPa for the corresponding blastfurnace and CEM I concretes respectively. A Grade 25 concrete can still be made from this specific corex slag mix and could possibly be used for low cost housing or for structural concrete where aspects like creep and durability are not critical. This could lead to considerable monetary savings.

4.6.2 Optimum Slag Replacement Level

The effect of slag substitution rate on compressive strength is shown in Figures 4.11 and 4.12.

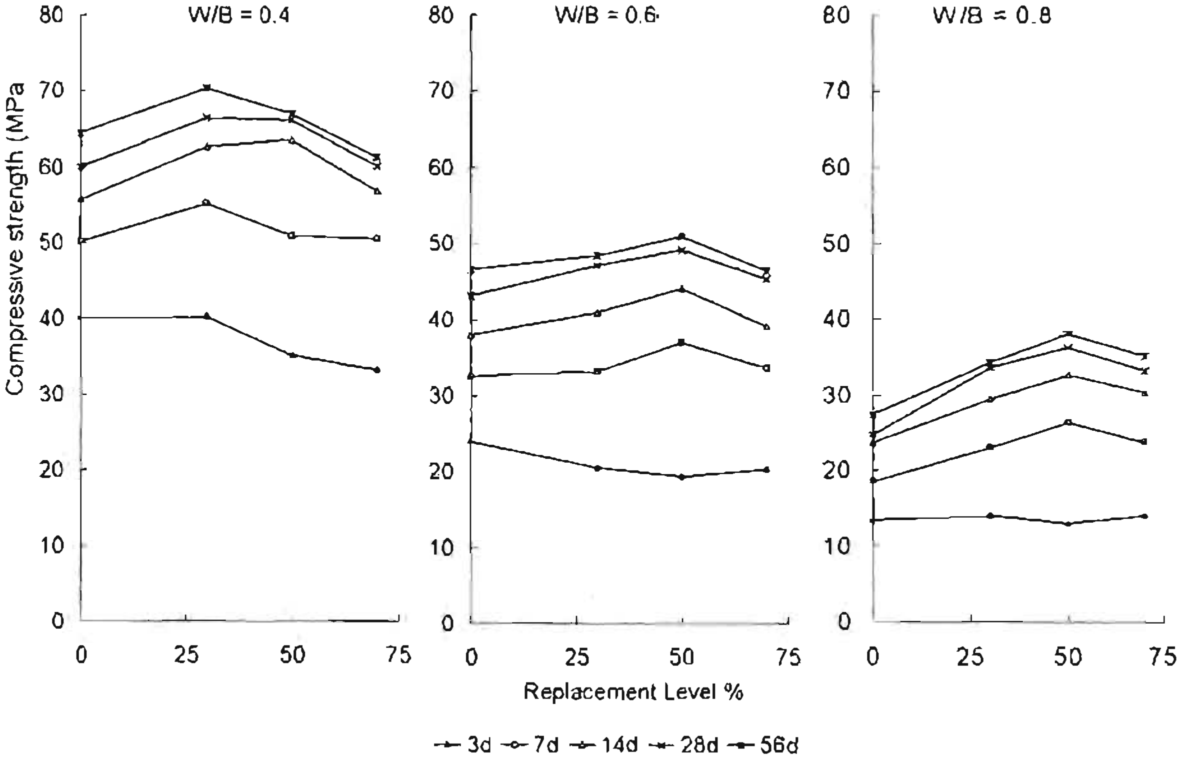


Fig. 4.11: Effect of corex slag replacement level on compressive strength

It can be observed from Figure 4.11 that the use of corex slag in concrete impacts negatively on the 3-day compressive strength, especially at low water:binder ratios. However, at a water:binder ratio of 0.8, it is interesting to note that increasing slag replacement level had virtually no effect on the initial compressive strength of the concretes. For water:binder ratios of 0.4, 0.6 and 0.8 the optimum corex slag replacement level, with respect to compressive strength, were found to be close to 45, 50 and 60 % respectively. This again reinforces the fact that at higher water:binder ratios, higher corex slag replacement levels can be used, subject to issues such as creep and durability. This impacts positively on the economics of such mixes.

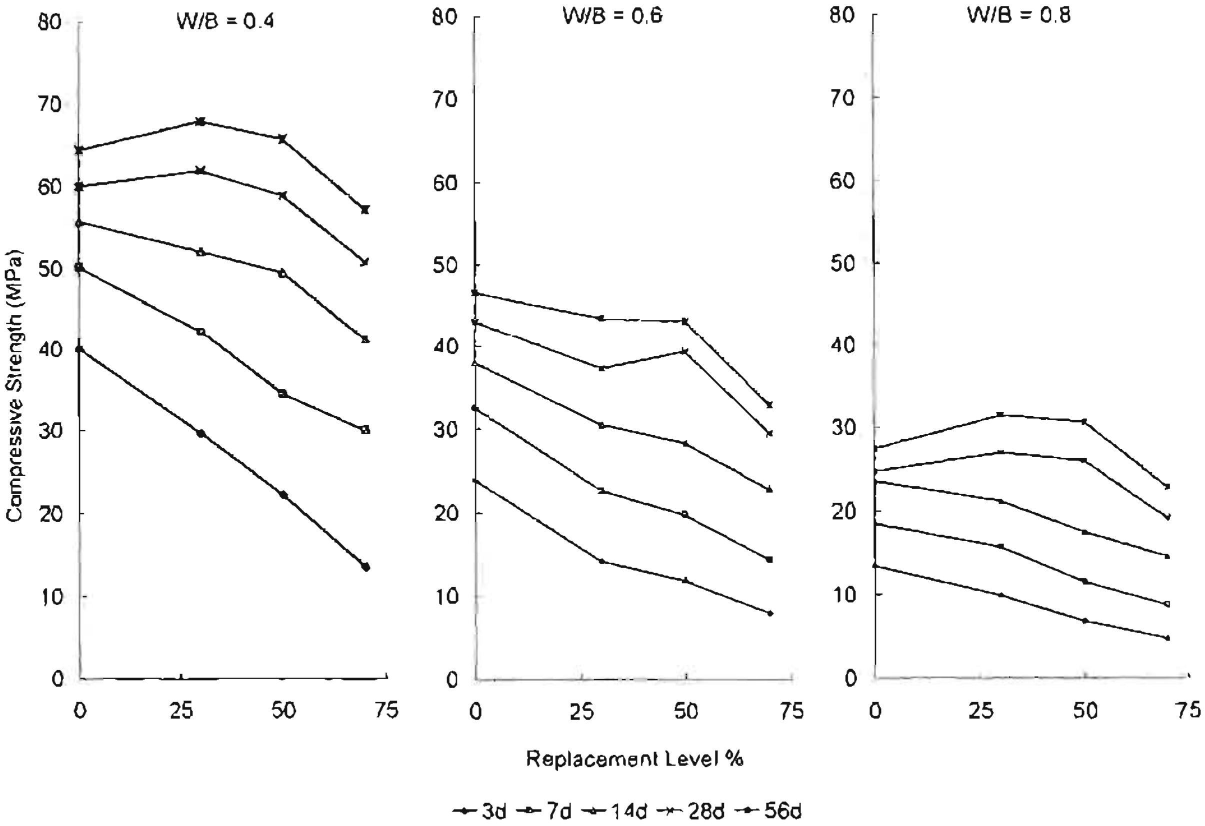


Fig. 4.12: Effect of blastfurnace slag replacement level on compressive strength

In the case of blastfurnace slag (Fig. 4.12), it was noted that the higher the replacement level, the lower the compressive strength of the concretes, up to the 14-day strength. At later ages, the optimum blastfurnace slag substitution rate was found to be near to 30 and 40 % for water:binder ratios of 0.4 and 0.8 respectively. In the case of the 0.6 water:binder ratio, no clear optimum value was observed.

For most of the water:binder ratios for corex slag, no major difference in compressive strength for replacement levels of 30 and 50 % was noted. Therefore, to reduce the cost of concrete, a substitution rate of 50 % should, preferably, be used.

4.6.3 Elastic Modulus

The elastic modulus values obtained in this research were comparable to results obtained by Davis and Alexander (1992), using ordinary portland cement and 50/50 Klipheuwel and Philippi sands. For concretes having water:binder ratios of 0.43 and 0.57, the 28-day elastic modulus values were 40.5 and 35.5 GPa respectively.

At higher compressive strengths, the 28-day elastic modulus of the slag mixes appear to be proportional to the compressive strength of the material, with corex slag concrete exhibiting the highest elastic modulus (Fig. 4.13). The modulus of elasticity of the CEM I controls, on the other hand, seemed to be independent of the compressive strength. However, as the compressive strength reduces, the relationship no longer seems to hold, with slag concretes showing lower elastic moduli than CEM I controls

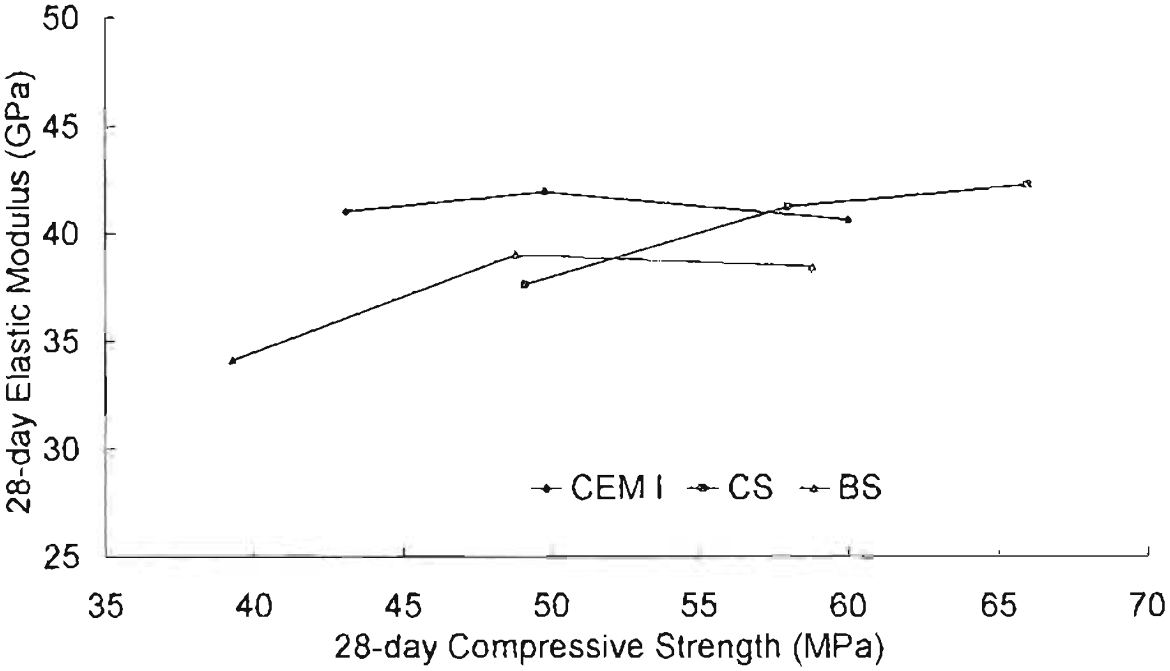


Fig. 4.13· Relationship between elastic modulus and compressive strength

At 90 days, the modulus of elasticity of the slag samples were very similar indicating that blastfurnace slag specimens experienced a higher increase in strength during the time interval. Furthermore, the high elastic modulus values could also be explained by an improvement in the interfacial transition zone. Detwiler et al (1987) noted that the modulus of elasticity is more dependent on the transition zone than is the compressive strength. However, to quantify the effects of slag on the ITZ, more appropriate studies should be performed.

Based on the modulus of elasticity values given in SABS 0100 for specific cube strength, it was observed that elastic modulus values obtained in this research were on average 4 GPa greater. Wainwright (1986) argued that higher moduli of elasticity have clear advantages, especially in relation to prestressed concrete structures. On the other hand, low elastic modulus are required to deal with thermal stresses at early ages. Consequently, during the design process, the designers should be aware of the exact properties of the materials in order to make efficient use of them

4.7 CONCLUSIONS

The compressive strength and elastic modulus properties were reported in this chapter and the following concluding remarks can be made:

- Slag concretes usually result in an initial lag in the compressive strength compared to CEM I concretes. The time lag varies between three and seven days for corex slag concretes and more than 56 days, in some cases, for blastfurnace slag concretes.

- At three days, corex slag concretes with water:binder ratios of 0.4, 0.6 and 0.8 were respectively 58, 64 and 91 % stronger in compression than the corresponding blastfurnace slag concretes for a replacement level of 50 % However, at 56 days, these values were reduced to only 2, 18 and 25 % respectively

- The rate of strength gain is high for corex slag concretes during the first 14 days but then decreases rapidly with time. Blastfurnace slag concretes, on the other hand, show a more gradual increase in strength and continue to gain in strength even after 56 days of curing.

- Generally, the initial strength decreases with increasing replacement level. For water:binder ratios of 0.4, 0.6 and 0.8, reductions in the three day compressive strength of 18, 2 and 0 % were observed when the replacement level was increased from 30 to 70 % for corex slag concretes and 54, 44 and 53 % respectively for blastfurnace slag concretes.

- The 28-day compressive strength was found to increase with decreasing water:binder ratio and was higher for corex slag concrete for all mixes considered A change in water:binder ratio from 0.8 to 0 4 caused a corresponding increase of 82 and 127 % for corex and blastfurnace slag concretes, respectively, for a 50 % slag replacement level.

- For both corex and blastfurnace slag concretes, the optimum substitution rate, with respect to compressive strength, was found to vary with water:binder ratio. In the case of corex slag, the optimum value varied between 45 and 60 % while for blastfurnace slag the optimum replacement level was between 30-50 %. Hence the use of corex slag could prove to be more economical.

- The use of corex slag in concrete results in higher modulus of elasticity at 28 days compared to blastfurnace concrete. The increase in elastic modulus was around 9 % on average. However, at 90 days, the differences were not as significant.

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CHAPTER 5

CREEP AND SHRINKAGE

Creep and shrinkage are important material properties that have a major impact on the long-term performance of concrete structures. Creep is defined as the time-dependent deformation of a solid body under sustained stress. Shrinkage, on the other hand, is the reduction in volume of unloaded concrete under drying conditions.

The phenomenon of concrete creep was first discovered by Hatt in 1907 but it was not until the 1930's that more comprehensive research was undertaken by Davis and Glanville (Rüsch et al, 1983). Between the 1940's and the beginning of the 80's, the needs of designing large concrete dams, long-span bridges and concrete structures for nuclear reactors led to great advances in the knowledge of creep and shrinkage. Nowadays, the impetus for research is provided by the use of new materials in the manufacture of normal and high performance concrete.

It is desirable for a number of reasons to consider both creep and shrinkage together in this chapter. This is because they both originate from the hydrated cement paste and both are influenced by the same factors, usually in the same manner. Also, creep and shrinkage are coupled in such a way that their combined effect is greater than the sum of the individual effects.

5.1 STRUCTURAL IMPLICATIONS OF CREEP AND SHRINKAGE

The positive effects of creep on concrete structures are the relief of stress concentrations caused by shrinkage, temperature changes or movement of the supports. It also gives a degree of ductility to concrete, without which the material would be too brittle for use in most structures (Alexander, 1994a).

Unfortunately, most consequences of creep are adverse to structures. In the case of prestressed members, a reduction in the compressive force caused by creep and shrinkage is observed, hence, leading to crack formation (Neville, 1975 and Rüsch et al, 1983). Concerning shrinkage, the induced strains result in cracking of significant size and also cause deflections that may be above the serviceability limit state (De Serio, 1971). Very often, the detrimental effects of creep are more damaging to non-structural members, such as claddings and partition walls, than to the structure itself (Alexander, 1994a). However, if due consideration is given to the problems of creep and shrinkage in the design process, their effects on concrete structures can be minimised.

5.2 COMPONENTS OF TOTAL DEFORMATION

It is often assumed for simplicity that creep and shrinkage are independent processes. Therefore, the total strains, ε_T, can be considered to be the algebraic sum of the creep, ε_C, and shrinkage strains, ε_S, together with the elastic strains, ε_E. However, this is not strictly true as another creep component arises if drying is permitted to occur while the applied load is still acting. It is, thus, essential to differentiate between the two components of creep which are, namely, basic and drying creep. In this context, basic creep, ε_{Cb}, refers to the creep that occurs under sealed conditions where no moisture exchange occurs with the ambient atmosphere (Rüsch et al, 1983). Drying creep, ε_{Cd}, on the other hand, is the additional creep that takes place when the concrete is also drying (Metha and Monteiro, 1993). It is sometimes also referred to as the Pickett effect. Figure 5.1 shows graphically the different components of total strains.

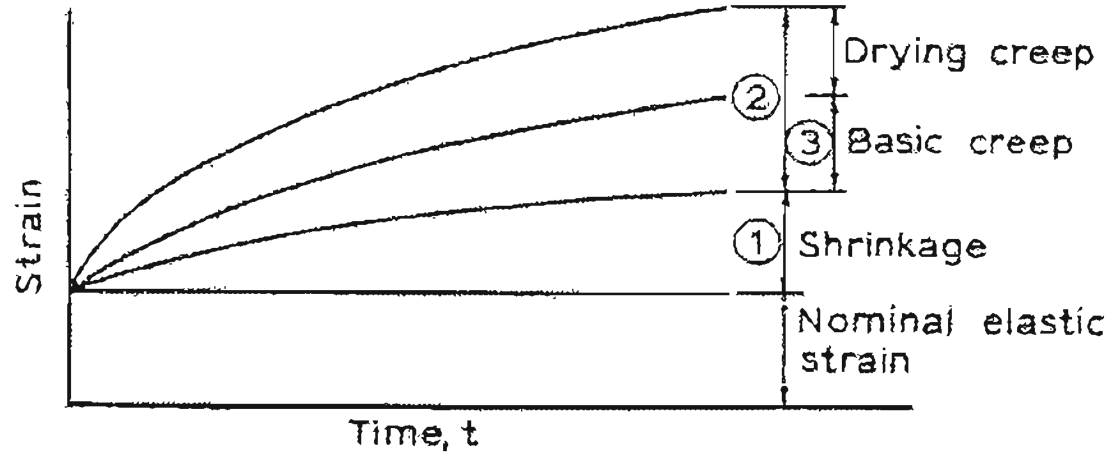

Figure 5.1 · Components of total strains (Neville, 1970)

According to Neville (1970), it should be pointed out that the modulus of elasticity of concrete increases with time, hence decreasing the elastic strain For greater accuracy, creep should be considered as the strain in excess of the elastic strain at that particular time and not at the time of loading However, the difference between the two methods is not significant.

Therefore, the total strain can be summarised as:

$$\varepsilon_T = \varepsilon_E + \varepsilon_S + \varepsilon_{Cb} + \varepsilon_{Cd}$$

5.3 MECHANISMS OF CREEP AND SHRINKAGE

Many models based on empirical data have been suggested for possible creep and shrinkage mechanisms. However, according to Neville (1970), the mechanisms are not yet fully understood, and this is still the case today. This is illustrated by the fact that some proposed mechanisms which were plausible when first put forward have later been disproved by new tests. It is suggested by Xi and Jennings (1992) that improvements to present models will only be achieved if they are based on a thorough and realistic understanding of the microstructure. The various possible mechanisms that have been proposed are briefly discussed below. However, until now no single hypothesis can clearly explain the phenomena of creep and shrinkage.

5.3.1 Creep Mechanisms

Plastic deformations

Plastic deformations include intracrystalline slips and local rupture of the hardened cement paste, hence leading to irrecoverable creep. However, the effect of moisture and moisture movements on creep cannot be explained in terms of the plastic deformation mechanism. According to Neville (1970), plastic deformation may contribute to creep only at stress levels nearing ultimate but has no significant importance to creep behaviour under normal loads.

Viscous flow

This theory considers the hardened cement as a viscous fluid surrounding the loose and relatively rigid aggregate material. It offers plausible explanations for the linearity of creep strain with stress up to a stress-strength ratio of about 50%, stress relaxation at constant deformation and sensitivity of creep to temperature, (Ali and Kesler, 1964). It cannot, however, explain certain characteristics of creep.

Seepage theory

Seepage theory was among the first postulated creep theories. It is based on the fact that during loading the water within the cement paste is squeezed out of the specimen. The volume change accompanying the resulting moisture movement is identified with creep. As pointed out by Xi and Jennings (1992), only the gel water is involved in the seepage movement. The capillary water and chemically combined water do not influence the mechanism. It is noted by the same authors that this theory provides an explanation for the large creep of drying concrete.

Activation energy

Hansen and Young (1991), based on the work of Wittmann, reported that creep can be described by rate-process with an activation energy. This theory can be used for predicting the effects of time, temperature and moisture content on concrete creep. The activation energy approach is based on the idea that movement of solid particles is responsible for creep and the rate is not affected by moisture movement. According to this hypothesis, cement paste contains regions which will undergo deformations to lower energy states, hence giving rise to creep strains.

Solidification theory

This theory was developed to specifically consider the ageing aspect of creep (Bažant, 1995). In this approach, the paste is divided into a liquid part which cannot bear load and two solid effective load-bearing parts. The main aspect of this theory is that an increase of the volume fraction of the effective load-bearing portion of solidified material is responsible for the ageing aspect of creep of cement paste (Bažant and Xi, 1993).

5.3.2 Shrinkage Mechanisms

Capillary tension

Capillary stress is a mechanism that possibly contributes to shrinkage at humidities exceeding 40% (Taylor, 1992). On drying, moisture is lost from capillaries resulting in the transfer of tension in the meniscus to the capillary walls. As a result, the pores tend to shrink.

Surface tension

This mechanism is a consequence of the surface free energy. Tensile stresses are created on the surface of gel particles and compressive stresses are induced within the solid. When adsorbed water molecules are removed, the tensile stresses increase and a reduction in volume of particles tends to occur. According to Xi and Jennings (1992), the surface tension mechanism is only valid at humidities below 30%.

Disjoining pressure

Disjoining pressure is associated with multilayer adsorption of water and hence affects shrinkage only at high relative humidities. A drop in humidity level will cause the water layers to become thinner, thus inducing a reduction in disjoining pressure. This, in turn, will cause shrinkage to occur.

Movement of interlayer water

This mechanism considers the interlayer water to be responsible for the bulk of volume change at low relative humidities. The loss of water from the layered particles will result in volume reduction by changing the spacing of the layers (Alexander, 1994a).

5.4 EFFECT OF MICROCRACKING AND MATURITY ON CREEP AND SHRINKAGE

Shrinkage is a result of a complex state of stress in a drying specimen. According to Wittmann (1993), the observed volume change does not only depend on a diffusion process but also on strain softening and crack formation in highly stressed areas. Experiments performed by Alvaredo and Wittmann (1993) have indicated that the initial rate of shrinkage is affected by the onset of crack formation. Microcracks occur because the moisture distribution within concrete is not uniform, hence inducing stresses while drying.

Concerning creep, many researchers (Gettu and Garciá-Álvarez, 1993, Bažant, 1993 and 1995 and Buyukozturk et al, 1993) have shown that there is a strong relationship between fracture and concrete creep. In fact, the presence of cracks increases creep and this is of importance for both ultimate and serviceability analysis of structures. Based on the work of Ross, De Schutter and Taerwe (2000) reported that creep also depends on maturity and is more sensitive to changes in maturity than to strength or elastic modulus. Meyers and Slate (1970) argued that the two most significant factors affecting the creep of concrete are the level of microcracking developed prior to and during the loading period and the degree of hydration.

Furthermore, Khalil and Ward (1977) found that, provided all mixes were loaded at the same stress:strength ratio and degree of hydration, then the same creep strain was observed for the same increase of hydration under load. This implied that the loading age only affects creep because of its relationship to the strength development and degree of hydration. Moreover, Rüsch et al (1983) showed that the fast initial strain for a given concrete composition depended greatly on the degree of hydration and this is illustrated in Figure 5.2 by the graph of the fast initial strain versus the corresponding degree of hydration. It is implied from the diagram that the fast initial strain for a completely hydrated sample is very small.

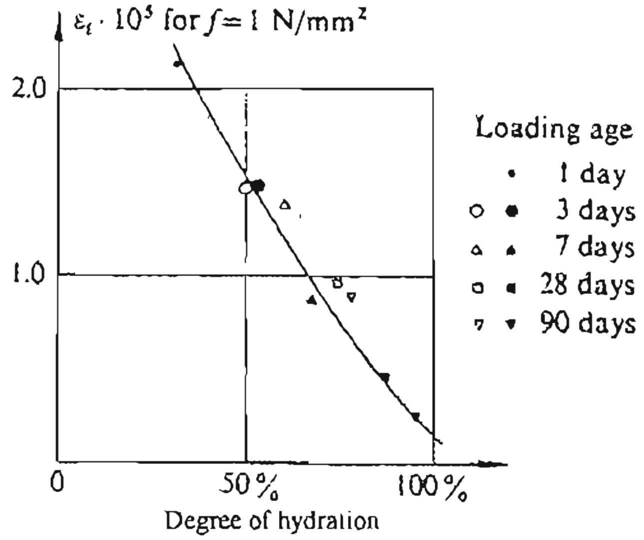

Fig. 5.2: Effect of maturity on initial strain (Rüsch et al, 1983)

5.5 EFFECT OF BLASTFURNACE SLAG ON CREEP AND SHRINKAGE

5.5.1 Creep

Experiments performed by Chern and Chan (1989) have shown that, under drying conditions, the total creep of blastfurnace slag concrete was greater than that of portland cement concrete but the basic creep component was smaller. They attributed the basic creep results to the fact that slag concretes show a greater increase in strength while under load, hence effectively decreasing the stress:strength ratio. Their explanations for the creep results under simultaneous drying and loading conditions were, firstly, the excess moisture loss impeded the hydration reactions of slag concrete and, secondly, the development of microcracks due to higher shrinkage strains resulted in more deformation.

Tazawa et al (1989) conducted creep experiments on concrete incorporating blastfurnace slag of different fineness. A replacement level of 55% was used together with a water:binder ratio of 0.5. The results indicated that the specific creep of slag concrete with or without moisture loss was smaller than that of non-slag concrete at extended times under loading. It was also observed that the concrete samples containing the slag with the highest specific surface area (7860 cm^2/g, Blaine) showed the lowest specific creep. The researchers also found, for a curing time of 28 days, that the specific creep of concrete having identical compressive strength was the same regardless of the concrete composition. This implied that high specific surface area slag concrete having greater strength also had a smaller specific creep. However, for a curing period of 7 days, slag concrete had a lower specific creep that non-slag concrete at the same compressive strength. This is because the development of compressive strength of slag concrete after loading was larger than that of non-slag concrete.

Neville and Brooks, as reported by Wainwright (1986), performed tests under drying conditions and observed that slag concrete had a slightly higher total creep than portland cement concrete (Fig. 5.3). This was attributed to a faster retrogression in strength of slag concretes. For sealed specimens, a decrease of about 42% was observed in basic creep for concrete having 50% slag replacement level as compared to plain cement concrete (Fig. 5.4).

Using South African slag, Boukendakdji et al (1996) showed that the ultimate basic creep of concrete containing 50 and 70 % slag was about 12 and 19 % lower than the reference portland cement samples. Concerning the total creep results, they indicated the ultimate values to be 31 and 34 % lower respectively. These results were achieved using a water:binder ratio of 0.43 and a water curing time of 14 days.

South African experiments conducted by Alexander (1994b) have indicated that the use of blastfurnace slag in concrete caused a possible increase in creep strains of about 20 % in drying samples, but at later ages, the effect was less significant. For sealed samples, reductions of up to 40 % in basic creep were noted. Addis (1987) reported similar findings based on South African research.

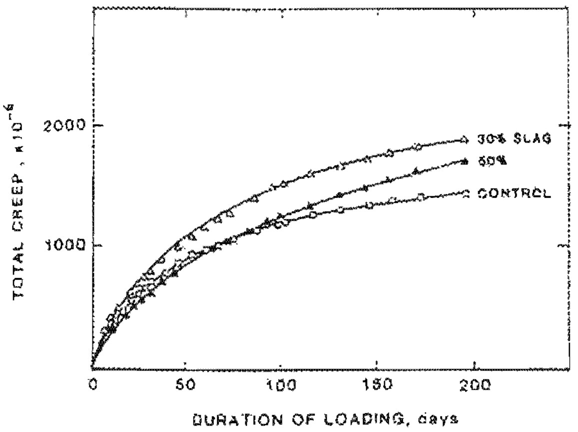

Fig. 5.3: Total creep strain of slag concrete (Wainwright, 1986)

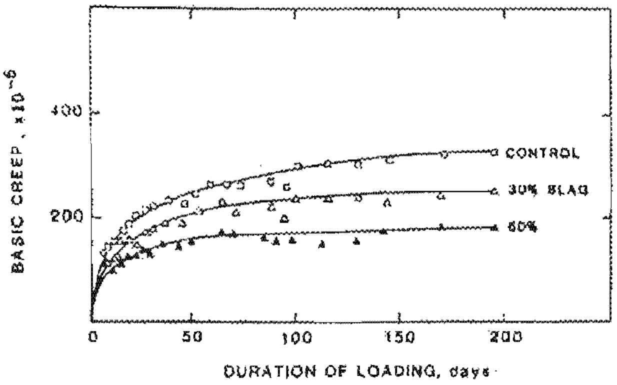

Fig 5.4: Basic creep strain of slag concrete (Wainwright, 1986)

5.5.2 Shrinkage

Olorunsogo (1997) conducted shrinkage experiments on slag cement mortar including blastfurnace slag of different fineness. He used a replacement level of 70 % and a 0.45 water:binder ratio. The results indicated that drying shrinkage increased with an increase in the fineness of slag (Fig. 5.5). This observation was also reported by Soroka (1979) who argued that finer materials increase the hydration rate, hence resulting in a higher degree of hydration. This, in turn, involved greater shrinkage. Olorunsogo, based on the work of Sato et al with two slag powders (3700 and 8000 cm^2/g) and a replacement level of 40 %, reported that the mortar specimens containing the finer slag showed higher drying shrinkage up to the age of four weeks. However, after this period of time, both mortar types exhibited similar shrinkage up to the age of one year.

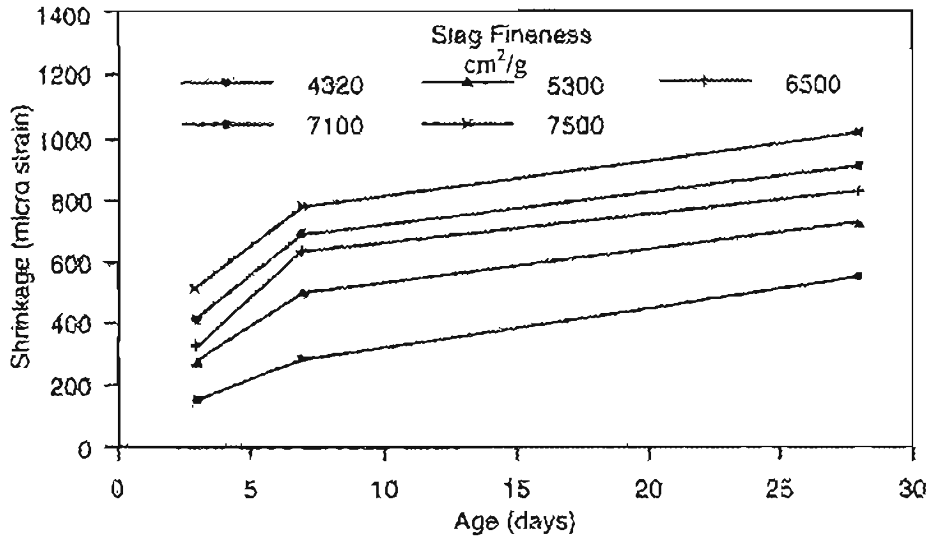

Fig. 5.5· Effect of slag fineness on shrinkage (Olorunsogo, 1997)

Olorunsogo attributed the higher shrinkage of finer slag mortar to a lower bleeding capacity and according to Neville (1975), finer cementitious products tend to offer less restraint on the shrinking paste than the coarser ones.

Tazawa et al (1989) also performed experiments with mortar containing different fineness of slag. They found that slag mortar containing finer material showed larger drying shrinkage at early ages but there was no significant difference at later ages. They also showed that slag mortar with high specific surface area resulted in larger shrinkage at short curing times than at longer times. For concrete, drying shrinkage was lower for specimens containing slag and an increase in specific area of slag resulted in lower shrinkage. This is mainly because the compressive strengths of slag concrete containing finer slag were also the highest.

Chern and Chan (1989), on the other hand, found that the use of blastfurnace slag in concrete caused the shrinkage deformation to increase and they attributed this to the greater volume of paste in slag concrete if slag replaces cement on an equal weight basis. Metha (1983) reported similar results based on the work of Hogan and Meusel. Investigations carried on by Sivasundaram and Malhotra (1992) found that drying shrinkage of high-volume slag concretes and portland cement controls were about the same. However, the shrinkage deformation seemed to decrease slightly with increasing replacement level of slag.

South African work conducted by Alexander (1994b) showed that the use of slag in concrete might result in an increase in the short-term shrinkage strains but at a later age this effect is reduced. This deduction was based on replacement level of 50% and water:binder ratios varying between 0.49 and 0.56. Lang and Geiseler (1996), Numata et al (1986), Boukendakdji et al (1996) and Grieve (1989), based on the work of Fulton, reported similar findings.

In summary, the literature indicates that generally the use of slag in concrete causes an increase in both creep and shrinkage strains but at later ages, the effects were less significant. Furthermore, creep and shrinkage are also dependent on slag fineness, replacement level and age at loading/drying.

5.6 TEST METHODS

5.6.1 Creep Test

Concrete cylinders of 105 mm in diameter and 300 mm long were used in the creep experiments. They were prepared in two batches, one for sealed specimens and the other for unsealed samples. For each different mix, two creep samples and two companion shrinkage specimens were prepared. All the samples were cast in two layers and water cured for 7 days. The creep cylinders had their rough face ground before loading to ensure plane bearing surfaces. An early loading age was used because nowadays, more and more structures are stressed within a week after construction.

The sealed specimens were coated with a thick layer of a water based bitumen emulsion and wrapped in heavy-duty aluminium foil. Adhesive tape was used around the cylinder perimeter to close the joints between the sealed specimens and other contact faces in order to prevent moisture exchange with the ambient environment. Thus, only basic creep could occur, and no drying creep. The companion shrinkage samples had their end faces dipped in warm wax so as to have the same surface area in contact with the atmosphere as the creep specimens, thereby presumably having the same shrinkage effects. After the curing period had elapsed, the creep specimens were put under load without any delay.

5.6.2 Creep Set-Up

The type of creep loading frame used was of the CEB hydraulic type as shown in Figure 5.6. The laboratory set-up consisted of two creep testing banks each containing three and six frames in series respectively (Fig. 5.7). The frames were calibrated prior to the beginning of the experiments by using a load-cell. The creep frames were kept in a room maintained at a temperature of 22 ± 2 °C and a relative humidity of 65 ± 5 %.

The axial load was applied by using a hydraulic jack. The pressure on the specimens was maintained by means of nitrogen accumulators and monitored with the help of dial gauges.

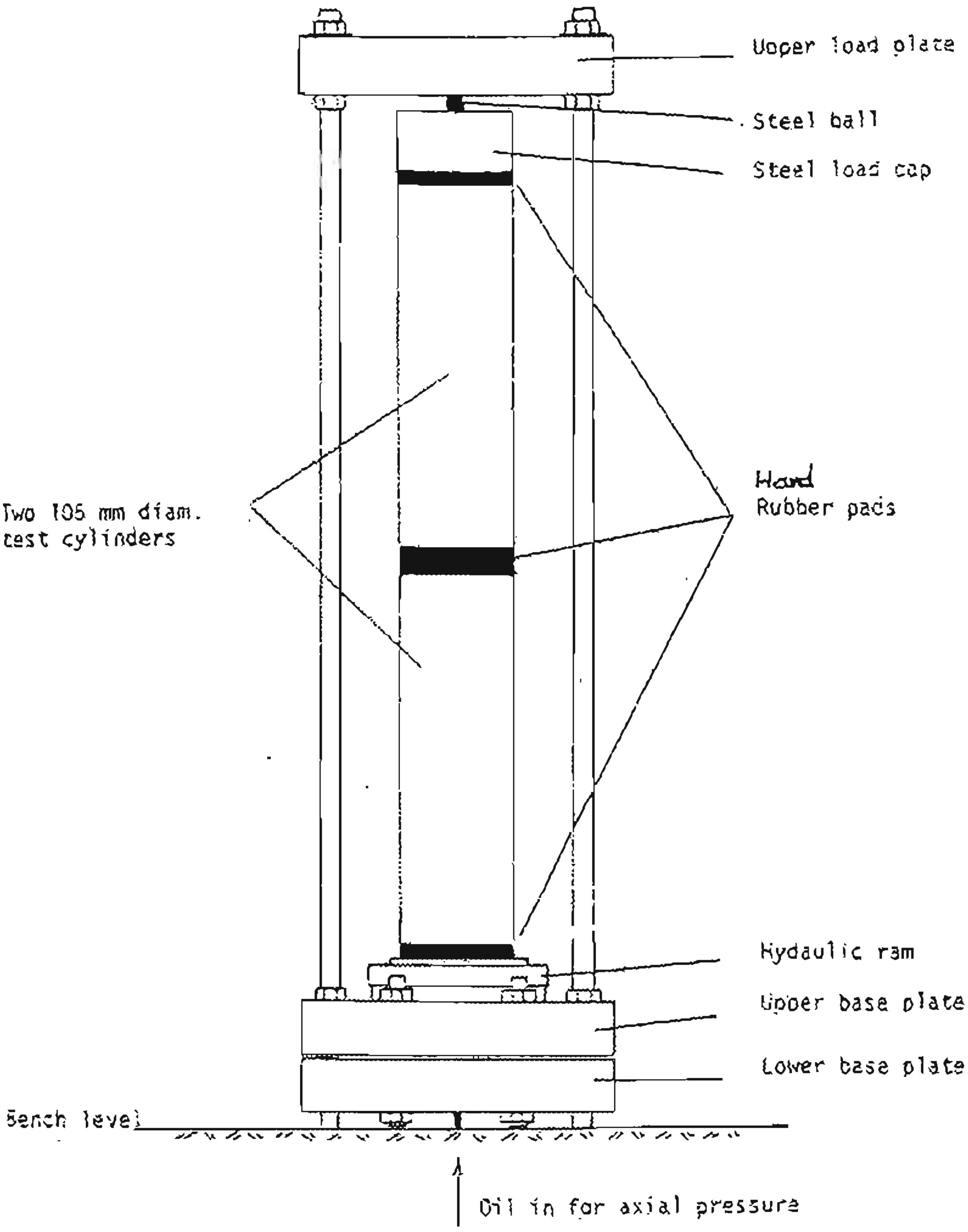

Fig. 5.6: Typical creep frame (Mallows, 1985)

5.6.3 Loading Procedure

The samples subjected to simultaneous loading and drying were loaded after 7 days, but due to a technical problem the sealed specimens were only loaded after 8 days of curing. Prior to loading, the cube strengths of the different specimens to be tested were determined. The pressure to be applied on the cylinders was determined by the strength of the weakest samples. Table 5.1 gives the stresses acting on the specimens together with the corresponding stress:strength ratio (expressed as a percentage) at loading.

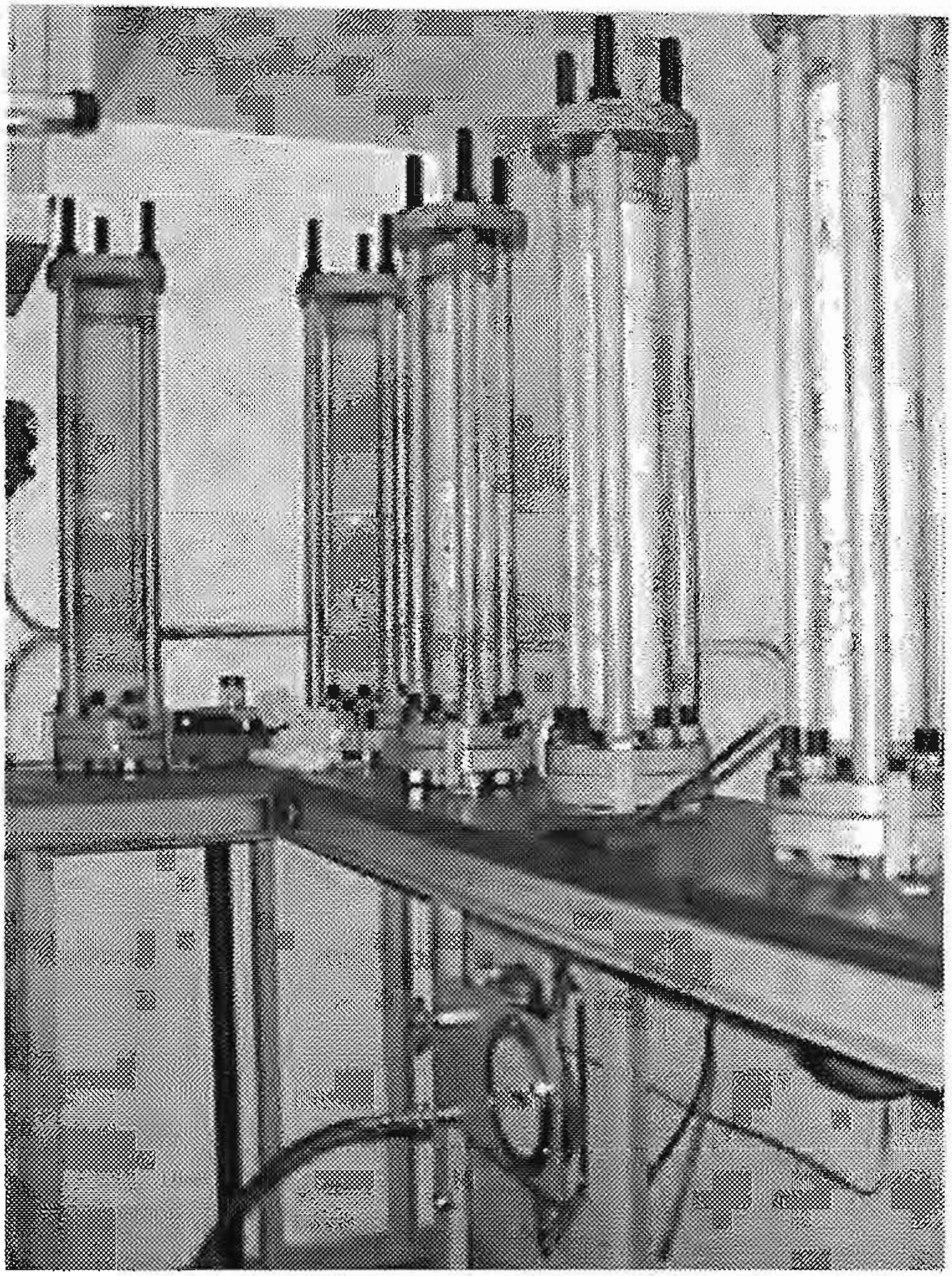

Fig. 5.7: Creep laboratory set-up

Table 5.1: Applied stresses on creep samples at time of loading.

	Water/Binder = 0.4		*Water/Binder = 0.5*		*Water/Binder = 0.6*	
Binder	**Applied stress (MPa)**	**Stress: Strength Ratio (%)**	**Applied stress (MPa)**	**Stress: Strength Ratio (%)**	**Applied stress (MPa)**	**Stress: Strength Ratio (%)**
CEM I	11.1	22.2	7.6	18.1	7.6	22.6
CS	11.1	21.8	7.6	18.2	7,6	23.1
BS	11.1	32.3	7.6	34.1	---	---

The creep samples were subjected to an initial preload of about 10% of the final load. This loading force was then removed and the cylinders were afterwards gradually reloaded to the final load. The initial elastic strains were then measured as quickly as possible (within 10 minutes) in order to minimise the effect of creep on the results. Concerning the basic creep tests, the same procedure was followed except that the initial elastic strains were determined at a lower stress level so as to further reduce the effect of creep.

5.6.4 Shrinkage Test

Separate shrinkage experiments were performed on 100 x 100 x 200 mm prisms and three samples were prepared from each mix. They were water cured for 14 days and then transferred to the same room as the creep samples. The end faces were also dipped in warm wax in order to prevent end drying.

5.6.5 Strain Measurements

The creep and shrinkage specimens were instrumented with small targets on their faces which were fixed in position using a quick setting epoxy. For the creep samples, the targets were fixed on three different faces of the cylinders, 120° apart, and on two opposite longitudinal faces for shrinkage prisms. The strain measurements were taken using a mechanical strain gauge (Staeger – Type Pfender) on a gauge length of 100 mm. Prior to taking any set of readings, the strain gauge was calibrated by using an Invar steel reference bar. Strain measurements were taken daily for one week, weekly for one month and then on a monthly basis until the end of the experiments. In the case of the creep tests, the strains were recorded at 2-hour intervals for the first six hours on the day of loading. Creep (and companion shrinkage) strains were taken as the mean of two different samples whereas the mean shrinkage strains were calculated from three samples.

5.7 PREDICTION OF LONG-TERM CREEP AND SHRINKAGE FROM SHORT-TERM TESTS

The 5-year creep and shrinkage values were calculated from the equations provided by Brooks and Neville (1978).

Basic creep :

$$\frac{c_t}{c_{28}} = 0.50t^{0.21}$$

Total creep :

$$\frac{c_t}{c_{28}} = \left(-6.19 + 2.15\log_e t\right)^{1/2.54}$$

Shrinkage :

$$s_t = B' s_{28}^{\,b'} \qquad B' = \left(-4.17 + 1.53\log_e t\right)^2 \qquad b' = \frac{100}{2.90 + 29.2\log_e t}$$

where c_t and s_t are the specific creep (10^{-6} per N/mm^2) and shrinkage (10^{-6}) respectively, for values of t ≥ 28 days,

and c_{28} and s_{28} are the 28-day specific creep and shrinkage values respectively.

According to Brooks and Neville (1978), for a short-term test having a duration in excess of 40 days, an error coefficient of less than 15% is achieved. This value gets lower the longer the duration of the experiment.

In this investigation, the long-term total creep and shrinkage values were calculated from the 4-month (112 days) measurements while the basic creep deformations were obtained from the 3-month (84 days) readings.

5.8 CREEP AND SHRINKAGE RESULTS

5.8.1 Shrinkage

The shrinkage results for the three water:binder ratios are shown in Figure 5.8. It can be observed from the 0.4 water:binder ratio graph that the initial rate of shrinkage was highest for blastfurnace slag concrete samples with the shrinkage of corex slag and CEM I concretes showing similar trends until the end of the first week of drying. After this period of time, CEM I concrete exhibited greater shrinkage than corex slag concrete. Beyond 28 days of drying, the strains of the control specimen were even higher than blastfurnace concrete. The early shrinkage patterns are illustrated in *Appendix D*.

For the results shown in Figure 5.8 (b), a different pattern was observed. In this case, blastfurnace slag concrete exhibited the least shrinkage at all ages. For the corex slag and CEM I concretes, the initial shrinkage trends were identical as for the 0.4 water:binder ratio except that the magnitudes were higher, as expected. However, it was noticed that at later ages the shrinkage strains of the two slag concretes became virtually identical. Moreover, for a water:binder ratio of 0.6 (Fig. 5.8 (c)), corex slag concrete yielded the highest shrinkage strains with blastfurnace slag and CEM I concretes showing similar shrinkage deformations, especially at later ages.

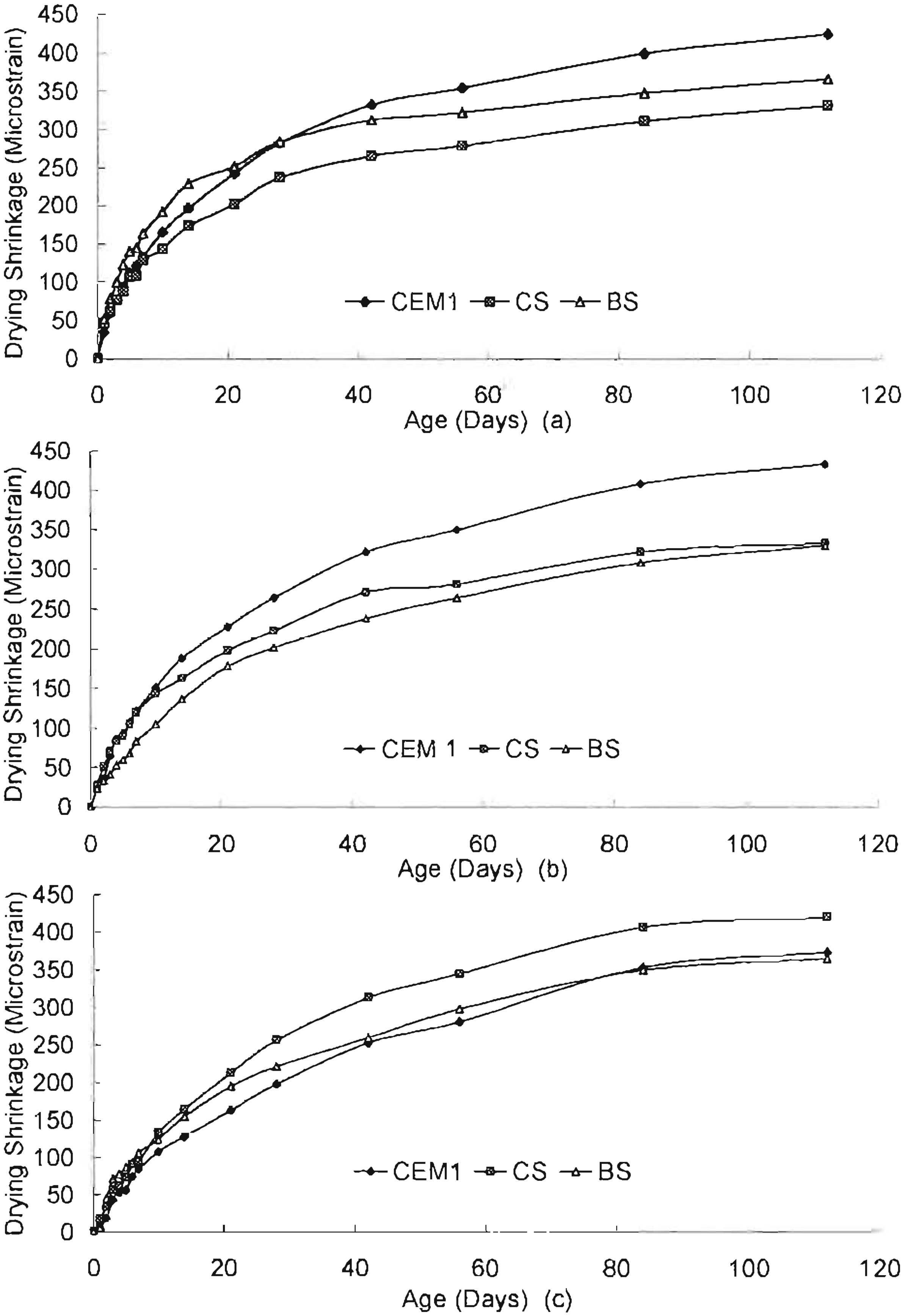

Fig. 5.8: Drying shrinkage of concrete having water:binder ratios of (a) 0.4 (b) 0.5 (c) 0.6

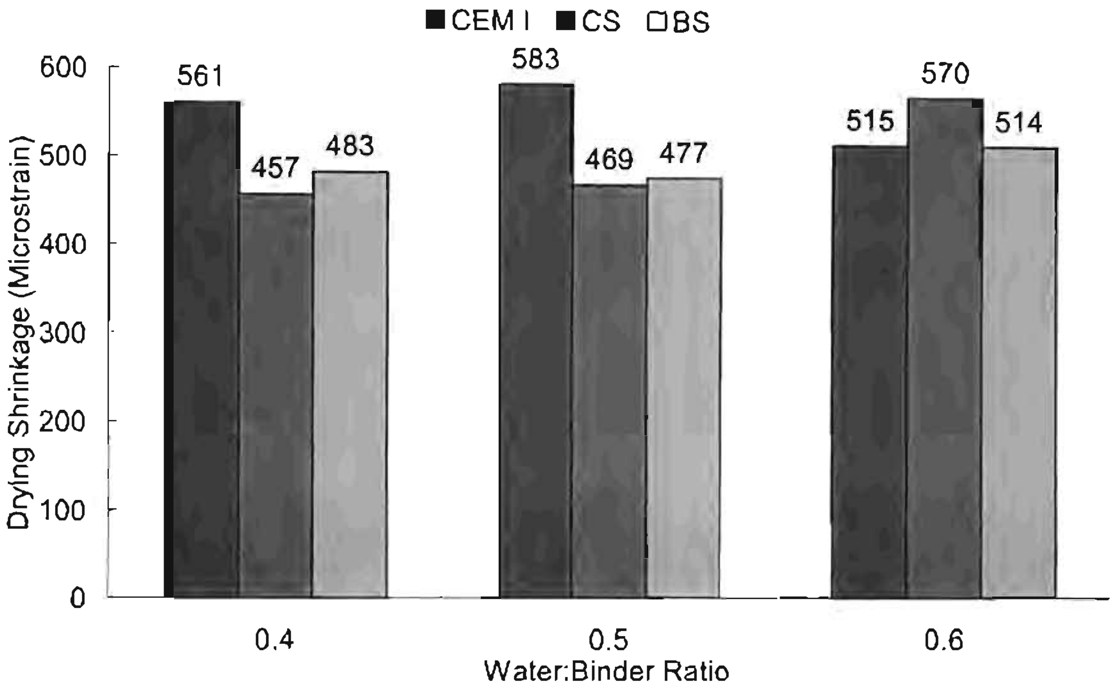

Figure 5.9: 5-Year extrapolated drying shrinkage strain

Figure 5.9 shows the 5-year extrapolated results based on the experimental data. For water:binder ratios of 0.4 and 0.5, the bar chart indicates that slag concretes result in about 25% less shrinkage than CEM I concretes at 5 years, with corex slag concretes marginally out-performing blastfurnace slag concretes. However, for the highest water:binder ratio, corex slag concrete results in about 10% more drying shrinkage than blastfurnace concrete. It must be noted that all the shrinkage strains were within the same range and this observation will be discussed later in this chapter.

5.8.2 Creep

Total creep

The total creep results for the three water:binder ratios investigated are shown in Figure 5.10. As given in Table 5.1, the stresses acting on the specimens were not the same. Hence, in order to be able to directly compare the creep characteristics of the different samples, the results were expressed in terms of specific creep. Specific creep is defined as the creep strain per unit stress.

With reference to Figure 5.10, it is evident that at low water:binder ratios, the mixes containing corex slag exhibited the least creep deformations. Blastfurnace concretes, on the other hand, yielded the highest creep at all ages. However, at 112 days there was only a marginal difference between blastfurnace and CEM I concretes.

An important point to note is the rapid initial rate of deformation of blastfurnace slag concrete. This is more obvious in the case of a water:binder ratio of 0.4. See Table D3 and Figure D5 in *Appendix D* for the detailed values. For a water:binder ratio of 0.6, the specific creep for the two different mixes was virtually identical until two months of loading. After this period of time, the creep deformations of corex slag concrete increased at a greater rate.

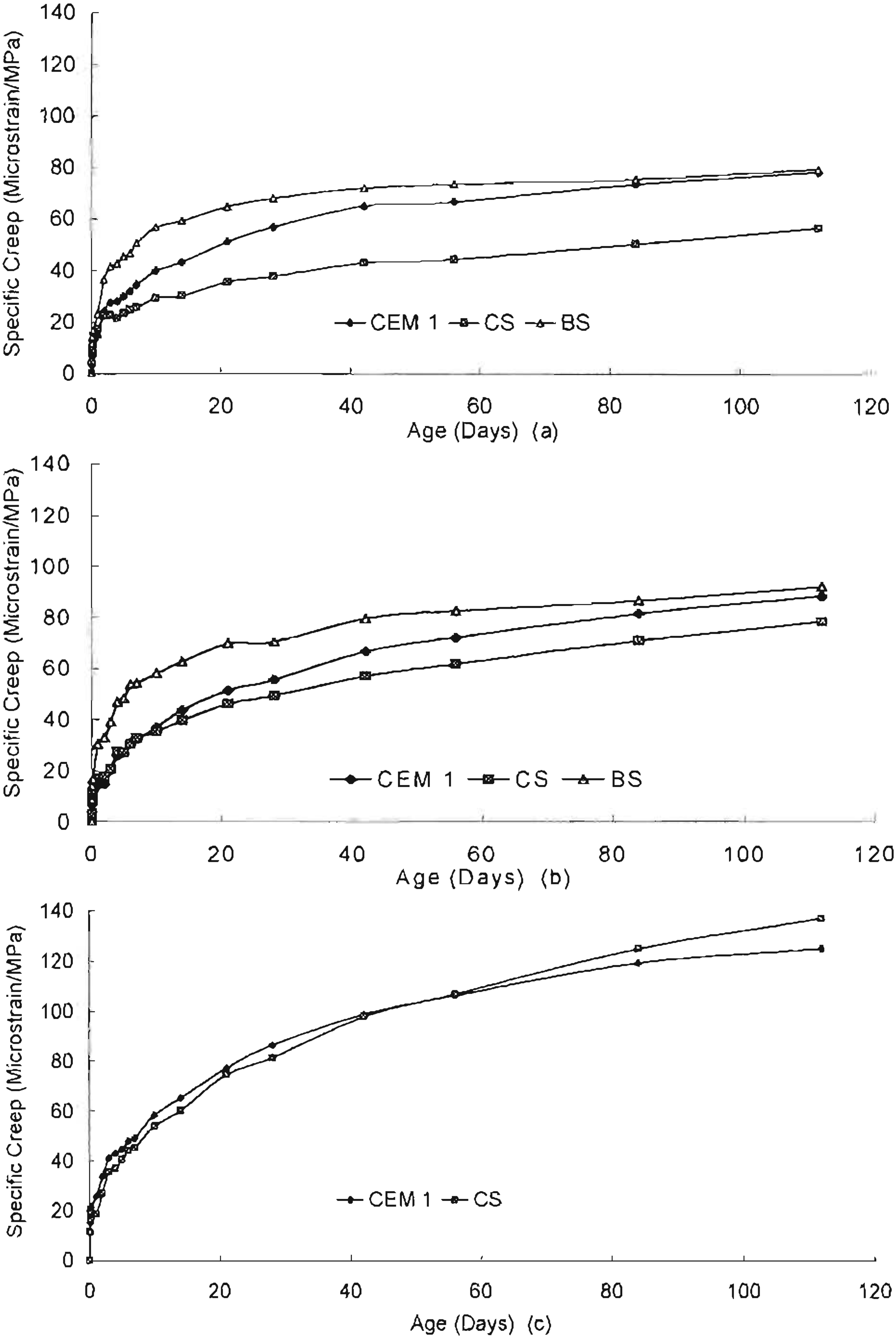

Fig. 5.10: Specific creep of concrete having water:binder ratios of (a) 0 4 (b) 0 5 (c) 0.6

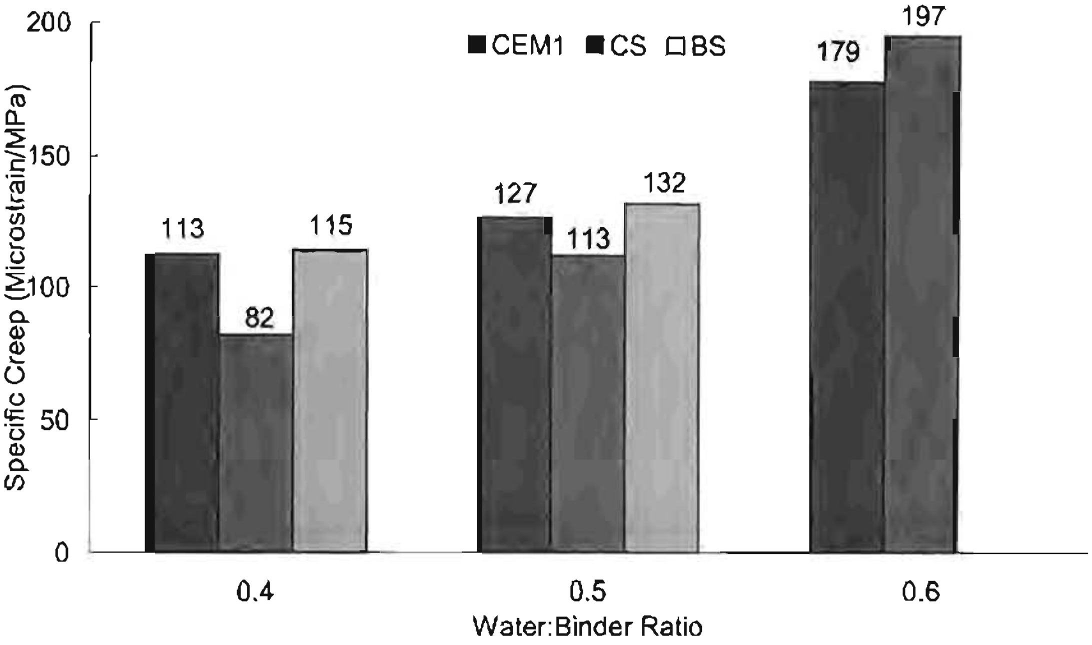

Figure 5.11: 5-Year extrapolated specific creep

It is clear from the bar charts (Fig. 5.11) that corex slag concretes exhibit the lowest specific creep at extended age. In fact, the specific creep values are about 40 and 17 % lower than those of blastfurnace concretes for water:binder ratios of 0.4 and 0.5 respectively. At the highest water:binder ratio considered, corex slag concrete yields approximately 10 % more creep deformation than CEM I concrete. However, it is important to note that if the stress/strength ratio was used instead of specific creep, then the apparent higher creep of blastfurnace slag concretes would be significantly reduced. This is because the effect of the initial concrete strength would be minimised.

Basic Creep

The specific basic creep results for the only water:binder ratio considered (w/b = 0.5) are indicated in Figure 5.12. It can be observed from the figure that corex slag concrete had the lowest specific basic creep at all ages. On the other hand, blastfurnace slag concrete had the highest rate of initial creep and after 2 hours under load its specific creep value was 118 and 684 % greater than those of CEM I and corex slag concretes respectively. However, the rate of change of creep with time for blastfurnace slag concrete decreased considerably after the first week of loading and after 84 days of loading, its specific basic creep value was almost the same as that of CEM I concrete. At an extended duration of time, the specific basic creep value of blastfurnace slag concrete will, most probably, be significantly lower than that of CEM I concrete. Concerning the corex slag sample, the 84-day specific basic creep value was almost 45 % lower than the other two specimens but this percentage is expected to decrease with time.

It can be deduced from Figures 5.12 and Table 5.2 that the long term creep of blastfurnace slag concrete is similar, if not less, than that of the CEM I specimens. It must be noted that the extrapolated 5-year values were based on the 3-month measured values. However, the creep deformations of portland cement and corex slag concretes were still on an increasing trend and, hence, the predicted 5-year values could be greater than the actual ones.

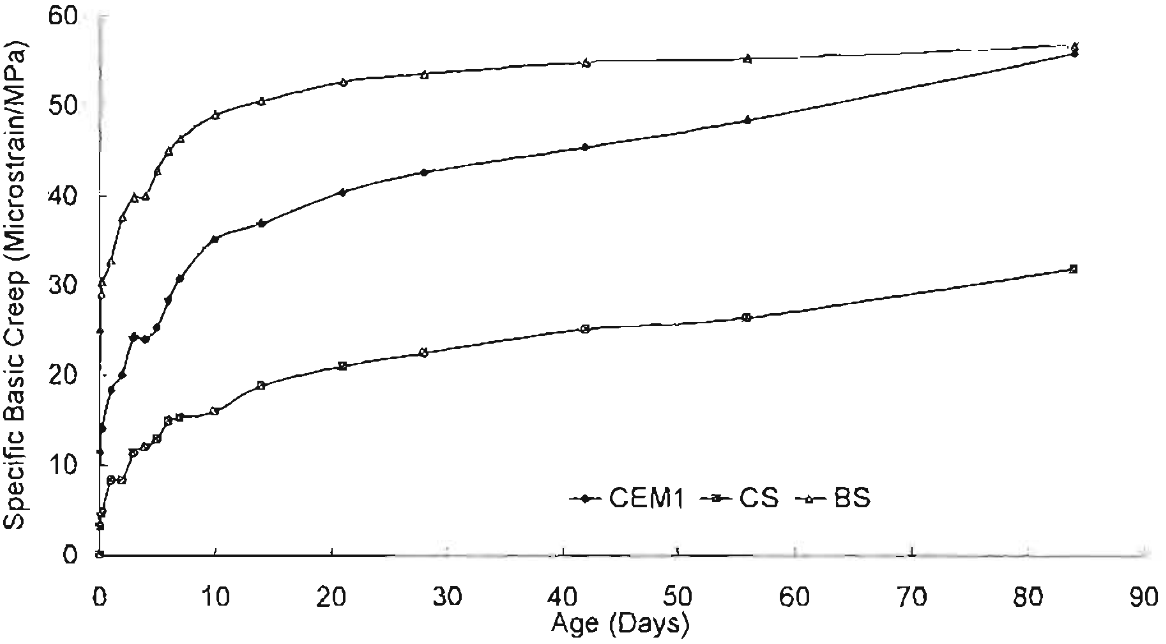

Figure 5 12 Specific basic creep of concrete (w/b = 0.5)

Table 5.2: 5-Year extrapolated specific basic creep

Binder Type	Specific basic creep (Microstrain/MPa)
CEM I	107
CS	61
BS	109

5.8.3 Comparison of Total and Basic Creep

Table 5.3: Percentage of specific basic to specific total creep

Specific basic/total creep (%)		
CEM I	**CS**	**BS**
68.6	45.1	65.7

Table 5.3 shows that the basic creep of blastfurnace and CEM I concretes are about one-third lower than the total creep results whereas the corresponding percentage for corex slag concrete is 55 %. This implies that drying creep is more significant in corex slag concrete. The fact that the creep under no moisture loss is low could possibly be detrimental to the material. This is because basic creep predominates in large columns, thick walls and any other member kept saturated. Therefore, the positive effects associated with creep, such as the relief of stress concentrations caused by shrinkage or temperature changes, are decreased.

5.9 DISCUSSION OF RESULTS FOR CREEP AND SHRINKAGE

The low creep deformation exhibited by corex slag concretes can possibly be attributed to its greater maturity and strength reached at an early age. Referring to Table 5.1, it can be seen that the stress:strength ratio was lower in the case of the corex slag samples compared to blastfurnace slag specimens. Hence, the lower stress:strength ratio resulted in lower creep strains. The stress:strength ratios of the CEM I mixes were almost identical to the corex slag ones, but these concretes still exhibited larger strains. This is probably due to the fact that the corex slag concrete samples showed a greater increase in strength after loading. However, this explanation applies mainly to creep samples having a low water:binder ratio.

The creep strains displayed by the blastfurnace slag samples can also be explained by the compressive strength and, hence, maturity of the material. The high initial deformation recorded is due to the relatively low maturity of the specimens, as indicated by the compressive strength values, and this is in accordance with Rüsch et al (1983). However, blastfurnace slag concretes continue to gain in strength while under load, consequently decreasing the stress:strength ratio. If all the samples were loaded at the same stress:strength ratio, the high creep strains associated with blastfurnace slag concretes would then be minimised. It must be remembered that although creep is mainly a long-term effect caused by sustained loading, it is also a very important phenomenon for early age concrete. Another explanation for the creep behaviour of blastfurnace slag concretes lies in the fact that, being weaker at earlier ages, the material could possibly show more microcracking at an early age.

The basic creep results can also be discussed on the same basis. However, the lower magnitude of creep deformations can be attributed to the longer hydration period resulting from the retention of the moisture within the specimens. Furthermore, Rossi et al (1993) pointed out the direct relationship between basic creep strains and the creation of microcracks in concrete. This implies that the large initial strains in blastfurnace slag concrete might be attributed to a high level of microcracking which in turn can be explained by the relatively low degree of maturity. However, microstructural work will have to be performed in order to assess the exact effects of microcracking on creep.

In the case of shrinkage, the effect of compressive strength is not as important as for creep. In fact, the determining factor is the paste fraction of the concrete as the paste shrinks when it dries. Shrinkage is also usually affected by the stone and water contents but these parameters were kept constant in all the mixes, thus effectively eliminating them as influencing factors. Consequently, the only effect the water:binder ratios had on the mixes were to alter the cement content and, hence, the volume of the paste. For a water binder ratio of 0.4, more paste was available for hydration and, as a result, more shrinkage was expected to occur. However, this was not the case as at a low water:binder ratio, the paste was also stiffer, consequently offsetting the effects of shrinkage. This is illustrated by the corex slag result which had the lowest shrinkage and highest strength. The fact that the blastfurnace specimens had the highest initial shrinkage strains and then decreased with time as the strength (and hence stiffness) of the material increased also demonstrates the same point. For water:binder ratios of 0.5 and 0.6, the strength of the mixes did not affect the shrinkage strains as the mixes with the least shrinkage were not the strongest ones.

Furthermore, the fineness of the slags had no apparent effect on shrinkage and this is also probably due to the stiffer paste resulting from the finer material.

It is interesting to note that for the three water:binder ratios considered, the shrinkage strains were all in the same range, thus further showing that the shrinkage is almost independent of the water:binder ratio for the mixes investigated. Another point of interest is the fact that the shrinkage deformations of the corex slag samples changed from smallest at a water:binder ratio of 0.4 to greatest at a water:binder ratio of 0.6, even though the strength was highest in all cases. A possible explanation lies in the fact that there could be a change in the microstructure of the material with an increase in the water:binder ratio. This statement is partially supported by the oxygen permeability index results (See Chapter 6). For a 28-day curing regime, the corex slag samples, with a water:binder ratio of 0.6, was the only one having an OPI value of less than 10. It should, however, be borne in mind that the oxygen permeability index test gives only a crude indication of the microstructure and for a better understanding of the behaviour of the corex slag, in depth microstructural work should be performed.

The high initial creep deformation of blastfurnace slag concrete, observed in this research, which became less significant with time was also noted by Chern and Chan (1989) and Alexander (1994b). Furthermore, the creep characteristics of corex slag concrete could be related to the findings of Tazawa et al (1989) who showed that concrete containing slag with the highest specific area exhibited the lowest specific creep. The shrinkage results for blastfurnace slag concrete were consistent with the findings of Boukendakdji et al (1996) and Numata et al (1986). However, the effect of the increased fineness of corex slag on shrinkage was not as reported by Olorunsogo (1997).

5.10 CREEP AND SHRINKAGE PREDICTIONS

It is of vital importance to predict realistically the creep and shrinkage deformations of concrete structures as they impact on the durability and long term serviceability. Errors in the prediction of these phenomena have been one of the causes of serviceability problems of concrete structures in many parts of the world.

Simple code-type models are available for the predictions of creep and shrinkage for structures that are not sensitive to deformation. These models are based on empirical considerations and hence do not require laboratory results as input. The prediction methods which were considered in this investigation include:

- British Standards Institution – Structural use of concrete, BS 8110-Part 2 (1985)
- American Concrete Institute- ACI Committee 209 (1992) – Revised (1996)
- Comité Euro-International du Beton – Féderation Internationale de la Precontrainte- CEB-FIP Model Code 1990
- International Union of Testing and Research Laboratories for Materials and Structures – RILEM Model B3 (1995)

A detailed explanation of the prediction equations, and their limitations together with the various correcting factors considered are given in the relevant references.

5.10.1 Assumptions

BS 8110 (1985)

The effective section thickness was calculated, using the BS standard, to be 50 and 52.5 mm for prism and cylinder samples respectively. However, the minimum effective thickness given in the BS standard creep monograph is 150 mm and no guidance is provided on how to adapt the code for smaller sections. Consequently, a size factor, based on the CEB-FIP (1990) model, was applied to convert the 150 mm effective thickness creep factor and shrinkage strains values to the equivalent 52.5 and 50 mm values respectively.

In the CEB-FIP model, the nominal creep factor was calculated for effective section thicknesses of 52.5 and 150 mm and the ratio was used as the correcting factor for the BS code. The same principle was used to adjust the shrinkage strains given in the BS code. The correcting factors are given in Table 5.4. In the case of basic creep predictions, an effective thickness of 600 mm was used.

Table 5.4: Size factors for creep and shrinkage

	CEB-FIP	BS 8110	
	Size factor	**150 mm values**	**50/52.5 mm values**
Creep factor	1.167	3.0	3.5
6-month Shrinkage	1.894	160	303
30-year Shrinkage	1.031	350	361

This method assumes that 40, 60 and 80 % of the ultimate creep occurs during the first month, six months and thirty months of loading respectively. From this information, Marques, as reported by Fanourakis (1998), developed an equation to predict the creep strain at any other age. This equation was used in this research.

$$\% \text{ of ultimate creep} = 100[0.257906(\log_{10}t) + 0.028622] \quad \text{for } t \geq 1 \text{ day}$$

where t = age after loading (days)

For shrinkage strains at ages other than the 6-month and 30-year values given in the code, the following hyperbolic equation was used.

$$\varepsilon_{sh}(t) = \frac{t}{a+bt}$$

where $\varepsilon_{sh}(t)$ = shrinkage strain at age t
t = age after drying has started (days)
a and b = constants

The constants a and b were determined by using the 6-month and 30-year values given in the code.

ACI (1996)

In this code, the correction factor for the slump of the fresh concrete, γ_{s}, was calculated from the slump value before the addition of plasticizer. Also, the correction factor for the air content of the concrete, γ_6, was taken as 1 as the exact value of the air content in the mixes was not known. In the case of the basic creep prediction, the effective thickness was taken to be 1200 mm as the ACI equation gives an effective thickness twice that of the British Standard.

ACI :
Effective thickness = 4V/S
British Standard :
Effective thickness = 2V/S

where V is the volume of the sample
S is the exposed surface area

CEB-FIP (1990)

It was assumed that blastfurnace slag concrete would behave as a slow hardening material, hence the age of loading was adjusted accordingly. Corex slag concrete, on the other hand, was assumed to have a normal hardening rate. The effective thickness for the basic creep prediction was considered to be 600 mm.

RILEM (1995)

In the Rilem model, the blastfurnace blend was assumed to act as a type II cement and the effective cross section thickness was also taken as 600 mm for basic creep consideration.

5.10.2 Calculation of Coefficients of Variation

The statistical evaluation of the different prediction models has been performed by using the coefficient of variation method developed by Bažant et al (1995). This method quantifies the degree to which the predicted creep and shrinkage values deviate from the measured ones at the same age. The coefficient of variation, which is expressed as a percentage, is calculated from the following equations.

$$\omega_j = \{[\Sigma_i \Delta^2{}_{ij}/(n-1)]^{1/2}\}/J_i$$

in which

$$J_i = \Sigma_j J_{ij}/n$$

where,

ω_j = coefficient of variation for data set j

Δ_{ij} = deviation (vertical) between the measured and predicted value for data point i on data set j

J_{ij} = measured values (labelled by subscript i) of specific creep in the data set number j

n = total number of data points in the set

The overall coefficient of variation (ω_{all}) was used to estimate the average coefficient of variation of a number of independent coefficients of variation, as follows:

$$\omega_{all} = [\Sigma_j \omega j^2/N]^{1/2}$$

where N = number of sets considered

5.10.3 Creep Predictions

Total creep predictions

The measured and predicted specific total creep graphs, for a water:binder ratio of 0.4, are shown in Figure 5.13. The results for the other two water:binder ratios are presented in *Appendix D*. Table 5.5 gives the coefficient of variation of each model compared with the measured values.

Table 5.5: Coefficients of variation (%) of predicted specific creep values

Mix	ACI	CEB-FIP	RILEM-B3	BSt	ω_{all}
Water:Binder = 0.4					
CEM I	66.3	32.4	28.9	19.0	40.7
CS	48.8	10.3	59.3	28.4	41.3
BS	64.0	36.8	9.1	25.1	39.2
Water:Binder = 0.5					
CEM I	62.7	25.7	41.9	19.0	41.0
CS	53.7	25.1	32.8	10.7	34.3
BS	53.8	31.3	10.5	19.3	33.0
Water:Binder = 0.6					
CEM I	71.2	48.4	31.1	43.2	50.6
CS	70.5	54.3	39.4	41.9	53.0
ω_{all}	61.9	35.5	35.2	28.0	

It is evident from the various graphs that the ACI-1996 model underpredicted the specific creep of the different mixes at all ages. The coefficient of variation varied between 49 and 71 %, with an overall coefficient (ω_{all}) of 62 %. The Rilem-B3 and BSt models, on the other hand, had the closest prediction to the 120-day measured values, with the Rilem method generally slightly overpredicting and the BSt method underpredicting the measured value. The Rilem prediction model was the only model where the initial predicted creep deformations exceeded the measured values.

In the case of the corex slag concretes, the Rilem model overpredicted the specific creep at all ages for a water:binder ratio of 0.4 and until 42 days after loading for a water:binder ratio of 0.5. This is because of the exceptionally low creep deformations exhibited by the corex slag concretes. Furthermore, for a water:binder ratio of 0.6, the four prediction models produced coefficients of variation in excess of 30 % for both corex slag and CEM 1 concretes.

The Rilem method produced excellent results with blastfurnace concretes with variations in the specific creep values of the order of 10 %. Moreover, when the overall coefficients of variation of the four predicting models were considered, the BSt model was found to be more accurate, with the CEB-FIP and Rilem models giving virtually the same accuracy, while the ACI method produced coefficients of variation almost twice as large as the others.

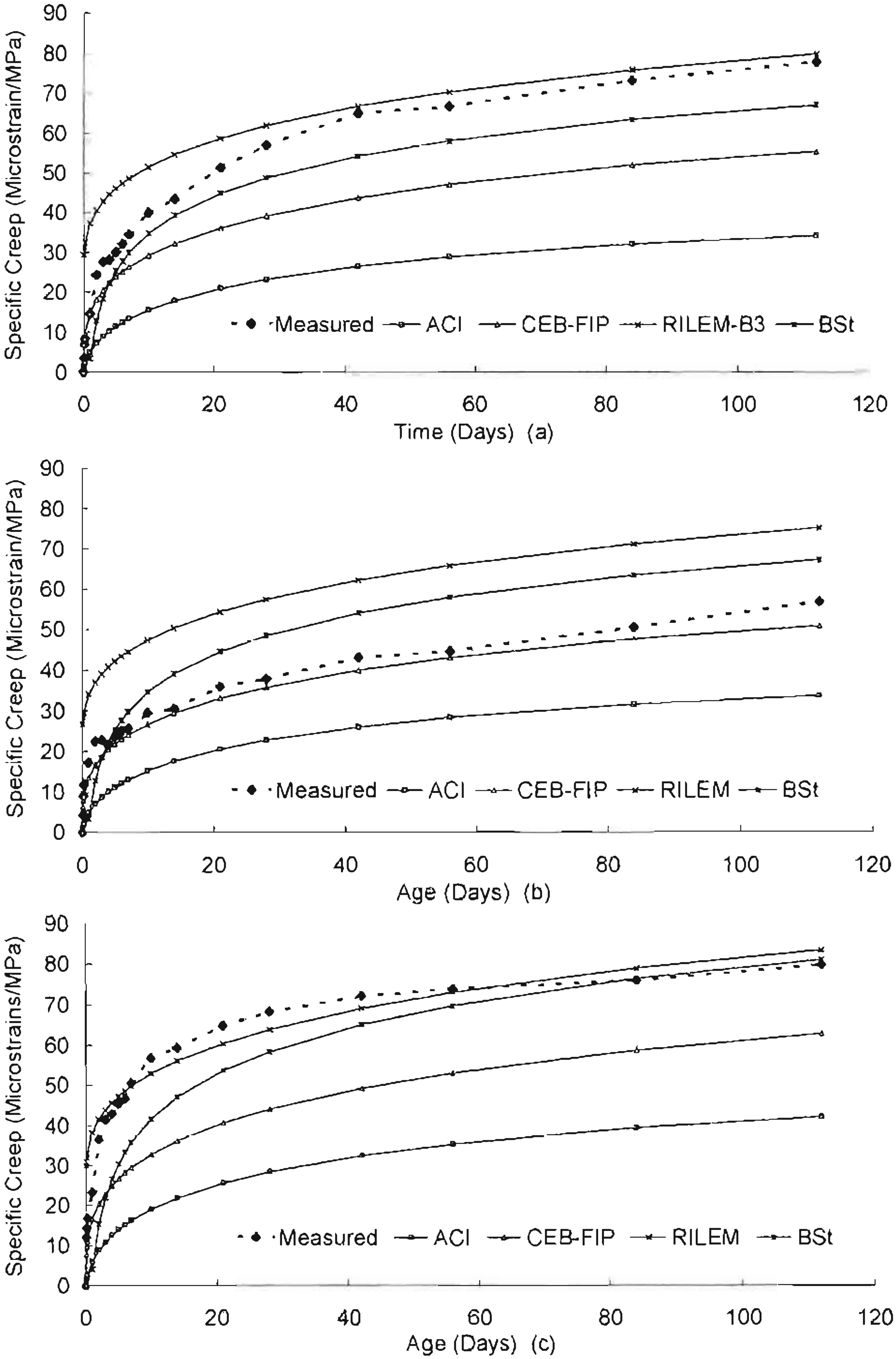

Fig. 5.13: Predicted specific creep for (a) CEM I (b) CS (c) BS concretes (w:b = 0 4)

Table 5.6. 5-Year predicted specific creep values (Microstrain/MPa)

MIX	Extrapolated	ACI	CEB-FIP	RILEM-B3	BS
Water:Binder = 0.4					
CEM I	113	49	80	124	106
CS	82	48	73	117	105
BS	115	60	90	130	126
Water:Binder = 0.5					
CEM I	127	57	94	128	110
CS	113	58	82	116	114
BS	132	81	105	135	150
Water:Binder = 0.6					
CEM I	179	69	100	129	122
CS	197	74	95	123	125

Table 5.6 gives the 5-year extrapolated and predicted specific creep values It is clear from the above data that at 5-years, the BS and Rilem models with water:binder ratios of 0.4 and 0.5 overpredict the specific creep values. Otherwise, the other two codes underpredict the 5-year deformations In the case of the ACI model, the predicted values are up to 61 % lower than the extrapolated values from the measured results On the other hand, the maximum underprediction arising from the Rilem model is only 35 %.

From the results presented above, it can be said that, generally, the higher the water binder ratio, the lower the accuracy of the predictions. This was also observed by Fanourakis (1998) and Ballim (2000) Also, the fact that models like the BS, Rilem and CEB-FIP give approximately the same overall accuracy implies that the degree of complexity of any particular method has no real effect on the quality of the results.

Basic creep predictions

Figure 5.14 gives the specific basic creep results for the water.binder ratio of 0.5. The coefficients of variation are given in Table 5 7.

It is worthwhile noting that for both blastfurnace slag and CEM I concrete samples, all prediction techniques underestimate the specific creep values. However, the Rilem model still gave good results, with coefficient of variation of about 19 %. This is because it is the only model which has a distinct equation for calculating basic creep effects. In the case of the corex slag concrete, the Rilem and BS models overpredicted the actual measured specific creep values. This is probably due to the exceptionally low basic creep characteristics exhibited by corex slag concrete. In fact, the Rilem model had a coefficient of variation of 94.2 %. It can, therefore, be said that this particular model is not suitable for concretes showing low basic creep potential. In such situations, models such as the CEB-FIP would be preferred.

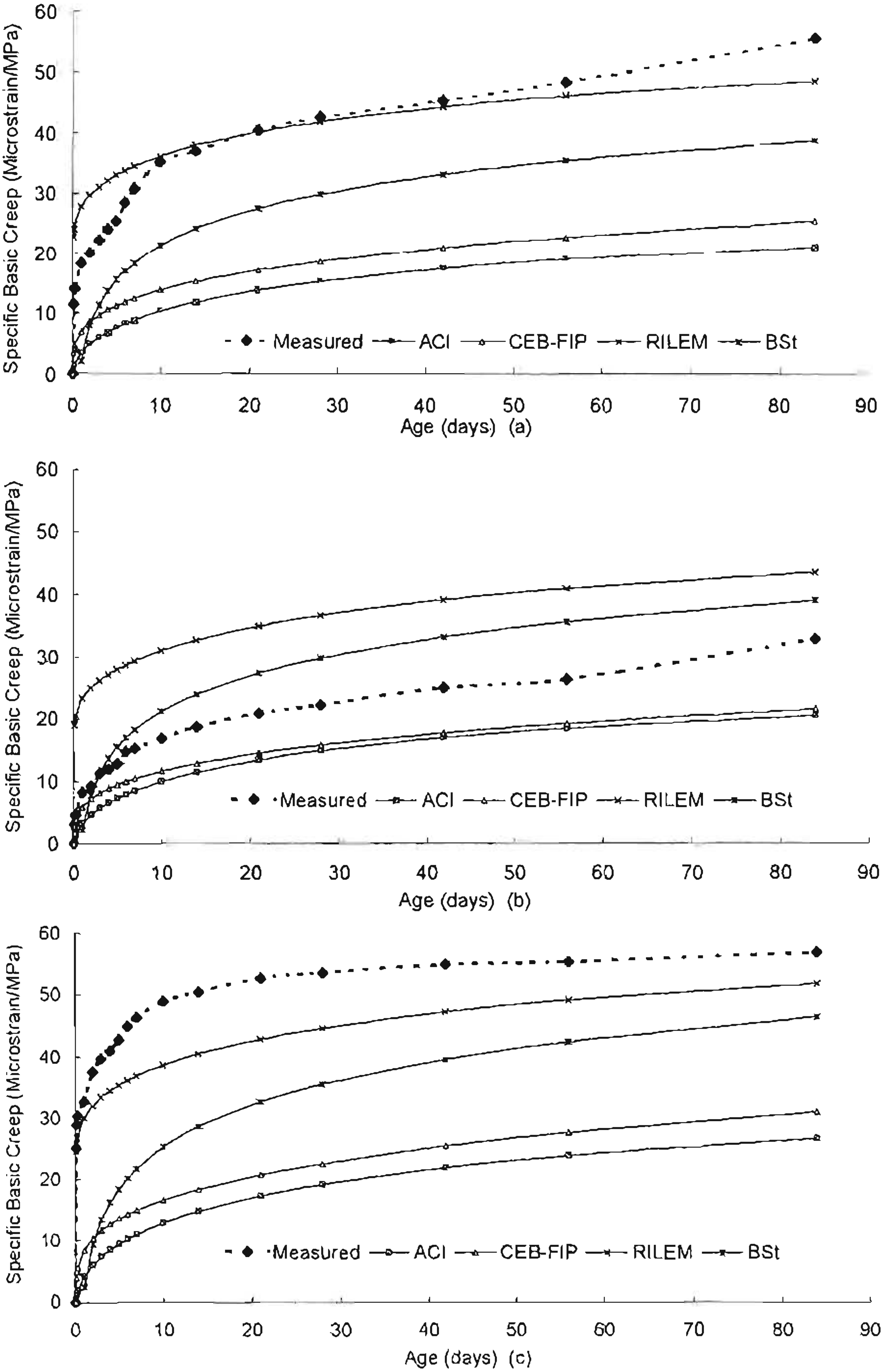

Fig. 5.14: Predicted specific basic creep for (a) CEM I (b) CS (c) BS concretes

Table 5.7: Coefficients of variation (%) of predicted specific basic creep values

Mix	ACI	CEB-FIP	RILEM-B3	BSt	ω_{all}
Water:Binder = 0.5					
CEM I	79.3	67.5	19.7	43.1	57.2
CS	47.2	37.8	94.2	34.9	58.6
BS	77.6	68.5	18.1	52.6	58.8
ω_{all}	69.6	59.7	56.5	44.1	

Table 5.8: 5-Year predicted specific basic creep values (μstrain/MPa)

Mix	Extrapolated	ACI	CEB-FIP	RILEM-B3	BSt
Water:Binder = 0.5					
CEM I	107	32	49	69	65
CS	61	31	42	64	65
BS	109	41	60	72	77

For the 5-year results, the predicted deformations for the blastfurnace and CEM I concretes were both below the extrapolated ones. In fact, the predicted ACI model values were 62 and 70 % lower for the respective mixes. In the case of corex slag samples, the predicted values at an extended duration of time were more accurate that for the early age with the Rilem and BSt models predicting the 5-year deformations to within 7 % of the measured ones. It should also be borne in mind that the measured values were calculated from three-month results. However, referring back to Fig. 5.12, it can be seen that the curves for the corex slag and CEM I specimens were still on an increasing trend and, thus, the 5-year deformation based on 6-month results, for example, could be even greater.

Based on the high uncertainties associated with the predictions, it can be said that it is not advisable to simply adjust the prediction models to obtain the basic creep characteristics of different mixes.

5.10.4 Shrinkage Predictions

The shrinkage predictions for a water:binder ratio of 0.4, based on the various codes, are given in Figure 5.15. The results for the other two water:binder ratios considered are given in *Appendix D*.

It is clear from the different graphs that the BSt model for shrinkage prediction underpredicted the strains at all ages. In fact, this particular model had a coefficient of variation as high as 51 %. Furthermore, it is also evident from the graphs that for water:binder ratios of 0.4 and 0.5, all prediction models underpredicted the strains for CEM I concretes while for the two slag concretes, only the ACI and Rilem models gave shrinkage values greater than the measured ones.

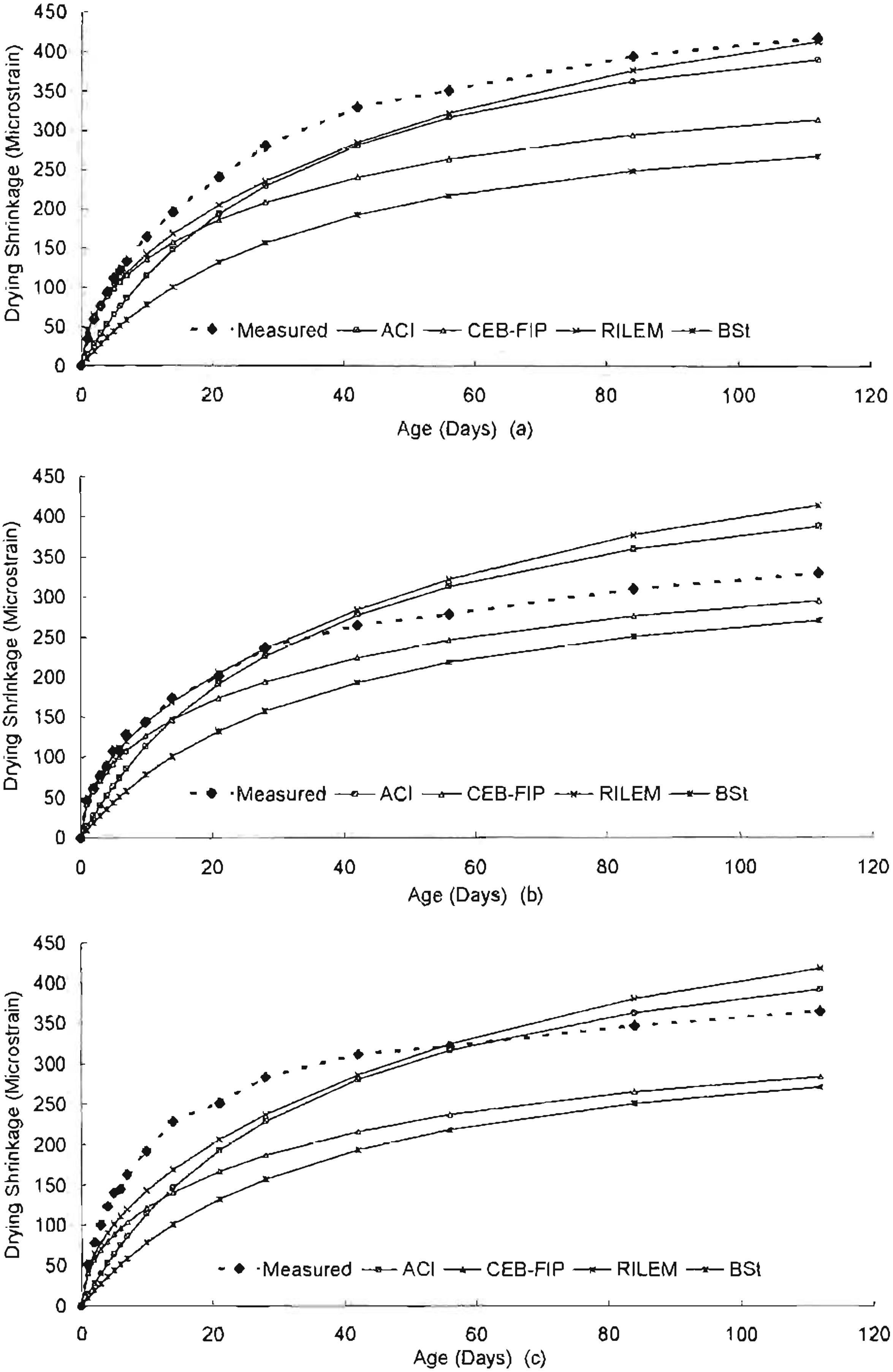

Fig. 5.15 Predicted drying shrinkage for (a) CEM I (b) CS (c) BS concretes (w:b = 0.4)

Table 5.9: Coefficients of variation (%) of predicted shrinkage strains

Mix	ACI	CEB-FIP	RILEM	BSt	ω_{all}
		Water:Binder = 0.4			
CEM I	21.4	29.3	12.2	51.4	32.0
CS	21.5	15.3	18.6	37.4	24.7
BS	29.0	34.5	18.8	50.0	34.9
		Water:Binder = 0.5			
CEM I	18.3	21.6	10.2	50.8	29.5
CS	18.5	7.8	18.9	36.2	22.8
BS	24.0	17.7	35.4	26.2	26.6
		Water:Binder = 0.6			
CEM I	16.0	30.2	29.0	34.2	28.2
CS	5.8	23.1	12.5	48.8	27.8
BS	14.9	14.2	17.7	37.7	23.2
ω_{all}	19.8	23.0	20.7	42.3	

It is interesting to note that for all the concretes considered, the Rilem model gave the highest shrinkage strains, for ages greater than 28-days, followed by the ACI, CEB-FIP and BSt models respectively. The CEB-FIP model predicted the behaviour of concretes very well for water:binder ratios of 0.4 and 0.5, especially at the early ages. For shrinkage at extended times, the ACI and Rilem models were generally more accurate. The overall coefficient of variation, given in Table 5.9, for the ACI, CEB-FIP and Rilem models were very similar, ranging from 19.8 to 23.0 %.

Table 5.10: 5-Year predicted shrinkage strains (μstrain)

MIX	Extrapolated	ACI	CEB-FIP	RILEM-B3	BSt
		Water:Binder = 0.4			
CEM I	561	508	415	566	350
CS	457	500	385	556	350
BS	483	504	370	567	350
		Water:Binder = 0.5			
CEM I	583	505	458	582	350
CS	469	506	421	568	350
BS	477	515	404	583	350
		Water:Binder = 0.6			
CEM I	515	518	474	589	350
CS	570	538	461	583	350
BS	514	529	427	596	350

Table 5.10 gives the 5-year extrapolated and predicted shrinkage values of all the mixes considered. For the BS model, shrinkage strains of up to 39 % lower were generated. The CEB-FIP and Rilem models underpredicted and overpredicted the 5-year shrinkage deformation values respectively for all samples considered, the maximum under and overprediction being 24 and 23 % respectively. Concerning the ACI model, the predicted values were generally greater than the extrapolated ones. However, they varied by less than 10 % from the extrapolated values, hence, making the modeling very good.

In the case of shrinkage predictions, it is not very clear if an increase in the water:binder ratio affects the accuracy of the values as was the case with creep.

Furthermore, the coefficients of variation of the various mixes were generally better than those for creep, indicating that the shrinkage models can be used with more confidence than the creep ones. This was also noted by Ballim (2000). Finally, as was the case with creep predictions, the accuracy of the shrinkage predictions did not increase with the complexity of the method used.

5.11 CONCLUSIONS

- Corex slag concretes, loaded at the early age of 7 days, generally exhibited the lowest creep deformations compared to blastfurnace slag and CEM I concretes. For water:binder ratios of 0.4 and 0.5, the 112-day creep strains for corex slag concretes were 29 and 28 % and 15 and 11 % lower than for blastfurnace and CEM I concretes respectively. However, for a water:binder ratio of 0.6, the 112-day creep strain for corex slag concrete was 10 % higher than for the CEM I control.

- The one day creep deformations experienced by blastfurnace slag concretes were 36 and 79 % higher than corex slag concretes at water:binder ratios of 0.4 and 0.5 respectively.

- The low creep behaviour of corex slag concrete was also noted in the basic creep experiments, where the specific creep for corex slag concrete was around 44 % less than for both CEM I and blastfurnace slag concretes, at 84 days.

- From the low total creep deformation characteristics, it can be concluded that this makes corex slag concrete ideal for use in prestressed concrete structures.

- For a water:binder ratio of 0.4, corex slag concretes showed the least shrinkage strains after 112 days of drying. The strains were 10 and 22 % lower than for the blastfurnace and CEM I samples respectively. However, at higher water:binder ratios, neither the type of binder nor the water:binder ratio have a significant impact on the shrinkage strains at extended ages.

- A comparison of the experimental creep and shrinkage values from this investigation with those predicted using the different models revealed that there was no defined model which provided the most accurate predictions for all three tests, namely total creep, basic creep and shrinkage, for all parameters involved. For creep prediction, the British Standard model was the most accurate with an overall coefficient of variation of 28 %, but for shrinkage prediction, the BS model was the least accurate with coefficient of variation of 42 %.

- It was found that the shrinkage predictions generally had lower coefficients of variations, hence concluding that the shrinkage models can be used with more confidence.

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CHAPTER 6

DURABILITY PROPERTIES OF COREX SLAG CONCRETE

The durability of a structure is defined as the ability of that structure to continue its intended functions of maintaining its required strength and serviceability during the specified or expected service life (Neville, 2001). More specifically, durability may be defined as the resistance of concrete to internal and external physical and chemical actions and to mechanical effects (Douglas, 1987).

The durability of concrete has received much importance lately due to the rapid deterioration of many modern concrete structures. It must be appreciated that no concrete yet manufactured will continue to fulfil its role indefinitely and that concrete can be durable under one set of environmental conditions of exposure and not necessarily under other conditions.

Presently, the only controls on durability are the guidelines and standards laid down in the various codes of practice. These guidelines generally give minimum 28-day compressive strengths and cover to reinforcement as measures of durability

According to Roper and Baweja (1994), there are three important procedural aspects which need to be accepted if durability is of vital significance in the function of a structure. These are:

> "As ensured durability comes at an initial higher cost, this must be allowed for in any construction planning.
>
> Time and attention should be given to the proper selection of materials at the design stage in the same manner as these are devoted to structural considerations.
>
> If special testing of mixture proportions, procedures or even prototype sections are called for, sufficient scope and time should be available to the concrete technologist to assess the results before final decisions are made."

Consequently, it is of utmost importance for structural engineers to foresee the various exposure conditions to which the given structure could be subjected during its service life at the design stage, and that enough time is given to the selection of the appropriate materials. Also, all costs for improved durability should be incorporated in the bill of quantities, either implicitly or explicitly or both.

In this chapter, the durability properties of corex slag concretes are investigated, in particular the sorptivity, permeability, alkali-aggregate reaction and resistance to chloride and carbon dioxide ingress. Being a new product, it is of vital importance to characterise the durability properties of corex slag concrete in aggressive environments so that design and materials engineers can take an informed decision when choosing the materials for a new structure.

6.1 EFFECT OF CURING ON DURABILITY OF CONCRETE

The importance of curing in strength development is well known but it is now recognised that curing has even greater effect on the durability of concrete. The cover concrete provides protection against attack by aggressive agents and, according to Ballim (1991a), improvements in the microstructure of the covercrete are vital to enhanced durability. These improvements are provided by curing.

The Highway Research Board, as quoted by Ballim (1991a), defines curing as:

> "the process of maintaining a satisfactory moisture content and a favourable temperature in concrete during the period immediately following placement so that hydration may continue until the desired properties are developed to a sufficient degree to meet the requirements of service"

This definition can be applied to the cover concrete as it is the part of the structure which is most affected by premature drying. Inadequate protection from aggressive environments will result if proper care of the concrete is not taken.

Dias (1997), based on the work of Chen and Parrott, reported that curing periods in excess of 7 days have no significant effect in reducing the permeability of normal portland cement concretes. However, longer curing duration was beneficial to the permeability of blended cements. This was also confirmed by Dias (1997), Swamy and Darwish (1997) and Ballim (1991a). The experiments performed by Ballim also showed that, at low water:binder ratios, the permeability and sorptivity of concrete samples cured for three and 28 days were about the same (Fig 6.1 and 6.2). Furthermore, the results indicate that the quality of concrete increases with depth.

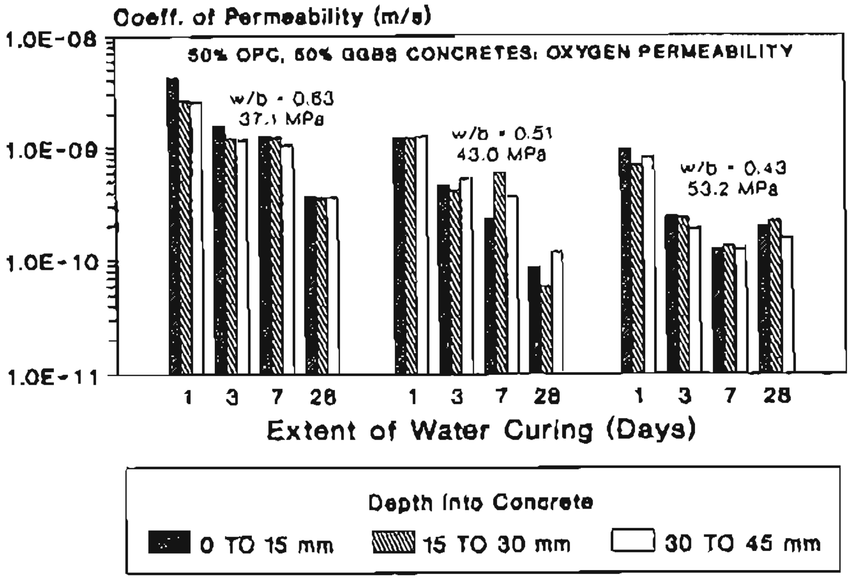

Fig. 6.1: Effect of curing on permeability of slag concrete (Ballim, 1991a)

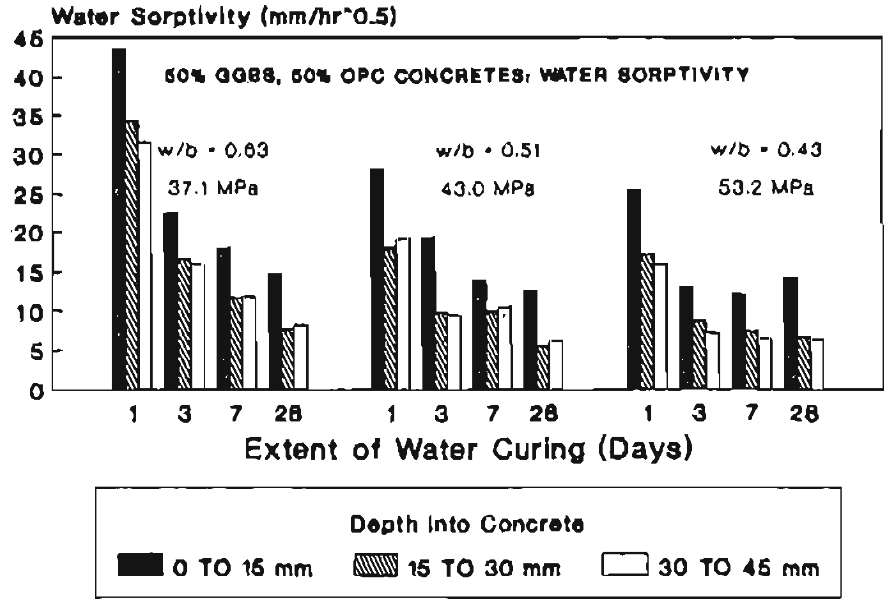

Fig. 6.2: Effect of curing on sorptivity of slag concrete (Ballim, 1991a)

Curing also affects the pore sizes and porosity. Ramezanianpour and Malhotra (1994) found that for full moist curing, plain portland cement mortar had the lowest porosity followed by 50 % slag mortar. However, for 3-day moist curing, the control portland cement mortar had almost the same porosity as for full moist curing but the 50 % slag mortar had slightly higher porosity. Similar results were reported by Kasai et al (1983). Swamy (1997), on the other hand, found that the quality of the internal microstructure and porosity are improved with the incorporation of slag in concrete. Using mercury-intrusion techniques, he showed that the total intrusion volume and total porosity were lower for slag concretes than portland cement controls, both under continued water curing. This was also confirmed by Roy and Parker (1983). When the slag fineness was increased in the experiment from 453 to 786 m^2/kg, no significant improvements in pore volume were noted by Swamy.

6.2 PENETRABILITY OF CONCRETE

The penetrability of concrete is defined as the ease with which fluids, or ions can enter the concrete pore structure. Permeability and sorptivity influence the penetrability of concrete.

6.2.1 Permeability

Permeability of concrete is defined as a measure of the capacity for concrete to transfer fluids through the pore structure under an externally applied pressure whilst the pores are saturated with the particular fluid. Permeability is an important aspect of concrete durability as it will influence the ease with which aggressive agents can penetrate into the concrete.

It is reported by Mehta and Monteiro (1993) that concrete has a higher permeability than both plain cement paste or mortar. This is attributed to microcracks present in the interfacial transition zone which are large enough to provide interconnections in the pore systems. However, Carcasses et al (1998) showed that, for high performance concrete, the influence of the ITZ on permeability is very small but no conclusions could be drawn for concrete having water:binder ratio of around 0.5. Therefore, the beneficial impact of slag on the ITZ cannot be directly related to improved durability.

According to Swamy (1997), slag has an effect on the pore size distribution. A decrease in large pore volume and an increase in fine pore volume are observed and these changes have positive and decisive influences on the permeability of concretes. This was also noted by Mehta (1983), Bakker (1983) and Luping and Nilsson (1991) who attributed the reduction in pore volume to the secondary hydration products filling the large pores and possibly to the generally higher fineness of slag.

Oxygen permeability experiments performed by Swamy (1997), Swamy and Darwish (1997) and Sudjono and Seki (2000) showed that the permeability of concrete is remarkably reduced with the addition of blastfurnace slag. However, at high slag replacement levels and limited water curing, the full permeability potential was not completely achieved. Ballim (1991a), van Dijk (1998) and Kasai et al (1983), on the other hand, found that the permeability of concrete increases with the use of slag and attributed it to the longer time required for the densification of the cement matrix (Fig. 6.3). Osborne (1989), based on field data, reported similar observations.

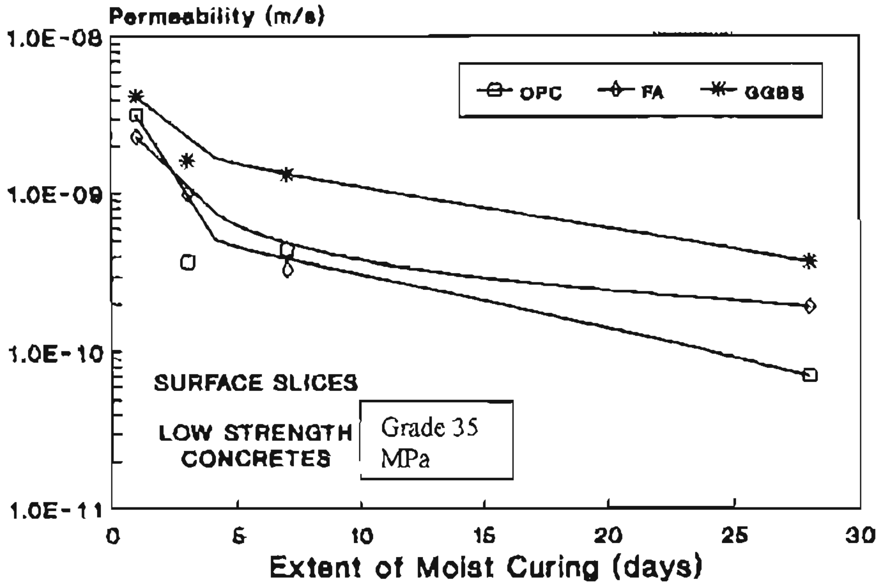

Fig 6.3: Effect of slag on oxygen permeability of concrete (Ballim, 1994)

The effect of water:binder ratio on the oxygen permeability index (OPI) was investigated by Mackechnie (2001) and the results are indicated in Figure 6.4. The concept of durability index is discussed in Section 6.6. The reduction of the oxygen permeability index with increasing water:binder ratio is a result of a less dense microstructure at higher water:binder ratios. Consequently, for a concrete to have high resistance to penetration by fluids, and hence to be durable, low water:binder ratios should be used.

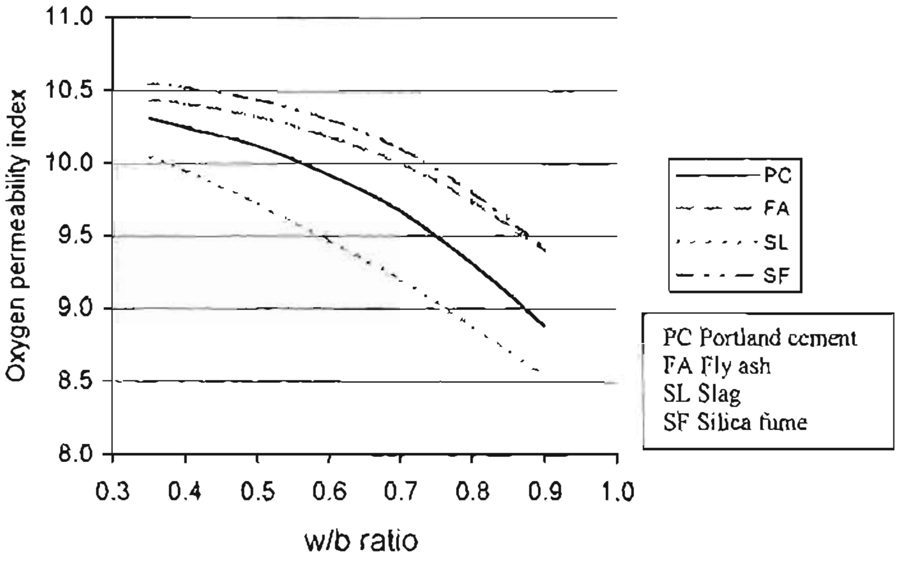

Fig. 6.4: 28-day OPI results for various binders (Mackechnie, 2001)

6.2.2 Sorptivity

Sorptivity is defined as the rate of movement of a wetting front through a porous material under the action of capillary forces. This property of concrete quantifies the effect of wetting and drying at the concrete surface on durability.

Water sorptivity experiments performed by Ballim (1991a) and Ho et al (1986) have shown that the addition of slag to concrete results in an increase in the sorptivity values and, in most cases, the curing had to be increased in order to reach the same durability potential as that of plain portland cement controls (Fig. 6.5).

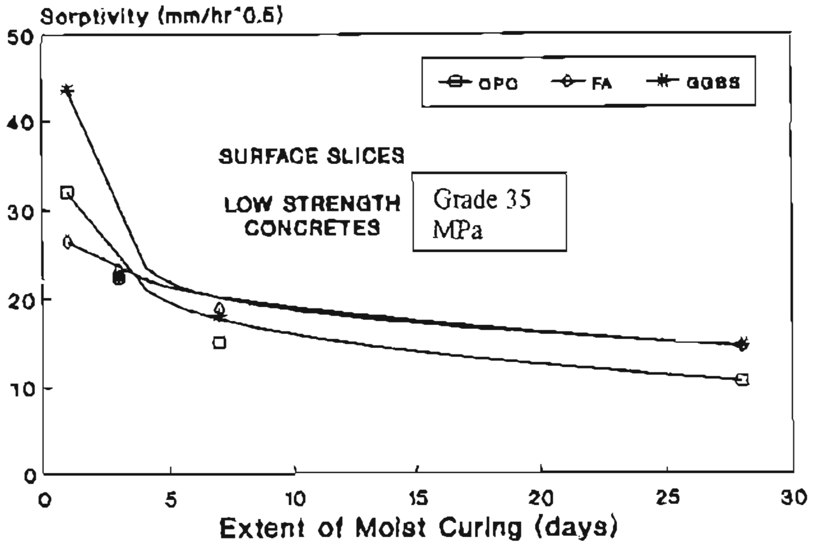

Fig. 6.5: Effect of slag on sorptivity of concrete (Ballim, 1994)

However, according to Ballim, the impact on sorptivity due to changes in moist curing is less marked than in the case of oxygen permeability. Mackechnie (1996), on the other hand, found that ordinary portland cement concrete had higher sorptivity values than slag concrete when moist or wet cured, hence showing the advantages that cement extenders can give when properly treated.

6.3 DETERIORATION PROCESSES

6.3.1 External

Chloride Ingress

Reinforced concrete structures exposed to chloride environments are subjected to extreme conditions which may lead to rapid deterioration. The source of chlorides is associated with the use of de-icing salt in winter in cold climates, and with marine environments. In the case of mild or tropical climates, the problem mainly lies with exposure to seawater. The construction of harbours, breakwaters, marinas and other concrete structures in marine environments can result in serious durability problems if appropriate design, materials and construction and curing methods are not used. The predominant form of deterioration of reinforced concrete marine structures is chloride-induced corrosion of reinforcement.

The chloride ion is very small in size (approximately 3.6Å), is highly mobile and able to penetrate concrete. Therefore, densified microstructures such as those produced by the use of cement extenders, like slag, resist chloride ion migration better than ordinary concretes. The presence of sufficient chloride at the surface of embedded reinforcement may depassivate the oxide film protecting the steel and allow corrosion to occur under favourable conditions of moisture and oxygen availability. Therefore, the durability of reinforced concrete is related to the rate of chloride ingress.

According to Bamforth and Price (1993) and Takeda et al (1997), the most severe attack of seawater on concrete occurs in the splash zone, which is just above the mean sea level of high water. This is followed by the tidal zone which is the zone between the high and low water levels. Both zones are subjected to cycles of wetting and drying which result in a gradual build up of chloride by a process of wetting with seawater, evaporation and salt crystallisation. However, it is reported by Eglinton (1998) that reinforced concrete structures up to several kilometres inland from the coast can also experience the corrosive effects associated with seawater due to the sea spray carried inland by prevailing winds.

Carbonation

Carbonation is the process whereby atmospheric carbon dioxide enters the concrete pore structure and reacts with calcium hydroxide to form calcium carbonate. The process of carbonation results in a reduction of the pH of the pore solution from about 12.5 to 8.3 upon complete carbonation and this, in turn, causes the gamma-ferric oxide layer to become unstable and the steel is depassivated. Corrosion may then occur if the conditions are favourable. Carbonation-induced corrosion is a threat to the durability of reinforced concrete structures and the rate of carbonation is strongly influenced by the moisture content and amount of calcium hydroxide present in the pore structure of the concrete (Basson and Ballim, 1994).

Dry concrete will allow easy access for gaseous diffusion of carbon dioxide but no carbonation is possible in the absence of moisture. Optimum conditions for carbonation are considered to occur at relative humidity values between 40 and 65 % which represents a compromise between access for carbon dioxide and moisture needed for the carbonation reaction. Reinforced concrete structures in the Western Cape region of South Africa are exposed to hot dry summers (conducive to carbonation) followed by cool wet winters which increase the moisture content of the concrete sufficiently to allow corrosion to occur.

Carbonation moves through concrete as a distinct front which does not advance beyond a particular point until all the calcium hydroxide has been converted to calcium carbonate. A schematic of the carbonation process is shown in Figure 6 6. At a pH of 9, the indicator changes colour from pink/purple to colourless, hence indicating the depth of carbonation.

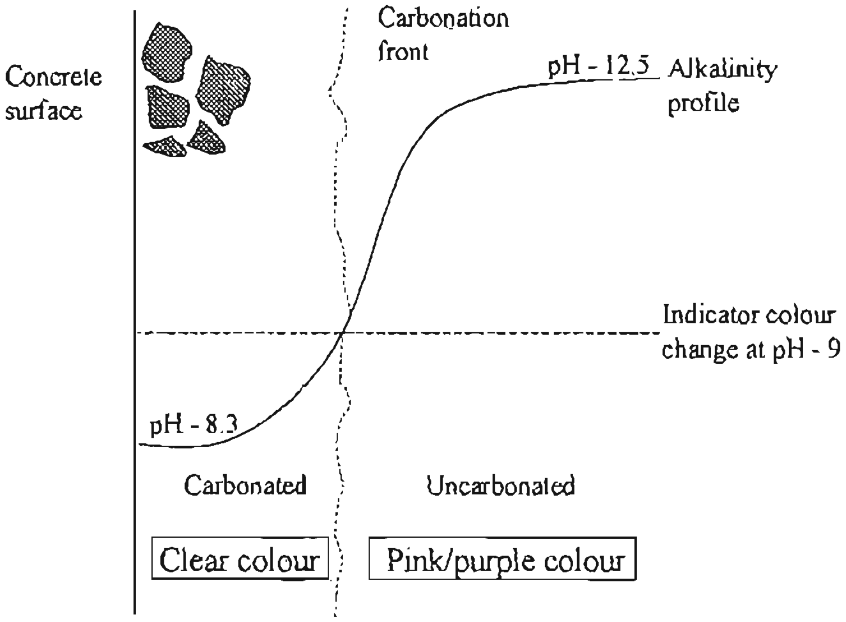

Fig.6.6: Schematic of carbonation process (Mackechnie and Alexander, 2001)

According to Bier et al (1989), carbonation is affected not only by the porosity of the hardened cement paste but also by the chemical composition. They refer more specifically to the CaO content of the cement. The investigators argue that with decreasing CaO content of the cement a higher carbonation depth is observed.

6.3.2 Internal

ASR

Alkali-aggregate reaction (AAR) has been reported as a cause of expansion and cracking of concrete structures in many parts of the world. The most widespread form of AAR is the alkali-silica reaction (ASR), which takes place between alkalis in the concrete and metastable forms of silica, such as opal, trydimite, crystobalite and volcanic glasses which are found in some aggregates. However, in South Africa, the problem lies with strained or microcrystalline quartz.

In South Africa, ASR was first identified in the South Western Cape in 1974 and the same region shows the highest incidence of ASR in the country, where more than half of the concrete structures built with Malmesbury aggregate since 1950 are showing signs of distress (Oberholster, 1987). However, according to Thomas (1997), the structural problems arising from ASR have rarely required the replacement of a concrete structure due to a loss in structural integrity.

For ASR to occur, it is important that a minimum amount of reactive silica is present in the aggregate together with sufficient alkali in the concrete and sufficient moisture According to Hobbs (1992), the external and internal relative humidities must be in excess of about 90 % and 95 %, respectively, for expansion and cracking to result from ASR.

The alkali content of cement is normally measured as the acid-soluble sodium and potassium oxides and is expressed as an equivalent percentage of sodium oxide as follows:

$\% Na_2O \text{ equivalent} = \% Na_2O + 0.658 \% K_2O$

Normally, cement with Na_2O equivalent of 0.6 % or more is regarded as high-alkali cement and should not be used with a potentially alkali-reactive aggregate.

6.4 MECHANISMS OF DETERIORATION PROCESSES

6.4.1 Chloride Ingress

Movement of chlorides into concrete may be caused by effects such as absorption, diffusion, permeation, conduction and convection. In most cases, it is, however, safe to assume that absorption is only significant near the surface of concrete while diffusion is the primary transport mechanism in the concrete interior (Mackechnie, 1997a).

The main process by which chlorides enter concrete is ionic diffusion through capillary and gel pores (Jones, 1992). This was also reported by Taylor (1992), based on the work of Page et al. According to Lawrence (1998), movement of chloride ions within concrete involves an exchange of chloride for hydroxyl ions rather than a simple diffusion process and in the case of blastfurnace slag concrete, the lower rate of penetration of chlorides is probably because of a lower concentration of free hydroxyl ions, giving a smaller OH^--Cl^- exchange capacity. Furthermore, the degree of connectivity of the pores is also important and cement extenders can assist by refining the pore structure, hence increasing the resistance to ingress by chloride ions.

It is reported by Basson and Ballim (1994) that the ionic diffusion of chlorides into concrete only occurs when moisture is available in the pore structure of concrete and higher moisture content results in higher diffusion rates.

6.4.2 Carbonation

Carbonation is the reaction between carbon dioxide from the atmosphere and the hydration products of the hardened cement paste. This is the result of the partial replacement of the pore water in the concrete by air. The carbon dioxide dissolves in the pore solution of cement paste to produce carbonic acid which then reacts with the calcium hydroxide to produce calcium carbonate. Hydroxyl ions and calcium ions are obtained by the dissolution of calcium hydroxide. The various equations are given below:

$CO_2 + 2OH^- \rightarrow CO_3^{2-} + H_2O$

$Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^-$

$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$

6.4.3 ASR

Alkali-silica reaction is the result of the chemical reaction between the hydroxyl ions in the pore solution of the concrete and aggregates containing certain types of siliceous material (Swamy, 1994). The product of the reaction is a calcium-alkali-silica gel which can imbibe water, swell and exert pressure. According to Oberholster (1987), the imbibition pressure of the gel is enough to cause concrete cracking.

The occurrence of ASR is not only characterised by external map cracking on surfaces of structural concrete elements but also by reaction rims around the aggregate particles, voids filled with reaction products, cracks in aggregate particles and loss of bond between the aggregate and matrix.

6.5 EFFECT OF SLAG ON DETERIORATION PROCESSES

6.5.1 Chloride Ingress

Absorption/diffusion experiments

Concrete containing blastfurnace slag provides high resistance to the penetration of chlorides. According to Higgins and Uren (1991), the addition of slag reduces the permeability of concrete and the slag-cement paste binds significant amounts of chlorides. The reduction of permeability, in turn, disrupts the concentration gradient needed for diffusion. It is generally accepted that aluminates are effective in binding chloride ions to form chemical complexes such as calcium chloro-aluminates and slag is very effective in chloride binding due to its high aluminate level. Blundell, as reported by Basson and Ballim (1994), showed that the chloride diffusion coefficient of blastfurnace slag concrete is only 25 % of that of plain portland cement concrete, although the two concretes tested had similar permeability values (Fig. 6.7). The high chloride binding capacity of slag concretes was also reported by Jones (1992).

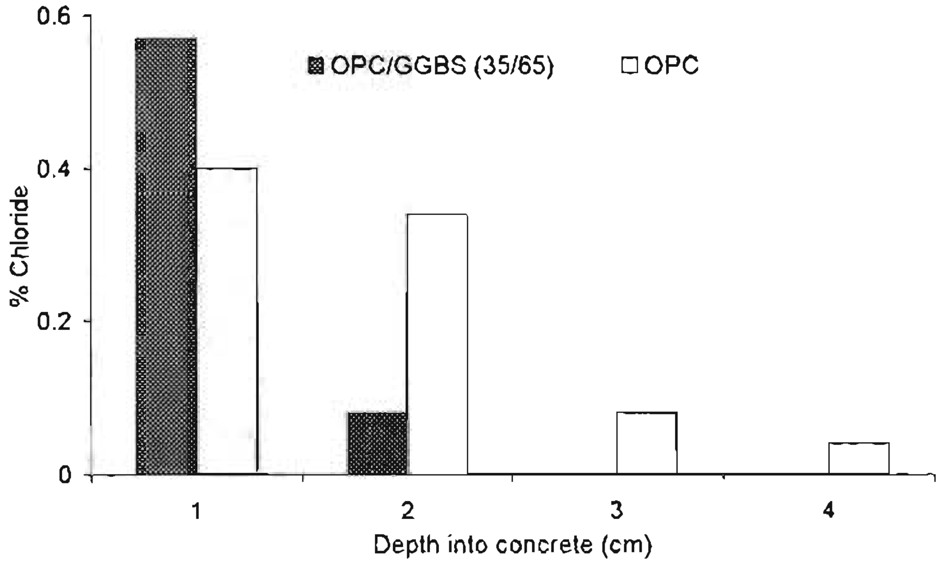

Fig 6.7: Effect of GGBS in reducing chloride penetration into concrete (Basson and Ballim, 1994)

Roy et al (1986) and Luping and Nilsson (1991), on the other hand, found that the lower connected porosity and finer pore structure arising from the use of slag in concrete were the main reasons for the slower diffusion of chloride ions in concrete.

Experiments performed by Mackechnie and Alexander (1996) in marine conditions on concrete having 50 % slag replacement level showed that the diffusion coefficients for slag concrete were lower than the portland cement controls, indicating a higher chloride resistance. This was also observed by Malhotra et al (1987) with concrete having slag substitution rates of 80 %. Moreover, Mackechnie and Alexander (1996) and Mangat et al (1994) also noted that slag concretes generally had higher surface concentrations than ordinary portland cement concretes and attributed these to the higher chloride binding capacity of the supplementary material. Bamforth and Price (1993), on the other hand, associated the higher surface chloride levels with higher sorptivities of the slag concretes when first exposed to salt spray.

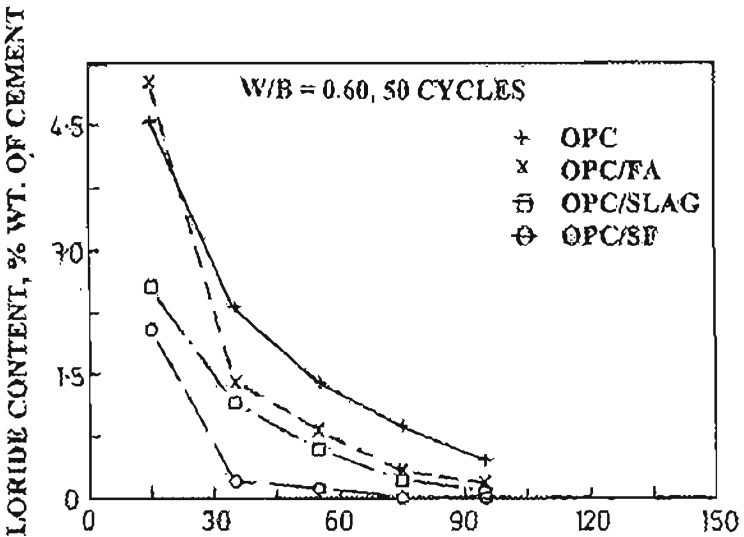

Fig. 6.8: Chloride profiles in concrete after 50 cycles of wetting and drying (Swamy, 1997)

Chloride testing conducted by Swamy (1997), using cycles of wetting and drying, have shown that slag positively reduces the penetration of chlorides into concrete, compared to portland cement concrete alone. This is indicated in Figure 6.8. This was also observed by McGrath and Hooton (1997) by using ponding tests, and Madej et al (1995) by using immersion in sodium chloride solution.

Conduction experiments

Accelerated chloride experiments, under an applied potential difference, performed by Ozyildirim (1994), Sivasundaram and Malhotra (1992) and Khatri et al (1997) have all found that slag concretes have superior resistance to chloride penetration than normal portland cement concretes. Sivasundaram and Malhotra also found that the resistance of the concretes to chloride ion ingress increased substantially with an increase in the slag content. At 50 % replacement level, the resistance of concrete to chloride ion penetration was 383 C, but at a substitution rate of 75 % the electrical charge was only 174 C. The testing was done at 28 days, according to AASHTO ; T277-83.

Mackechnie (2001) investigated the effect of water:binder ratio on chloride conductivity of a range of South African concretes and the results are illustrated in Figure 6.9. The results imply that for concrete structures to be durable in marine environments, slag concrete having low water:binder ratios should be used. The higher chloride conductivity values with increasing water:binder ratio can be attributed to an increase in the permeability of the concretes and to a decrease in the chloride binding capabilities since the amount of binder is also reduced.

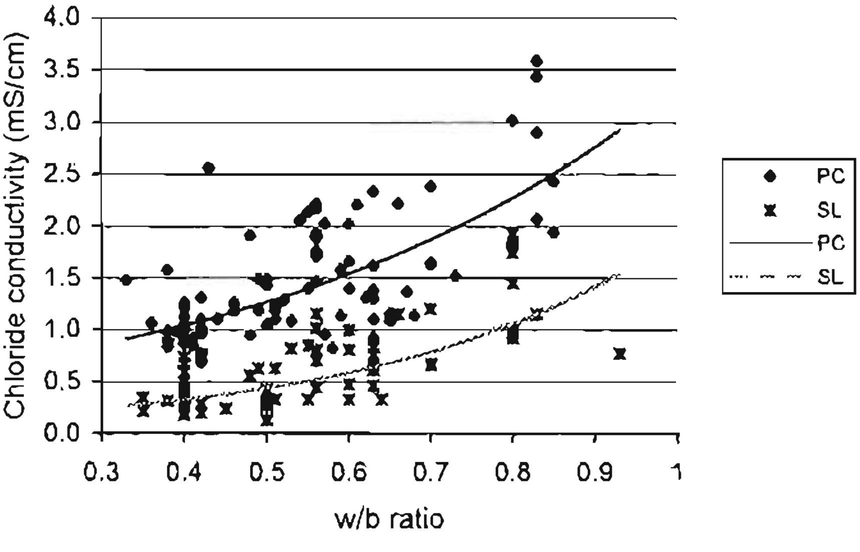

Fig.6.9: 28-day chloride conductivity for various binders (Mackechnie, 2001)

6.5.2 Carbonation

Carbonation experiments performed by Kasai et al (1983), van Dijk (1990) and Lang and Geiseler (1996) have shown that the use of slag in concrete results in higher carbonation depths than portland cement concretes (Fig. 6.10), with other parameters being equal.

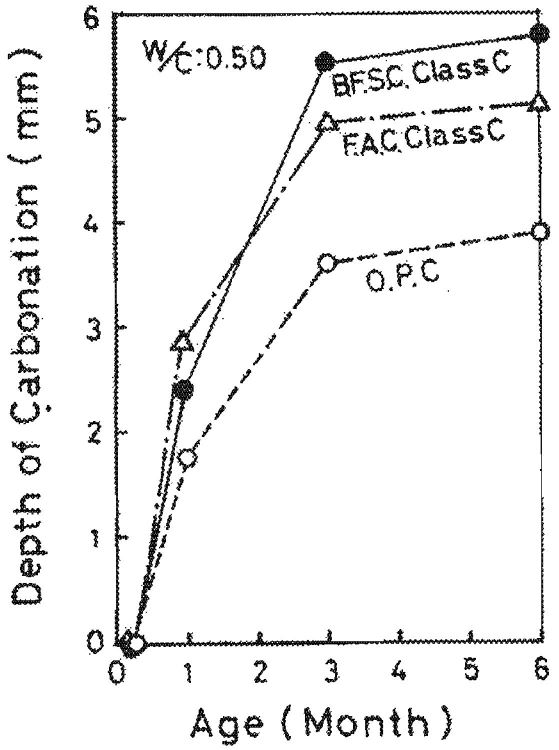

Fig. 6.10: Carbonation depth of slag concrete (Kasai et al, 1983)

This was also noted by Osborne (1989) from field observations. Madej et al (1995), on the other hand, found that concretes containing 40 % slag by mass had extremely small diffusivity of carbon dioxide and attributed it to the high density of the mortars with relatively small amount of calcium hydroxide formed.

Nakamato et al (1997) and Horiguchi et al (1994) observed that for increasing slag replacement levels, the carbonation depth also increases and at high replacement level, the increase was rapid. This is illustrated in Figure 6.11, where carbonation is expressed in terms of the carbonation constant. Carbonation constant, k, is the ratio of carbonation depth, d (mm), and square root of time, √t (√days).

Wee et al (1999) observed the same trend and also found that the resistance to carbonation increased gradually on increasing the fineness of blastfurnace slag from 300 to 800 m^2/kg.

Concerning the effect of slag on the alkaline environment of concrete, Litvan and Meyer (1986) argued that the replacement of cement by slag results in a low initial concentration of calcium hydroxide which is further reduced when slag cures. On carbonation, this small lime reserve can be easily exhausted, hence providing no protection against corrosion.

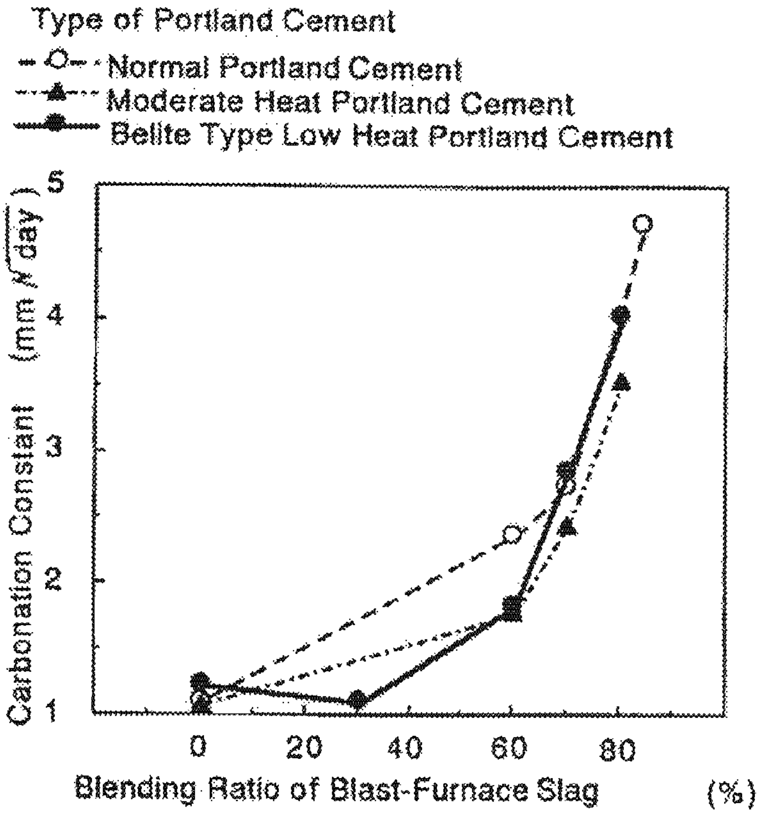

Fig. 6.11: Influence of slag replacement level on carbonation depth (Horiguchi et al, 1994)

6.5.3 ASR

The use of blastfurnace slag is accepted worldwide as a means of reducing the risk of damage due to ASR. Experiments performed by many investigators (Connell and Higgins, 1992, Thomas and Innis, 1998 and Oberholster and Westra, 1981) on concrete prisms kept at 38 °C and in a moist environment have confirmed the ability of slag to reduce significantly the deleterious expansion caused by ASR. This was also demonstrated by Lumley (1992) who performed the experiments at 20 °C and 100 % RH. Chen et al (1993) using various Canadian aggregates came to the same conclusion.

Hogan and Meusel, as reported by Douglas (1987), investigated the effectiveness of granulated slag by using Pyrex glass, which is known to be highly reactive, as an aggregate. They found the expansion of mortar bars containing slag to be significantly less than for those made with portland cement alone. This is illustrated in Figure 6.12.

In the same study, it was observed that the higher the replacement level of slag, the lower was the expansion. Oberholster and Westra (1981) showed the same effect (Fig. 6.13). According to Thomas and Innis (1998), the Canadian Standard specifies a minimum of 50 % slag replacement level and that amount is generally accepted in the UK and South Africa to provide suitable protection against ASR expansion.

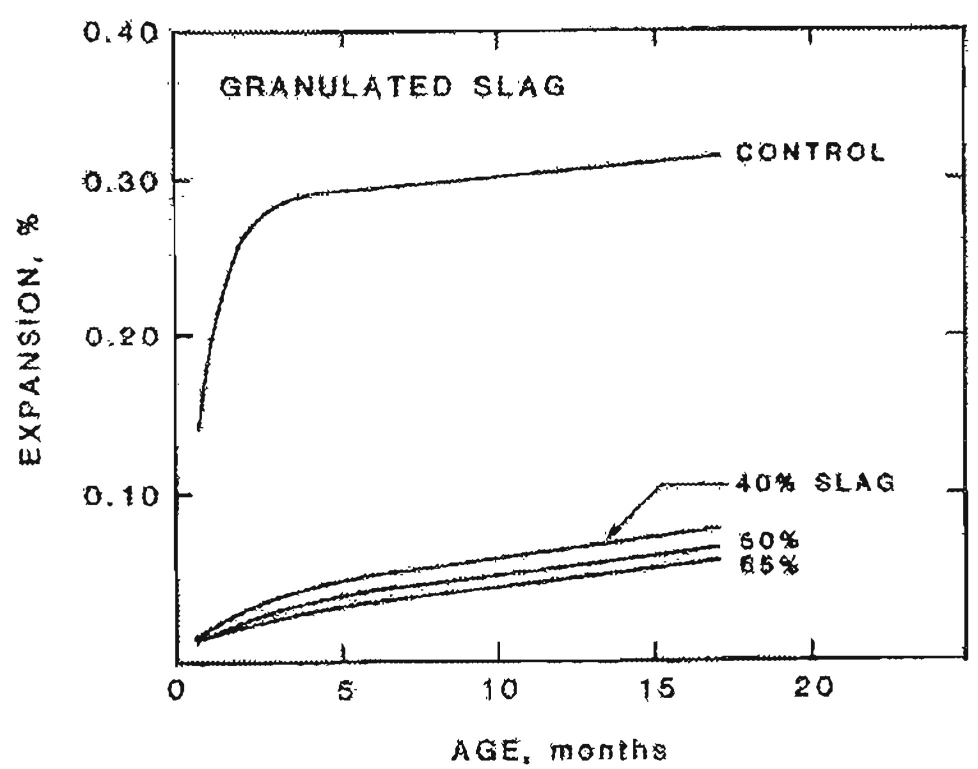

Fig.6.12: Effect of slag on ASR expansion (Douglas, 1987)

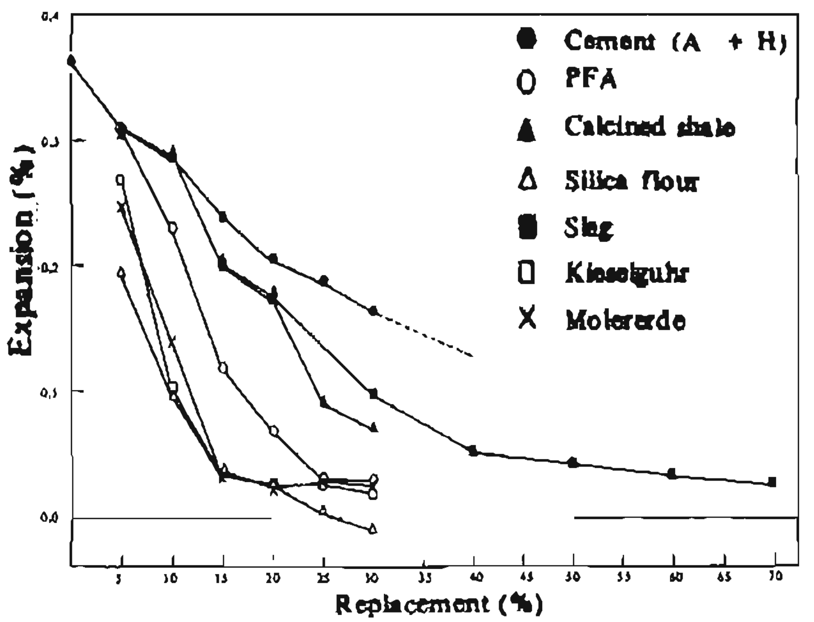

Fig. 6.13: Effect of slag replacement level on ASR expansion (Oberholster and Westra, 1981)

The exact mechanism of the addition of slag in controlling ASR expansion is still unclear but pore refinement and reduced permeability are important factors influencing the expansive reactions (Swamy, 1997). Bakker (1981) found from his experiments that blastfurnace slag cement mortar appeared to be ten to one hundred times less permeable to water than portland cement mortar and the movement of water in the blastfurnace specimens comes almost to a standstill after a certain hardening period. The low permeability of slag concrete as a reason for the high resistance to ASR was also reported by Douglas (1987), based on Dutch research.

Furthermore, Bakker (1981) also found the rate of diffusion of ions in two-week-old portland cement mortar to be about fifteen times faster than through an identical blastfurnace slag mortar. Consequently, taking the rate of diffusion and permeability into account, it follows that potential detrimental reaction in blastfurnace slag concrete will proceed slower than in ordinary portland cement concrete.

Duchesne and Bérubé (1995), on the other hand, attributed the effectiveness of blastfurnace slag in suppressing alkali-silica reaction to mostly an alkali dilution effect. This is because the hydrates formed in the presence of slag do not contain significantly more alkalis than portland cement hydrates and also they do not bind a higher percentage of alkali released by the cementitious materials. Consequently, this could explain why ASR expansion decreases at higher replacement level.

6.6 DURABILITY INDEX APPROACH

The durability index approach was developed in South Africa as a result of the need for a simple way of characterising the durability of concrete. In the past a simple quality control test – the cube or cylinder test – was adopted to characterise concrete strength and the same approach was used when developing the durability index tests. Each test is linked to a specific transport mechanism, such as gaseous and ionic diffusion and water absorption, and hence the results can be used to characterise the transport properties of concrete which are critical parameters controlling potential durability. Refer to Alexander et al (1999b) for a detailed explanation of the philosophy of the durability index approach.

6.6.1 Definition of Terms

Durability index

A durability index of concrete is a quantifiable physical or engineering parameter which characterises the quality of concrete at early ages.

Potential durability

The potential durability of concrete indicates the durability performance to be expected of a particular concrete on the basis of tests conducted at a relatively early age (usually 28 days), and as characterised by suitable durability indexes.

6.7 TEST METHODS

6.7.1 Durability Index Tests

The three durability index tests are the oxygen permeability, water sorptivity and chloride conductivity tests.

In this work, the indexes were determined on four discs (25 mm thick and 68 mm in diameter) cut from concrete cubes specially prepared for the durability index tests. The index testing was conducted on samples cured for 1, 3 and 28 days of wet curing. The samples were preconditioned by oven drying at 50 °C for at least one week. Schematics of the tests are given in *Appendix E*.

The *oxygen permeability index test* is conducted to measure the capacity of the concrete to transfer gas by permeation. A falling head permeameter is used and the pressure decay with time is measured as oxygen permeates through concrete. A Darcy coefficient of permeability is then determined and converted into OPI by taking the negative log of the Darcy coefficient.

The *water sorptivity index test* measures the rate of movement of a wetting front through concrete under the action of capillary forces This is achieved by exposing the concrete specimens to a few millimetres of calcium hydroxide solution and measuring the mass of the samples at regular time intervals using an electronic balance.

The *chloride conductivity index test* is performed to assess the resistance of concrete to ingress by chloride ions, such as would occur in marine environments. The rapid chloride conductivity test is done by applying a 10 V potential difference across a pre-saturated concrete sample and the conductivity is determined by measuring the current flowing through the concrete specimen.

All three tests are described in full detail in the Concrete Durability Index Testing Manual (Alexander et al, 1999a) published by the University of Cape Town as well as in other references (Streicher and Alexander, 1995, Ballim, 1991b and Alexander and Magee, 1999).

6.7.2 Marine Exposure

Concrete blocks were cast for exposure to marine conditions. The blocks were 250 x 300 x 200 mm in dimensions and were cast in two layers. After demoulding, the blocks were kept under damp hessian until the 28th day when they were transferred to the marine site at Simonstown harbour. The site is sheltered with little wave action and fairly warm sea temperatures (13 to 20 °C) due to the shallow bay and prevailing winds. The blocks were placed in the tidal zone and experienced little abrasive action because of the protected location. Figure 6.14 shows the concrete blocks submerged at high tide.

The specimens were exposed to marine conditions for eight months before cores were taken. The cores were cut at 10 mm intervals and the chloride content of each disc was determined. This was done by crushing the discs to powder and then digesting them in nitric acid to release all chlorides. The total acid-soluble chlorides were then analysed by using a Mettler DL 40GP autotitrator and the chloride content was expressed as a percentage by mass of binder. From the results, the chloride profiles were plotted. Figure 6.15 shows the process of chloride content determination.

Fig. 6.14: Marine exposure blocks at Simonstown

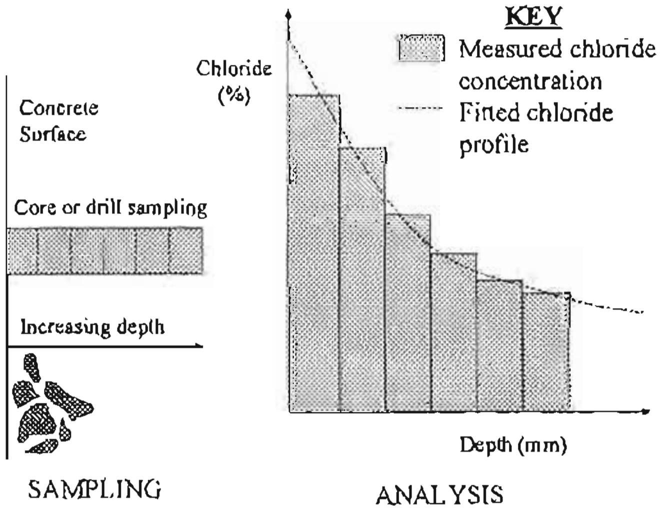

Fig. 6.15: Chloride content determination and typical chloride profile (Mackechnie and Alexander, 2001)

6.7.3 Carbonation

The carbon dioxide content in the atmosphere is around 0.03 % and hence the movement of a carbonation front through concrete is very slow. Consequently, for the purpose of this research it was necessary to accelerate the carbonation process and this was achieved by using a Leec carbonation chamber. The chamber provided a more aggressive carbonation environment with a higher carbon dioxide level.

Concrete cubes were specially cast for use in the accelerated carbonation experiment. The 100 mm cubes were water cured for 28 days before being transferred to a dry environment (25 °C and 50 % RH) until they were placed in the carbonation chamber (3 months after casting). The carbonation chamber was maintained at a carbon dioxide level of 10 ± 1 % and a temperature of 30 °C throughout the testing period to ensure the accelerated carbonation of the samples. The RH in the chamber was found to be 85 ± 5 %. The conditions within the chamber were monitored on a regular basis.

Three cubes were prepared from each mix and they were tested after 6, 12 and 20 weeks of accelerated carbonation. The cubes were sliced into two and the faces were sprayed with a phenolphthalein indicator solution (1 % by mass in ethanol/water). Phenolphthalein remains clear where concrete is carbonated but turns pink/purple where concrete is still strongly alkaline (pH > 9.0). The depth of the carbonation front was then determined from the average of the four sides

6.7.4 ASR

Accelerated alkali-silica reaction testing was performed according to the principles of SABS Method 1245.1994 Mortar prisms of 50 x 50 x 300 mm were used instead of those recommended by the standard (50 x 50 x 280 mm). Slag replacement levels of 25 and 50 % were used and they were compared to normal portland cement samples which had an equivalent Na_2O content of 0.58 %. The mortar contained Malmesbury Shale aggregate crushed to specific fractions (-4 750 µm, +150 µm) Malmesbury Shale is recognised to be a very reactive material (Crosswell, 1992 and Oberholster, 1981).

The expansions of the mortar bars were monitored at 2-day intervals until the 12th day after which the percentage expansions were calculated.

6.8 RESULTS

6.8.1 Durability Index Tests

The durability index tests results are provided in Table 6.1 and illustrated in diagrammatically in Figures 6.16 to 6.18. The suggested ranges for durability classification are given in Table 6.2.

The results generally indicate improvements in durability indexes with increasing wet curing times and this is more evident for the blastfurnace concrete samples. In the case of CEM I and corex slag concretes, there was almost no improvement in durability indexes for curing regimes greater than three days. It is also clear that increases in water:binder ratios have detrimental effects on concrete durability. Moreover, corex slag concretes appear to suffer a loss in durability especially when the water:binder ratio is increased from 0.5 to 0.6.

Based on the suggested ranges for durability classification given in Table 6.2, it can be said that, for water:binder ratios of 0.4 and 0.5, the three different mixes result in good to excellent potential concrete durability, while for a water:binder ratio of 0.6, some of the mixes cured for one day resulted in concrete with poor potential durability.

Table 6.1: Durability index results measured at 28 days

	W/B = 0.4			W/B = 0.5			W/B = 0.6		
	1-DAY CURING								
MIX	OPI	WS	CC	OPI	WS	CC	OPI	WS	CC
CEM I	10.58	4.7	1.05	10.36	5.2	0.40	9.76	8.0	2.25
BS	10.25	5.7	0.85	9.51	7.9	1.03	9.19	11.2	1.60
CS	10.05	5.0	0.43	9.89	5.8	0.56	9.45	6.1	0.68

	3-DAY CURING								
MIX	OPI	WS	CC	OPI	WS	CC	OPI	WS	CC
CEM I	10.59	5.2	1.06	10.62	4.6	1.45	10.35	5.5	1.80
BS	10.80	3.7	0.50	9.96	5.3	0.80	9.70	5.4	1.04
CS	10.18	4.1	0.24	10.11	4.6	0.38	9.73	5.7	0.48

	28-DAY CURING								
MIX	OPI	WS	CC	OPI	WS	CC	OPI	WS	CC
CEM I	10.77	4.6	0.92	10.72	5.0	1.49	10.46	5.5	1.66
BS	10.76	3.1	0.18	10.45	3.6	0.41	10.17	3.8	0.47
CS	10.18	3.9	0.22	10.04	5.4	0.35	9.63	7.0	0.50

Where OPI: Oxygen permeability index
WS: Water sorptivity index (mm/√h)
CC: Chloride conductivity index (mS/cm)

Table 6.2: Suggested ranges for potential durability classification (Alexander et al, 1999b)

Durability Class	OPI (log scale)	Sorptivity (mm/√h)	Conductivity (mS/cm)
Excellent	>10	<6	<0.75
Good	9.5-10	6-10	0.75-1.50
Poor	9.0-9.5	10-15	1.50-2.50
Very poor	<9.0	>15	>2.50

It is worthwhile to note that the chloride conductivity results for the CEM I mix with a water:binder ratio of 0.5 and cured for one day had an exceptionally low value. It is believed that there is an error associated with this result, and it will not be further considered. Moreover, the results obtained in this research were better than values obtained by Alexander et al (1999b).

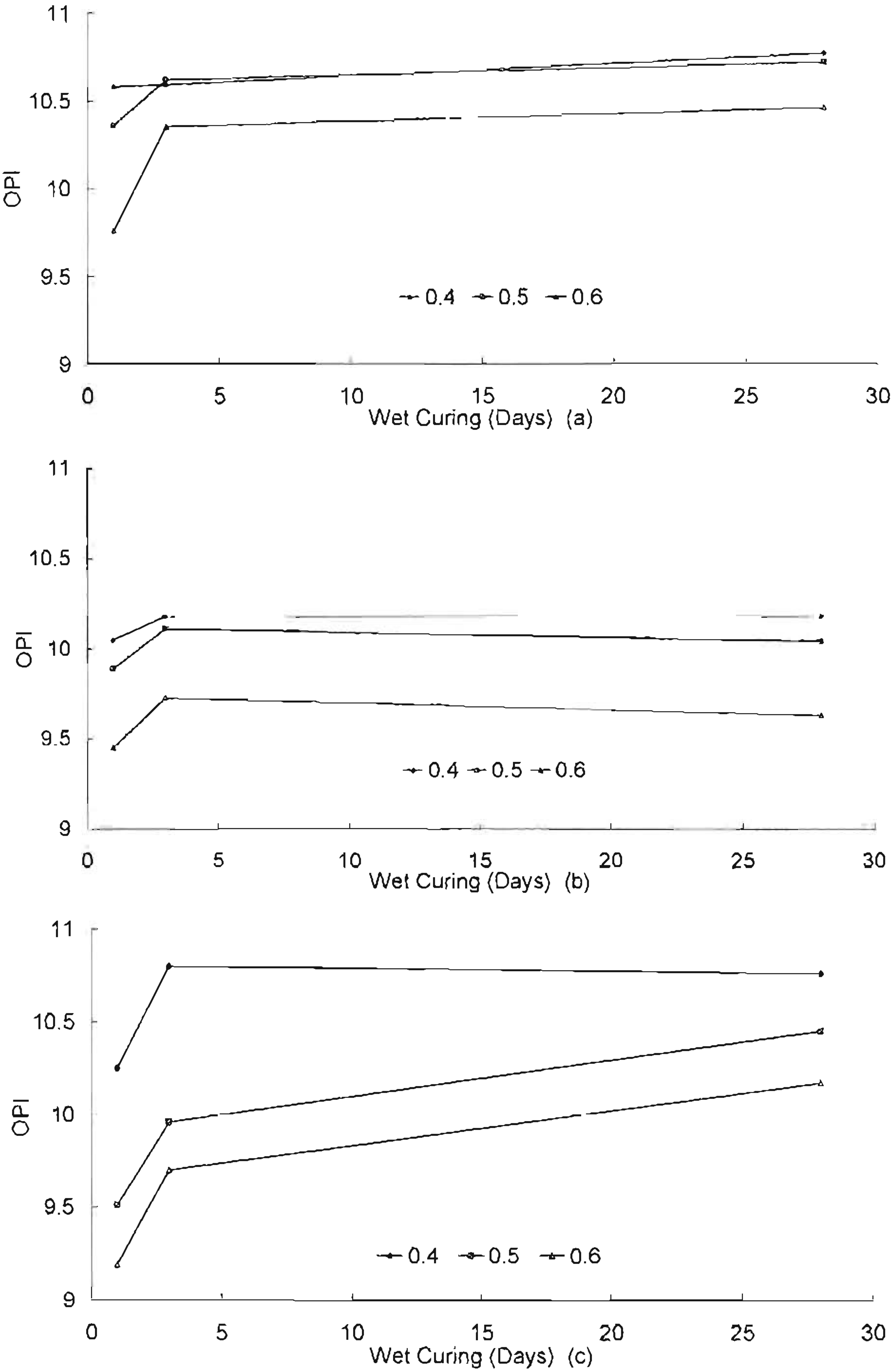

Fig.6 16: Effect of water curing on permeability of (a) CEM I (b) CS (c) BS concretes

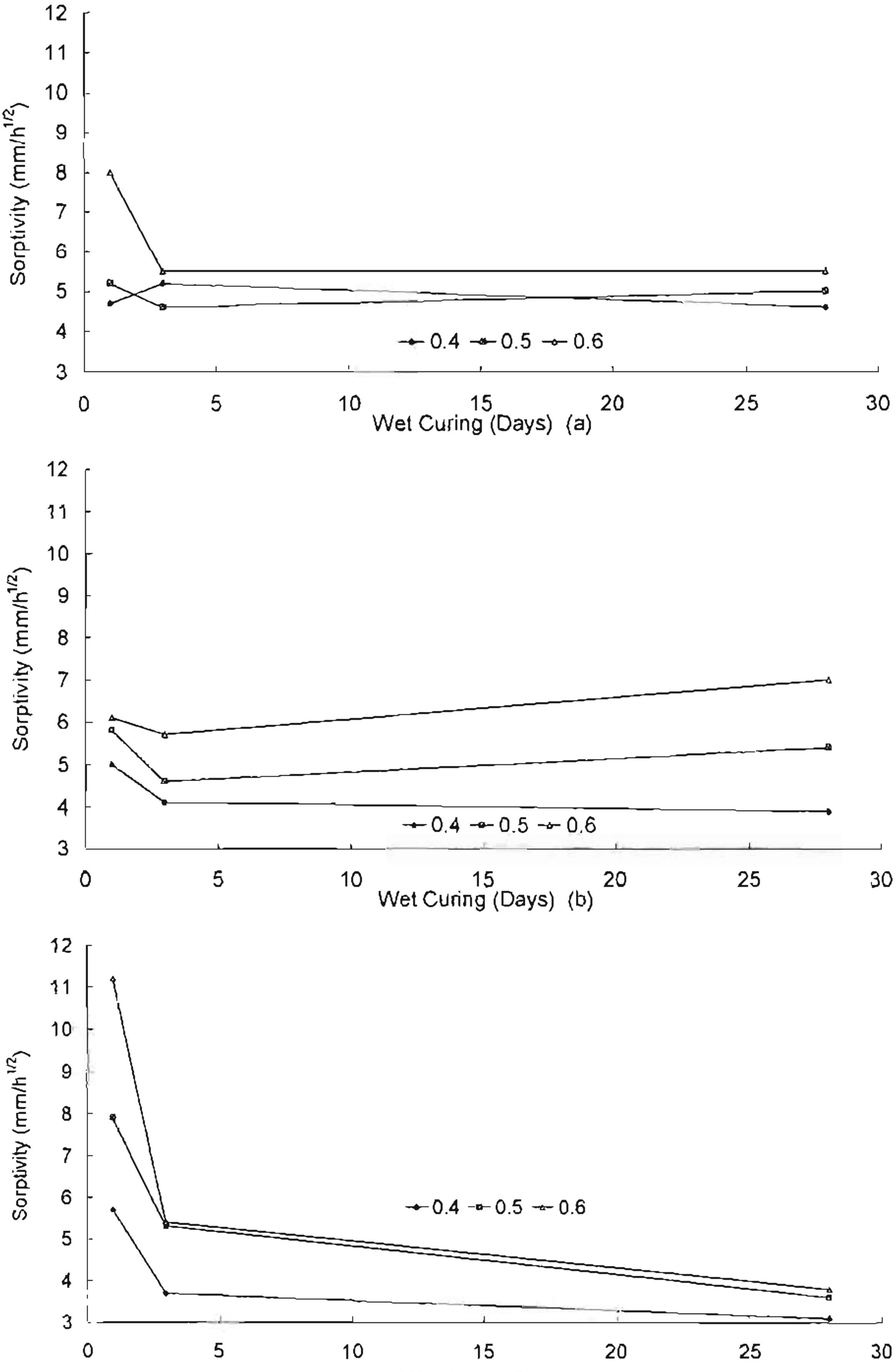

Fig.6.17: Effect of water curing on sorptivity of (a) CEM I (b) CS (c) BS concretes

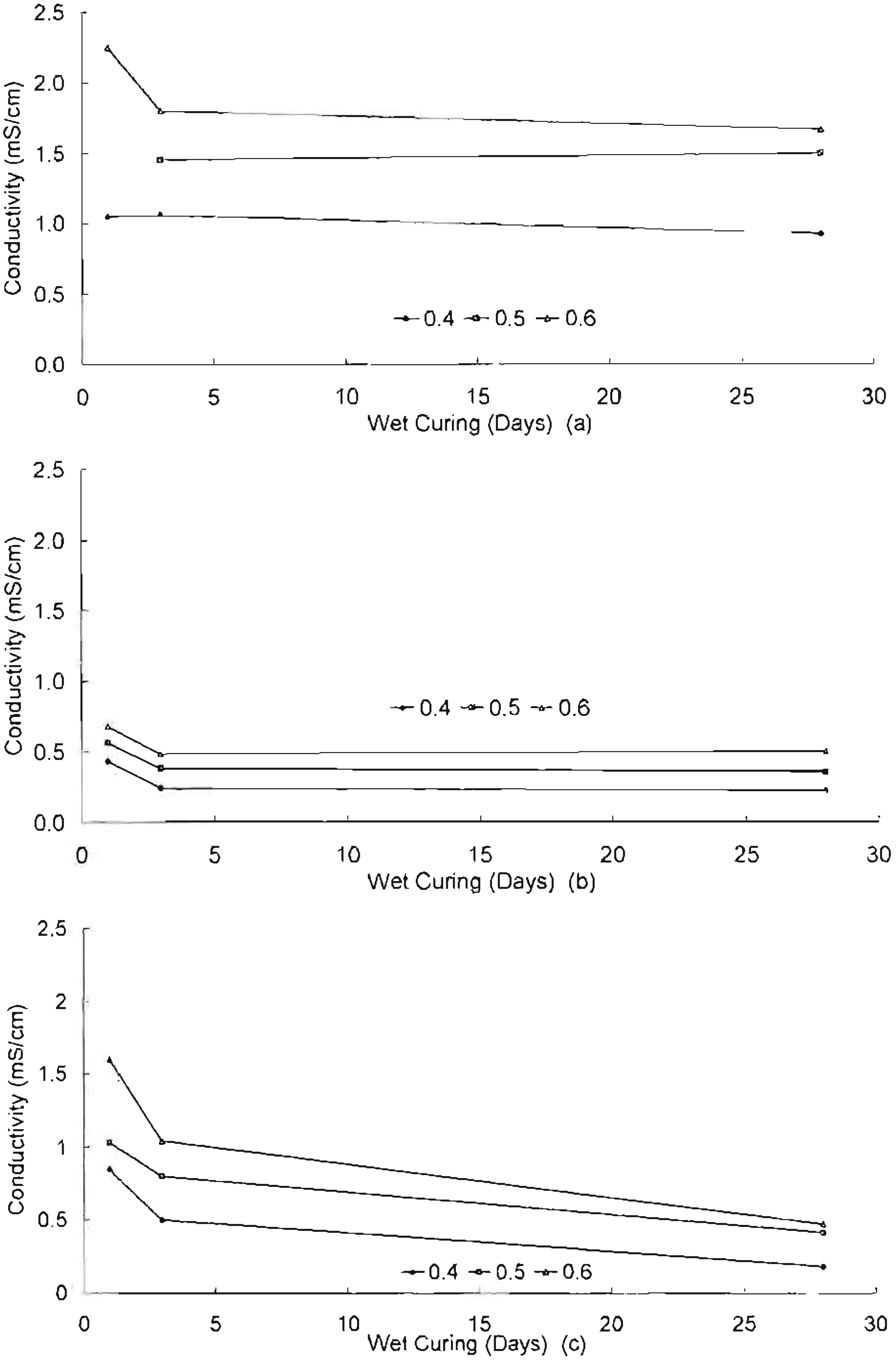

Fig.6.18: Effect of water curing on chloride conductivity of (a) CEM I (b) CS (c) BS concretes

6.8.2 Marine Exposure

The chloride profiles for water:binder ratios of 0.4, 0.5 and 0.6 are given in Figure 6.19 The measured chloride contents and analysis of the profiles are provided in Table 6.3, and the risk of corrosion based on chloride levels is given in Table 6 4 The diffusion coefficients, surface concentrations and critical chloride depth were all calculated from the chloride profiles by applying a curve-fitting technique using the solution of Fick's second law of diffusion.

Table 6.3: Chloride contents (% by mass of binder) and analysis for Simonstown tidal exposure after 8 months

Binder Type	**CEM I**			**BS**			**CS**		
Depth (mm)	***Water:Binder***			***Water:Binder***			***Water:Binder***		
	0.6	***0.5***	***0.4***	***0.6***	***0.5***	***0.4***	***0.6***	***0.5***	***0.4***
5	1.196	1.071	1.043	2.191	1.152	1.349	2.788	1.723	1.212
15	0.876	0.451	0.248	0.392	0.077	0.060	0.397	0.082	0.085
25	0.472	0.042	0.016	0.109	0.058	0.033	0.096	0.073	0.026
35	0.125	0.019	0.009	0.029	0.050	0.032	0.056	0.047	0.008
45	0.034	0.014	0.008	0.030	0.017	0.011	0.047	0.023	0.006
C_s	1.55	1.50	1.70	3.60	2.40	3.00	4.80	3.75	2.45
D_c ($\times 10^{-8}$)	11	3.9	2.2	2.0	1.0	0.88	1.7	0.92	1.1
$x_{0.4}$	26.5	15.5	12.4	15.4	9.6	9.6	15.4	10.6	10.1

Where D_c denotes diffusion coefficient (cm^2/s)
C_s denotes surface concentration (%)
$x_{0.4}$ denotes critical chloride depth (mm)

For all three water:binder ratios considered, the surface concentration of chlorides was higher in the case of the slag specimens and this is typical of slag concretes.

Chloride values at the steel above 0.4 % by mass of cement, referred to as the corrosion threshold level, are generally sufficient to depassivate reinforcement. The corrosion threshold depends on several factors including concrete quality, depth of cover and saturation level of concrete. According to Mackechnie (1997b), it may be assumed that chloride levels below 0.4 % indicate a low risk of corrosion while levels of above 1.0 % indicate a high risk The $x_{0.4}$ value denotes the depth below which the chloride level is not critical. The effect of water:binder ratio on critical chloride depth is given in Figure 6.20. It can be deduced from the figure that the consequences of an increase in water:binder ratio on the critical chloride depth are less significant for slag concretes than for CEM I concretes

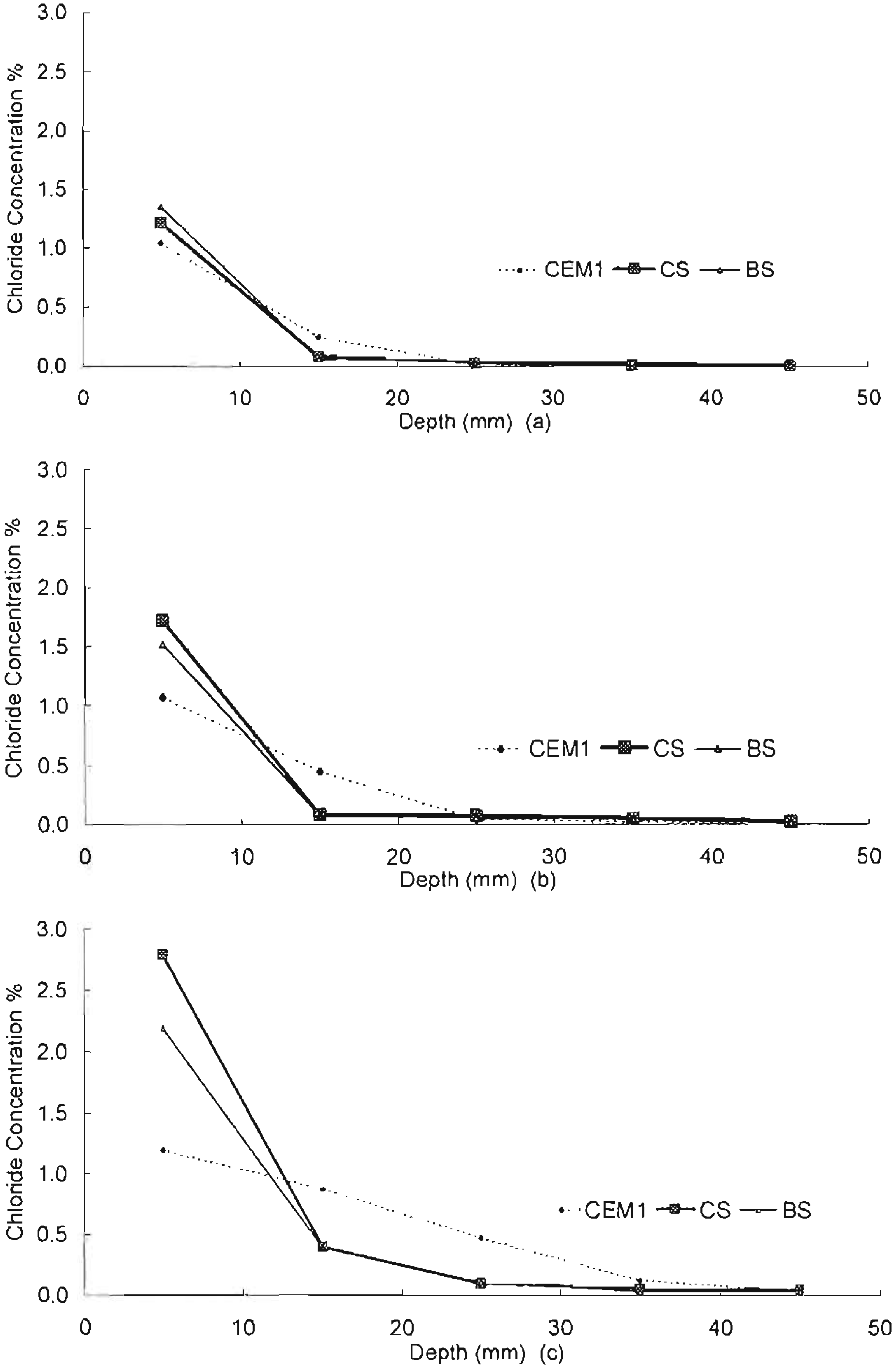

Fig. 6.19: Chlorides profiles for concretes having water:binder ratios of (a) 0.4 (b) 0.5 (c) 0.6

Table 6.4: Qualitative risk of corrosion of steel based on chloride levels (Mackechnie and Alexander, 2001)

Chloride content by mass of binder %	Probability of corrosion
<0.4	Low
0.4-1.0	Moderate
>1.0	High

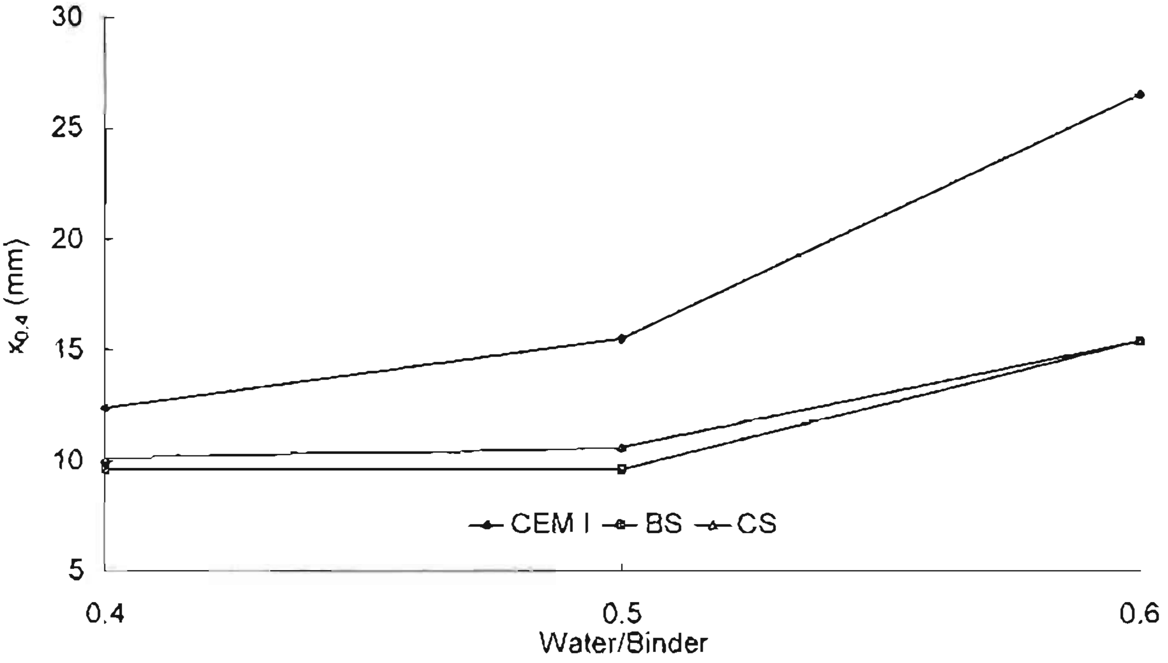

Fig. 6.20: Effect of water:binder ratio on critical chloride depth (after exposure of 8 months)

6.8.3 Carbonation

The carbonation results are given in Figure 6.21 for 6, 12 and 20 weeks of exposure to the concentrated carbon dioxide environment.

For a water:binder ratio of 0.4, the CEM I and corex slag mixes experienced no visible carbonation, at six weeks, having zero carbonation depth. The corex slag samples, at a water:binder ratio of 0.4, showed no visible carbonation at any age up to 20 weeks. The depth of carbonation was observed to generally increase with water:binder ratio and exposure times Blastfurnace slag concrete samples were noted to be more prone to carbon dioxide ingress relative to the other concretes, especially at low water:binder ratios. However, it must be borne in mind that only one cube was tested at a specific age and hence the variability of the results is not known.

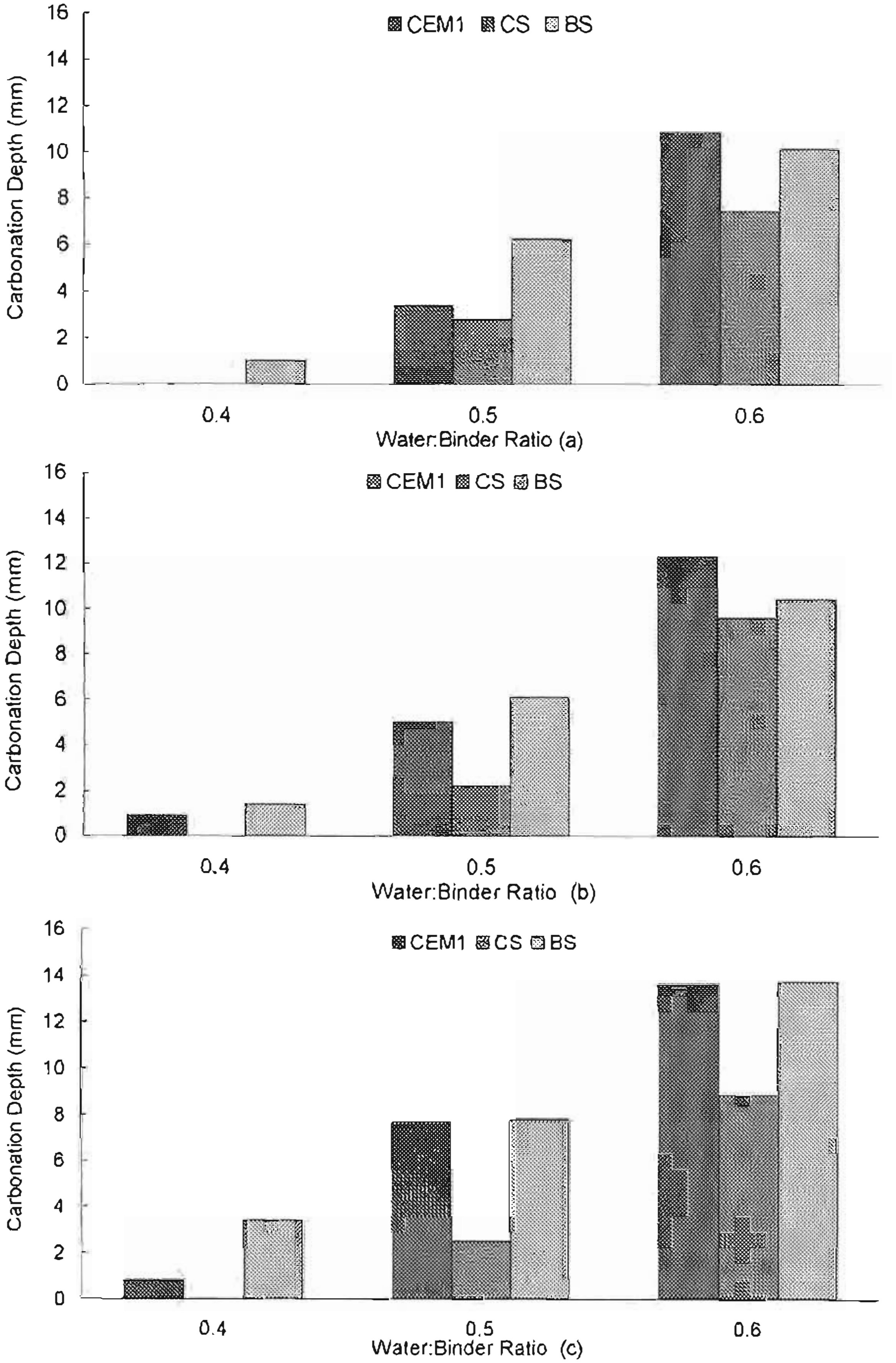

Fig. 6.21· Carbonation depth of concretes exposed to (a) 6 (b) 12 (c) 20 weeks of carbonation

6.8.4 ASR

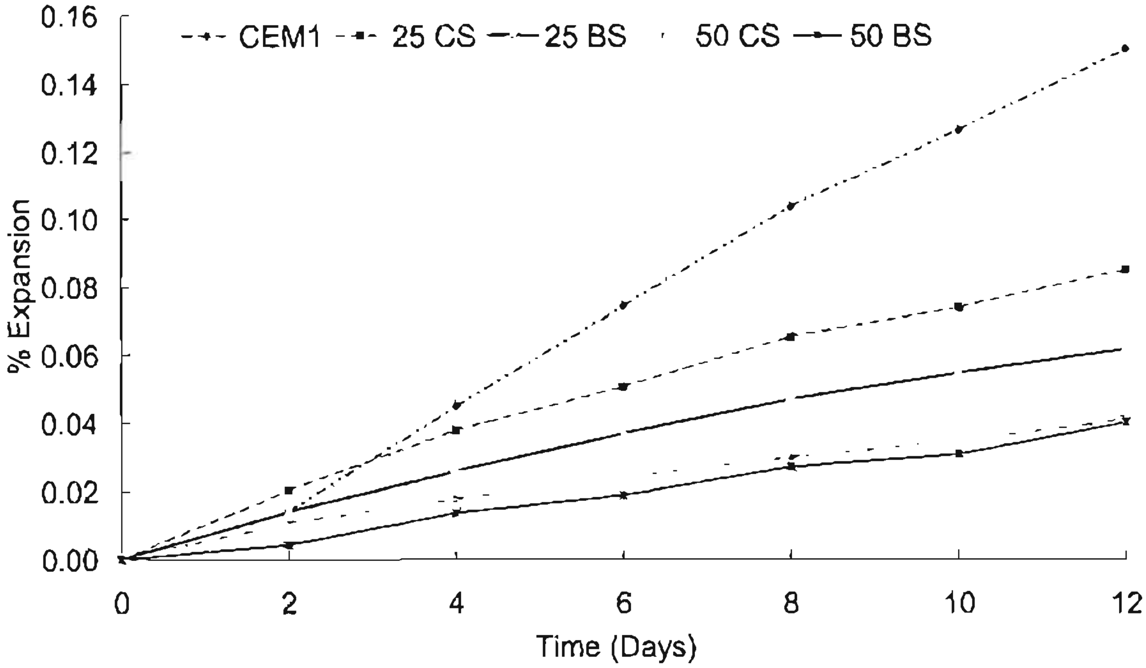

Fig. 6.22: Effectiveness of the binders in controlling ASR expansion

The ASR expansion of the slag samples compared to the portland cement controls are illustrated in Figure 6.22. The results indicate that the higher the replacement level of slag, the lower the total percentage expansion. A similar trend was observed in experiments performed by PPC Technical Services. Furthermore, it can also be observed from the graph that at a lower replacement level, the performance of corex slag specimens is slightly inferior to the corresponding blastfurnace slag samples.

6.9 DISCUSSION OF RESULTS

6.9.1 Durability Indexes

The fact that the durability indexes improve with prolonged wet curing can be attributed to the continued formation of hydration products. The gel blocks capillaries and pores, hence reducing the movement of gases, fluids and ions through the concrete. The extended curing periods were especially beneficial for blastfurnace slag concretes because of their slower initial reactivity. Consequently, they showed the most improvement in durability indexes between the 3-day and 28-day curing times. This has also been reported in the literature (Dias 1997, Swamy and Darwish 1997 and Ballim 1991a).

The effect of water:binder ratio on durability can be explained by a reduction in the cementitious content with an increase in the water:binder ratio. This has the consequence of decreasing the total products of hydration, thus making the concrete less dense and more permeable to fluids. This is illustrated by the superior results at the water:binder ratio of 0.4.

The generally better results for the CEM I and corex slag mixes, for one day curing, compared to blastfurnace slag concrete, can be attributed to the more rapid rate of development of the microstructure for these two materials. However, most of the mixes showed good to excellent durability indexes, after three days of curing, implying that a minimum of three days of wet curing should be applied to all structures if durability is of concern. Comparing the durability indexes for the 3-day and 28-day curing regimes, it can be seen that the corex slag mixes result in the least change in durability for the additional curing period. This could probably be attributed to a rapid initial development of microstructure which then shows little further improvement with time.

From the oxygen permeability results, it might be deduced that the use of corex slag results in more permeable concrete than both blastfurnace slag or CEM I, after 28 days of curing. However, the observed trend is somewhat better with the water sorptivity results. This was also noted by Mackechnie (2001) who argued that the durability index tests measure different transport mechanisms through concrete and therefore will not always show consistent trends. The oxygen permeability test is more concerned with the macro-properties of the concrete while the sorptivity tests measures the near-surface micro-properties of concrete. Ballim (2001), on the other hand, attributed the results to some degree of cracking in the concrete specimens resulting from the pre-conditioning period in the oven at 50 °C.

The better 28-day durability indexes of blastfurnace slag compared to the equivalent corex slag concretes is most probably due to a lower porosity and a higher degree of densification of the cement matrix. Consequently, for fully cured concrete, blastfurnace slag would be more resistant to fluids than corex slag.

The overall results show that longer curing periods are more beneficial for improved durability. However, it should be borne in mind that site concrete hardly ever receives more than three days of moist curing. As a result, corex slag concrete could prove more durable in the long run especially in the marine environment. It is also worthwhile to note from the results that an increase in the water:binder ratio from 0.5 to 0.6 leads to a substantial change in durability indexes for corex slag concrete samples. This was also observed for the creep and shrinkage results, given in Chapter 5, and could possibly be attributed to a change in the microstructure of the material. However, in depth microstructural studies need to be performed in order to confirm this.

Concerning the chloride conductivity experiments, it was found in all cases that slag specimens performed far better than the portland cement controls. This observation is widely reported in literature (Ozyildirim 1994, Sivasundaram and Malhotra 1992, Khatri et al 1997 and Mackechnie, 2001). The reduction in chloride conductivity values can be attributed to a combination of a greater degree of impermeability and higher chloride binding properties associated with slag concretes. In the case of the chloride conductivity testing, corex slag concretes had better or similar resistance to ingress by chloride ions than blastfurnace samples under all curing regimes and a plausible reason is that corex slag has marginally better chloride binding capabilities.

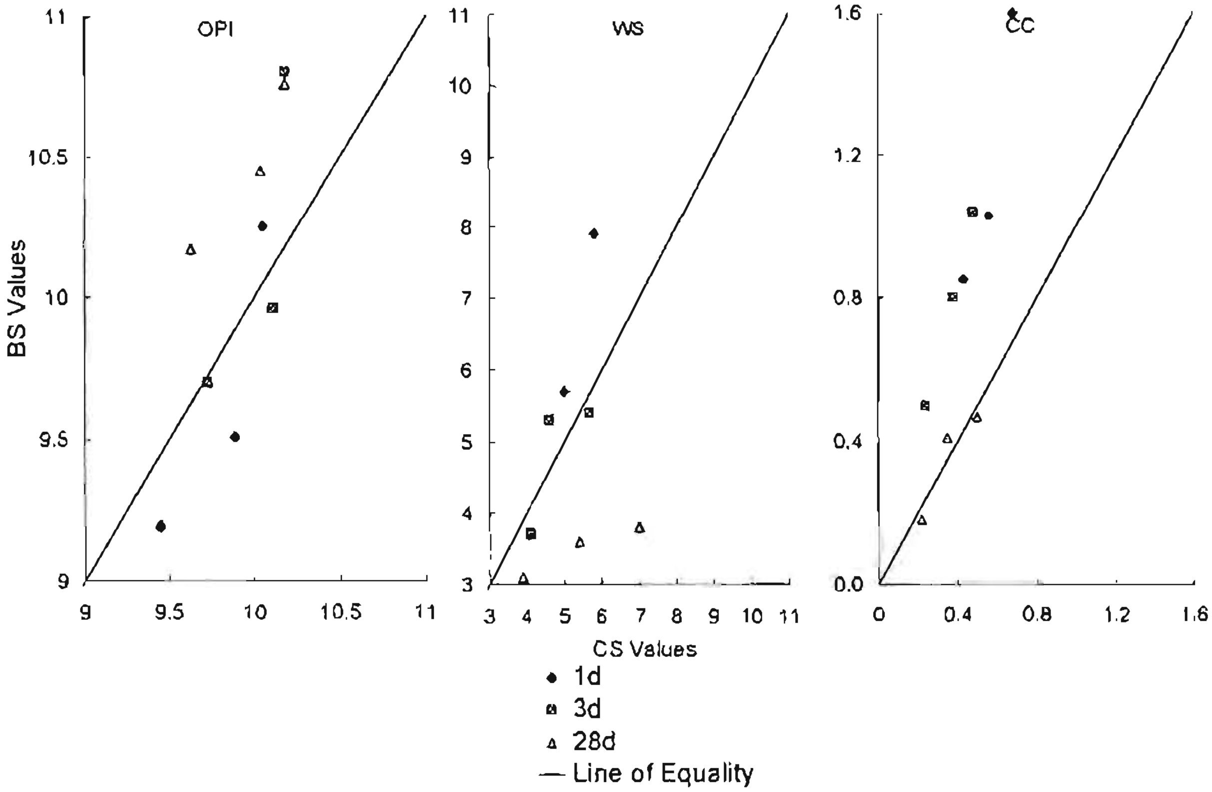

Fig. 6.23: Relative performance of corex and blastfurnace slag

From Figure 6.23, it can be observed that corex slag concretes generally perform better than the corresponding blastfurnace slag concretes for one and three days of wet curing. However, for full 28-day curing regimes, blastfurnace slag concretes have marginally better durability indexes. This is more obvious in the case of the chloride conductivity results. On the whole, corex slag concretes exhibit relatively superior durability characteristics.

6.9.2 Marine Exposure

From Figures 6.19 and Table 6.3, it can be observed that slag concretes have a higher surface concentration than CEM I mixes. This is attributed to the higher level of chloride binding generally associated with slag. Increases in water:binder ratio result in higher surface concentration as a result of increases in the porosity of the materials. However, the concentration of chloride for slag concretes falls very rapidly and at a depth of around 10 mm the chloride level is below that of CEM I concretes. For water binder ratios of 0.5 and 0.6, corex slag had higher surface concentrations which could possibly imply greater chloride binding abilities for the material.

The high surface concentration of chlorides in slag concretes gives rise to steep diffusion gradients, giving diffusion coefficients that were lower than the corresponding CEM I mixes. For water:binder ratios of 0.4 and 0.6, the diffusion coefficients of slag concretes were about two and six times lower, respectively. This can best be attributed to lower porosity and permeability associated with the use of slag in concrete. The improvement in impermeability characteristics, in turn, disrupts the concentration gradient required for diffusion.

In the case of the CEM I control mixes, there was no such resistance to ingress by chloride ions and consequently, the diffusion front was able to advance freely through the concrete. This is indicated by the high critical chloride depth, which is the level above which the corrosion risk is considered to be high. For CEM I concretes the critical chloride depths are greater, implying that the reinforcing bars are at a greater risk of corrosion than in slag concretes. CEM I concrete structures would require more cover for the reinforcing bars to have the same amount of protection as in slag concretes.

6.9.3 Carbonation

Corex slag concretes generally minimised the penetration of carbon dioxide while blastfurnace concretes showed the least resistance to ingress by the gas. The better carbonation characteristics of corex slag concretes can be mainly explained by its chemical composition. It was argued by Bier et al (1989) that increasing CaO content of cement resulted in smaller carbonation depth This is because the higher the CaO content the greater the amount of calcium hydroxide which is being produced during cement hydration. Consequently, the carbonation front takes more time to advance as carbon dioxide has to convert all "carbonatable" material at a given point to calcium carbonate first.

In the case of blastfurnace and corex slags, the chemical analysis revealed that corex slag had a higher CaO content than blastfurnace slag (37.2 % compared to 34.0%). It is believed that this is the major cause of the improved resistance to carbon dioxide ingress for corex slag concrete in comparison to blastfurnace slag concrete. The fineness of the material is also important as it helps in the formation of a denser cement matrix, hence decreasing the permeability of the concrete and the tendency for carbon dioxide to penetrate the concrete. The fineness in combination with the chemical composition of corex slag are probably the factors determining the smaller carbonation depth of corex slag compared to CEM I concretes.

The fact that the carbonation depth increases with increasing water:binder ratio is because of increasing permeability of the concrete and a reduction of the densification of the paste matrix. At extended exposure times, blastfurnace concretes showed similar carbonation characteristics as CEM I concretes and it is believed that this is due to the improved impermeability of the material which more than offset the reduction in carbonatable material.

6.9.4 ASR

The alkali-silica reaction results reveal that corex slag can be used to minimise the expansion arising from the reaction between the binder and the aggregate. The use of only 25 % slag was able to reduce the ASR expansion of the reactive aggregate to below the 0.1 % expansion mark which is considered to be the value at which aggregates are assumed to be innocuous.

The higher the replacement level, the lower was the percentage expansion. This is because as the slag content increases, the permeability of the concrete decreases to some extent. As a result, the diffusion of alkali ions into the mortar is decreased, hence reducing the expansion arising from ASR.

Furthermore, increasing the proportion of slag in the binder has a dilution effect whereby the alkali content is reduced. The Na_2O equivalent of portland cement used in this research was 0.58 % while that of blastfurnace and corex slags were 0.74 % and <0.35 % respectively. According to Oberholster (1994), the percentage of active alkali in South African portland cement is on average 85 % of the total alkali content while this proportion is only about 42 % in blastfurnace slag. Therefore, the use of slag reduces the active alkali content of the pore solution hence producing a dilution effect.

From Figure 6.22, the efficiency of corex slag appeared to be slightly lower than blastfurnace slag. This is more obvious at the 25 % substitution rate. Oberholster (2001) attributed it to the chemical composition of the material. According to him, the main action of slag in reducing ASR expansion is by the removal of free calcium from the pore solution through their reaction with calcium hydroxide. Since corex slag has a higher CaO content compared to blastfurnace slag, this could be the cause of the lower efficiency in reducing ASR expansion. However, at the 50 % replacement level, the improved impermeability of the material could be the governing factor.

6.10 CONCLUSIONS

From the durability investigations performed, the following conclusions on the durability properties of corex slag concretes can be drawn:

- Based on the oxygen permeability test, concretes containing slag generally have higher oxygen permeabilities. This is particularly the case for corex slag concretes. However, the test is not an intrinsic permeability test, being subject to extraneous influences.

- The near surface characteristics of slag concretes are good to excellent in preventing the absorption of water through the pores of the material, with blastfurnace slag concretes showing better results, in terms of water sorptivity.

- Both types of slag provide excellent resistance to ingress by chloride ions, with corex slag performing marginally better.

- For short curing periods, binders reacting rapidly, like CEM I and corex slag, showed higher durability potential. However, for 3-day wet curing regimes, most of the mixes exhibited good to excellent durability indexes, implying that a minimum of three days of curing should be applied to all concrete.

- The performance of slag concretes in marine environments is very good, with corex slag appearing to have slightly higher chloride binding capabilities. CEM I concretes, on the other hand, put marine structures at a greater risk of corrosion. The critical chloride depths for CEM I controls were 80 and 50 % greater than slag concretes at water:binder ratios of 0.6 and 0.4 respectively.

- Corex slag concretes have exceptionally low carbonation depths, making the material ideal for use in structures like parking garages. After 20 weeks of exposure, corex slag concrete experienced no carbonation at a water:binder ratio of 0.4 while at a water:binder ratio of 0.6 the depth of carbonation was 36 % lower than both CEM I controls and blastfurnace slag concrete.

- The use of corex slag is beneficial in reducing the expansion due to ASR and the effectiveness of the material is increased at higher replacement level. For a substitution rate of 25 %, corex slag samples showed 37 % more expansion while at 50 % replacement level, corex and blastfurnace slags had virtually the same efficiency in resisting ASR.

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CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

Slag is a by-product of the reduction of iron ores to metallic iron (pig iron) and it has been used in concrete for almost half a century in South Africa. The main reasons for the use of the material are because slag is cheaper than cement, and also because it can enhance the properties of concrete, particularly in relation to durability. Furthermore, its use in concrete helps to reduce a serious risk to the environment.

Until recently, only blastfurnace slag was available for use in concrete but now a new type of slag called corex slag has also been put on the market. Being a new product, there was a need to characterise the properties of corex slag in concrete and this was the main objective of this research. It is considered to be of vital importance to provide data to structural and materials engineers about the effects of corex slag in concrete so that they are aware of all its properties when designing a new structure. In this study, the properties of corex slag concretes were compared to blastfurnace slag and CEM I concretes.

The fresh and hardened properties investigated in this research were assessed on concrete containing selected water:binder ratios (0.4, 0.5, 0.6, 0.8) and replacement levels (30, 50, 70 %). In the future, these two variables could be changed and more specific tests performed in order to characterise the properties of corex slag concretes over a wider range of variables.

7.1 CONCLUSIONS

7.1.1 Materials and Mixes

The chemical and physical characterisations of corex slag were performed. The oxide analysis revealed corex slag to have higher percentages of CaO and MgO and lower percentage of SiO_2 compared with blastfurnace slag. It is reported in the literature that these three constituents have the most significant effects on the hydraulic activity of the binder and hydraulicity formulae indicate corex slag to be more reactive than blastfurnace slag. The physical characterisation of corex slag showed that the material had a higher fineness and this was also observed from the SEM images. Furthermore, the particle size distribution revealed that corex slag had, on average, 5 % more ultra-fine particles and this greatly added to the initial activity of the material.

7.1.2 Fresh Concrete Properties

The fresh concrete properties investigated included consistence, setting time and bleeding. Corex slag was observed to have no real beneficial effect on the consistence of concrete especially at low water:binder ratios. In fact, plasticizer was needed in order to achieve the required slump. An increase in water:binder ratio had the effect of improving the slump values compared to the CEM I controls but the consistence was marginally less than the corresponding blastfurnace slag mixes. Furthermore, the consequences of replacement levels on slump values were not obvious. However, it should be borne in mind that the slump test characterises concrete consistence and not workability. Since the behaviour of corex and blastfurnace slags was fairly similar with regard to consistence, it can be said that the higher fineness of the material is not a detrimental factor.

From the setting time experiments, it can be concluded that slag, in general, causes an increase in the setting time. This observation is widely reported in the literature. It was observed that the higher the replacement level, the longer the setting times, and generally corex slag mixes had longer initial setting time but shorter final setting time compared to blastfurnace slag. The fact that the final setting time of corex slag is shorter is beneficial for the early finishing of the concrete.

The use of slag in concrete has a positive effect on the bleeding characteristics as the bleed volume is significantly reduced, with corex slag out-performing blastfurnace slag at low water:binder ratios. Reduction in bleed volume of up to 50 % was noted in the case of corex slag concrete. Therefore, it can be said that corex slag improves the overall quality of concrete as the effects associated with bleeding such as poor bond between matrix and aggregate or steel and variation in the effective water:binder ratio are minimised. Moreover, the higher the replacement level, the greater the bleed volume and consequently greater care should be taken when working with such mixes.

7.1.3 Compressive Strength and Elastic Modulus of Concrete

The initial compressive strength of concrete is suppressed when slag is used. Generally, during the first three to seven days, corex slag causes the compressive strength of concrete to lag behind the CEM I controls but after that period of time, the compressive strength is higher. In some cases, blastfurnace slag even causes time delays of greater than 56 days before equal strength is reached. Furthermore, the rate of strength gain for corex slag concretes is higher during the first 14 days and then decreases rapidly with time. Blastfurnace slag samples, on the other hand, exhibit steady rates of strength gain typical of slag concretes.

Concerning the effect of replacement level on compressive strength, the results showed that the higher the substitution rate of slag, the lower the early age (less than 7 days) strength. An increase in the water:binder ratio also had the same effect. It was found in this research that the optimum slag replacement level, with respect to compressive strength, varies with water:binder ratio, ranging from 45 to 60 % for corex slag.

The use of corex slag in concrete results in higher elastic modulus values (9 % higher on average) than blastfurnace slag concrete at 28 days and the modulus of elasticity values appear to be proportional to the compressive strength. However, at later ages, the modulus of elasticity of both blastfurnace and corex slag mixes became almost identical indicating that the type of slag has no particular effect on the long-term elastic modulus of the concrete.

7.1.4 Creep and Shrinkage of Concrete

From the results of the creep investigation, it can be concluded that the use of corex slag in concrete gives rise to low creep deformations. In fact, at low water:binder ratios, the creep strains are lower than those of CEM I concretes at all ages. Blastfurnace slag, on the other hand, leads to high initial rate of creep strain which then decreases with time. Eventually, the creep deformations become lower than the CEM I controls. The good creep behaviour of corex slag concrete was also observed in the basic creep experiment. Thus, it can be said that the creep characteristics of corex slag concrete make the material ideal for use in prestressed concrete structures. However, the low deformations exhibited by corex slag concrete could be harmful for the structure as the degree of ductility is reduced. This, in turn, could possibly result in more cracking.

The shrinkage results indicate that, at low water:binder ratios, corex slag exhibits the lowest shrinkage strains and this is a direct result of its higher stiffness. However, with increases in water:binder ratio, this effect is no longer the controlling factor and the measured shrinkage strains fall in the same range as for blastfurnace slag and CEM I concretes. No definite trend was apparent when shrinkage results were compared.

A comparison of the experimental creep and shrinkage values from this investigation with those predicted using the various models considered revealed that there was no defined model which provided the most accurate predictions for both creep and shrinkage for all parameters involved. Furthermore, it was found that the shrinkage predictions generally had lower coefficients of variations, hence concluding that the shrinkage models can be used with more confidence.

7.1.5 Durability of Concrete

The durability index tests revealed that curing time has an effect on the durability of concrete, with the impact being more apparent on blastfurnace slag concrete, less so for corex slag concrete. It can be deduced from the results that a minimum of three-days wet curing period is required to ensure adequate potential durability of the resulting concrete. The longer the curing period, the more durable the resulting concrete structures. The durability indexes also indicated that slag reduced the rate of advance of a wetting front through concrete. However, the improvements in permeability generally associated with the use of slag in concrete were not apparent. When permeability was measured in a gas permeameter, blastfurnace slag performed better than corex slag when prolonged curing regimes were adopted but it is a well known fact that site concrete only receives limited curing and the use of corex slag could then become advantageous.

Rapid chloride conductivity experiments and marine exposure results indicated that slag significantly improves the resistance of concrete to ingress by chloride ions, with corex slag marginally out-performing blastfurnace slag. CEM I concretes, on the other hand, put marine structures at a greater risk of corrosion and require greater cover to provide the same level of protection to reinforcing bars as in slag concretes.

Contrasting results were obtained for the two different types of slags regarding carbonation depth. Corex slag concretes experienced the least carbonation while the ingress of carbon dioxide gas was highest in blastfurnace slag samples. The carbonation depth was observed to increase with water:binder ratio and exposure time. The fact that corex slag concrete exhibits excellent carbonation resistance makes the material ideal for use in high carbonation environments such as parking garages.

Slag concretes in general were found to be efficient in resisting alkali-silica reaction and its associated expansion This efficiency was noted to increase with increasing replacement level. Blastfurnace slag was observed to be more effective in limiting ASR expansion. At a replacement level of 25 %, corex slag samples experienced 37 % more expansion than the corresponding blastfurnace slag specimens but at a higher substitution rate of 50 %, corex slag had similar efficiency as blastfurnace slag. It can, therefore, be said that corex slag can be used to resist the effects associated with ASR provided that an appropriate replacement level is used.

7.1.6 General Conclusions

From the results of this investigation, it can be concluded that corex slag is an excellent material for use in concrete. Corex slag concrete behaves very well in the fresh state and it has very good compressive strength and dimensional properties. Furthermore, the use of corex slag in concrete can help to achieve durable structures and this is of utmost importance nowadays

However, to translate the excellent properties of corex slag concrete from laboratory conditions to real structures, good construction practices are required. It is important for the concreting team to understand that the rate of setting and hardening may be slower and the finishing time extended compared to a normal CEM I concrete. Moreover, the props and formwork should remain in place for a longer period of time such that the strength and durability aspects of corex slag concrete are developed.

Finally, after completing this study, it can be said that by characterising some of the properties of corex slag concrete and making the information available, the aim and objectives of the investigation were fully achieved.

7.2 RECOMMENDATIONS

Microstructural Study

Appropriate microstructural studies need to be performed on corex slag concretes in order to fully characterise the structure of the material. This will, in turn, help to clarify the behaviour of corex slag concretes under various experimental conditions. More importantly, the results will explain why there is a rapid decline in the excellent characteristics of the concrete when the water:binder ratio is increased from 0.5 to 0.6. Furthermore, the impact of corex slag on the interfacial transition zone should also be quantified.

Broader Range of Replacement Levels and Water:Binder Ratios

In this study, most of the experiments were performed on concrete having a slag replacement level of 50 %. However, in the future, the effects of other substitution rates on the deformation and durability properties of corex slag concrete should also be investigated. This is of particular importance to the Western Cape region where there is a tendency for the local construction industry to use a 30 % slag replacement level.

Furthermore, the water:binder ratios could also be varied from those used in this research and, in particular, the effect of low water:binder ratios on the properties of corex slag concrete could be investigated. The results would then indicate if corex slag concrete is suitable for use in high performance concrete.

Consequences of Low Creep Deformations

The effects of low creep deformations associated with corex slag concrete should be investigated more fully. This is because creep, to a certain extent, is beneficial to the concrete as it causes the relief of stress concentrations arising from shrinkage, temperature changes or movement of supports. Consequently, a reduction in the creep deformation will imply a lower degree of ductility of concrete which may cause the material to be too brittle for use in some structures.

Effects of Other Aggressive Agents

In this research, the durability of corex slag concrete was investigated in specific aggressive environments. It would be vital in the future to quantify the effects of acid, softwater and sulphate attack on corex slag concrete in order to know the durability potential in such environments. Also, knowledge of the freeze-thaw characteristics of the material could be useful.

Thermal Problems

The amount of heat of hydration produced by corex slag concrete should be quantified since it is believed that, being more reactive, it produces more heat than blastfurnace slag concrete. This would then make corex slag less appropriate for use in mass concrete due to the possibility of thermal cracking.

Other Properties of Corex Slag Concrete

In the future, other structural properties of corex slag concrete such as dynamic modulus of elasticity, modulus of rupture and shear strength should also be determined. Moreover, the consequences of elevated curing regimes on corex slag properties could be investigated.

APPENDIX A – MATERIALS AND MIXES

Table A1: Grading analysis of Klipheuwel sand

Sieve size µm	Mass retained g	Cumulative % Retained	% of Material passed
4750	1.2	0.2	100
2360	35.1	7.3	93
1180	96.0	26.6	73
600	139.7	54.7	45
300	92.6	73.3	27
150	75.2	88.4	12

Fineness Modulus = 2.50

Table A2: Oxide analysis of CEM I 42.5

Oxides	Proportion of sample (%)
CaO	67.16
SiO_2	22.25
Al_2O_3	4.42
Fe_2O_3	3.42
Mn_2O_3	0.08
TiO_2	0.22
MgO	1.01
P_2O_5	0.09
SO_3	0.58
K_2O	0.56
Na_2O	0.21
Na_2Oeq	0.58

Bogue potential compounds composition (%):

C_3S	:	59.7
C_2S	:	18.8
C_3A	:	6.6
C_4AF	:	10.6

Table A3: Proportions of concrete mixes (per m^3)

Aggregates	**Replacement Level**			
	0	**30**	**50**	**70**
	Water:Binder = 0.4			
Water	180	180	180	180
Stone	1100	1100	1100	1100
Sand	740	730	720	715
Cement	450	315	225	135
Slag (BS & CS)	0	135	225	315
	Water:Binder = 0.5			
Water	180	180	180	180
Stone	1100	1100	1100	1100
Sand	815	810	800	800
Cement	360	252	180	108
Slag (BS & CS)	0	108	180	252
	Water:Binder = 0.6			
Water	180	180	180	180
Stone	1100	1100	1100	1100
Sand	870	860	855	850
Cement	300	210	150	90
Slag (BS & CS)	0	90	150	210
	Water:Binder = 0.8			
Water	180	180	180	180
Stone	1100	1100	1100	1100
Sand	930	930	925	920
Cement	225	158	113	68
Slag (BS & CS)	0	68	113	158

Table A4: Amount of plasticizer added (ml/m^3)

Mix	**Plasticizer (ml)**
Water:Binder = 0.4	
CEM I	1575
30-CS	1215
30-BS	1575
50-CS	1575
50-BS	1575
70-CS	1125
70-BS	1575
Water:Binder = 0.5	
CEM I	900
50-CS	900

APPENDIX B – BLEED VOLUMES

Table B1: Bleed Volume of mixes

Time	Cumulative Bleed Volume (ml)						
	Replacement Level						
(min)	0	30	50	70	30	50	70
	CEM I	BS			CS		
	Water:Binder = 0.4						
0	0	0	0	0	0	0	0
30	4.02	1.59	1.99	2.22	1.03	1.25	1.37
60	9.12	4.01	4.44	5.47	3.03	3.40	3.72
90	17.18	6.38	7.39	9.21	5.27	5.75	6.38
120	20.87	8.76	10.5	12.65	7.14	7.91	9.12
150	21.53	10.75	13.01	15.16	9.14	9.95	10.89
180		12.05	14.45	18.56	10.60	11.50	12.55
210		12.54	15.02	19.47	10.94	12.70	14.07
240		12.62	15.17	19.85		13.02	14.96
270				19.97			15.31
300							15.35
	Water:Binder = 0.6						
0	0	0	0	0	0	0	0
30	6.11	4.64	1.78	4.50	4.53	2.01	4.07
60	13.45	10.87	6.75	10.22	9.64	6.31	9.17
90	19.33	15.72	11.69	15.24	14.14	10.21	13.34
120	23.56	17.96	16.14	18.50	16.74	12.37	14.94
150	24.57	18.19	18.54	19.54	17.06	13.21	15.29
180	25.41		19.56	19.88		13.33	
210			19.80				
	Water:Binder = 0.8						
0	0	0	0	0	0	0	0
30	8.06	8.52	6.13	5.01	6.99	6.36	4.99
60	17.18	15.73	11.75	9.85	14.99	13.19	10.50
90	23.61	19.59	15.58	13.74	21.01	18.01	16.01
120	27.48	20.79	17.50	17.31	24.00	21.49	19.69
150	29.62	21.05	21.05	19.21	24.58	22.92	21.00
180	30.04		22.53	20.59		24.16	22.74
210			22.99	21.78		24.69	23.26
240				22.45			23.99

APPENDIX C – COMPRESSIVE STRENGTH RESULTS

Table C1: Compressive strength results

Age (Days)	Compressive Strength (MPa)						
	CEM1	**BS**			**CS**		
	0%	**30%**	**50%**	**70%**	**30%**	**50%**	**70%**
	Water:Binder = 0.4						
0	0	0	0	0	0	0	0
3	40.0	29.6	22.3	13.5	40.3	35.2	33.2
7	50.1	42.2	34.4	29.9	55.2	50.9	50.5
14	55.7	52.0	49.4	41.1	62.7	63.5	56.8
28	60.0	61.9	58.8	50.6	66.4	66.0	60.1
56	64.4	67.8	65.7	57.0	70.3	66.9	61.3
	Water:Binder = 0.6						
0	0	0	0	0	0	0	0
3	23.9	14.2	11.8	7.9	20.5	19.3	20.2
7	32.5	22.6	19.7	14.3	33.2	37.0	33.6
14	38.0	30.5	28.2	22.7	40.9	44.1	39.1
28	43.1	37.7	39.3	29.4	47.1	49.1	45.3
56	46.6	43.5	43.1	32.8	48.4	50.9	46.4
	Water:Binder = 0.8						
0	0	0	0	0	0	0	0
3	13.4	9.9	6.8	4.7	14.0	13.0	14.0
7	18.5	15.7	11.5	8.7	23.0	26.3	23.7
14	23.6	21.2	17.5	14.5	29.5	32.6	30.3
28	24.7	26.9	25.9	19.2	33.6	36.3	33.2
56	27.4	31.4	30.6	22.8	34.3	38.1	35.2

Table C2: Coefficients of Variation of elastic modulus results

	Std Deviation	**CoV (%)**	**Std Deviation**	**CoV (%)**
	28-day		90-day	
	Water:Binder = 0.4			
CEM I	0.8	1.9	0.3	0.5
BS	0.2	0.5	1.3	2.7
CS	5.0	12.3	2.4	5.0
	Water:Binder = 0.5			
CEM I	2.6	6.1	2.5	6.0
BS	0.7	1.8	1.5	3.2
CS	0.3	0.7	1.4	2.9
	Water:Binder = 0.6			
CEM I	0.4	0.9	1.5	3.8
BS	1.5	4.4	1.3	3.1
CS	0.7	1.7	1.3	3.0

Table C3: Coefficients of Variation of compressive strength results

	Standard Deviation	CoV (%)	Range/Mean (%)
	Water:Binder = 0.4		
CEM I	0.3	0.6	1.0
30BS	1.3	2.1	4.2
50BS	1.7	2.9	5.4
70BS	0.3	0.6	1.2
30CS	0.9	1.4	2.7
50CS	2.4	3.7	7.3
70CS	3.2	5.3	9.8
	Water:Binder = 0.6		
CEM I	1.2	2.9	5.1
30BS	0.5	1.3	4.5
50BS	0.4	1.0	1.8
70BS	1.2	4.2	7.8
30CS	1.3	2.7	5.3
50CS	0.5	0.9	1.8
70CS	1.3	2.8	5.5
	Water:Binder = 0.8		
CEM I	0.4	1.6	3.2
30BS	0.5	1.8	3.3
50BS	1.0	4.0	7.7
70BS	0.8	4.0	7.8
30CS	1.7	5.1	10.2
50CS	1.5	4.1	8.3
70CS	1.8	5.3	10.5

APPENDIX D – CREEP AND SHRINKAGE RESULTS

Table D1: Creep results for 0.4-CEM I mix

Age (Days)	Ave Creep Strain (µstrain)	Creep Factor	Specific Creep (µstrain/MPa)	Creep Strain / Unit Stress / Strength Ratio (µstrain)
0	0	0	0	0
0.08	40	0.06	3.6	181
0.17	78	0.12	7.1	354
0.25	95	0.15	8.6	423
1	163	0.25	14.7	737
2	270	0.42	24.3	1217
3	307	0.47	27.6	1384
4	313	0.48	28.2	1414
5	335	0.52	30.2	1512
6	357	0.55	32.1	1610
7	383	0.59	34.5	1730
10	443	0.68	39.9	2001
14	482	0.74	43.4	2174
21	570	0.88	51.4	2573
28	633	0.97	57.1	2859
42	723	1.11	65.2	3265
56	743	1.14	67.0	3355
84	818	1.26	73.7	3694
112	872	1.34	78.5	3934

Table D2: Creep results for 0.4-CS mix

Age (Days)	Ave Creep Strain (µstrain)	Creep Factor	Specific Creep (µstrain/MPa)	Creep Strain / Unit Stress / Strength Ratio (µstrain)
0	0	0	0	0
0.08	48	0.08	4.4	222
0.17	102	0.16	9.2	466
0.25	132	0.21	11.9	604
1	192	0.31	17.3	879
2	250	0.40	22.5	1147
3	253	0.41	22.8	1162
4	240	0.39	21.6	1101
5	262	0.42	23.6	1200
6	277	0.45	24.9	1269
7	285	0.46	25.7	1307
10	327	0.53	29.4	1498
14	338	0.55	30.5	1557
21	398	0.64	35.9	1826
28	420	0.68	37.8	1926
42	478	0.77	43.1	2194
56	495	0.80	44.6	2270
84	560	0.91	50.5	2568
112	632	1.02	56.9	2897

Table D3: Creep results for 0.4-BS mix

Age (Days)	Ave Creep Strain (μstrain)	Creep Factor	Specific Creep (μstrain/MPa)	Creep Strain / Unit Stress / Strength Ratio (μstrain)
0	0	0	0	0
0.08	133	0.15	12.0	413
0.17	160	0.18	14.4	496
0.25	187	0.21	16.8	579
1	260	0.29	23.4	806
2	407	0.45	36.6	1260
3	460	0.51	41.4	1426
4	477	0.53	42.9	1477
5	505	0.56	45.5	1565
6	518	0.58	46.7	1606
7	562	0.62	50.6	1741
10	632	0.70	56.9	1958
14	658	0.73	59.3	2040
21	720	0.80	64.9	2231
28	757	0.84	68.2	2345
42	800	0.89	72.1	2479
56	818	0.91	73.7	2536
84	842	0.94	75.8	2608
112	885	0.98	79.7	2743

Table D4: Creep results for 0.5-CEM I mix

Age (Days)	Ave Creep Strain (μstrain)	Creep Factor	Specific Creep (μstrain/MPa)	Creep Strain / Unit Stress / Strength Ratio (μstrain)
0	0	0	0	0
0.08	53	0.12	7.0	294
0.17	70	0.15	9.2	386
0.25	93	0.20	12.3	515
1	108	0.24	14.3	597
2	113	0.25	14.9	625
3	153	0.34	20.2	846
4	197	0.43	25.9	1084
5	203	0.44	26.8	1121
6	235	0.51	30.9	1296
7	243	0.53	32.0	1342
10	280	0.61	36.8	1544
14	332	0.72	43.6	1829
21	392	0.86	51.5	2160
28	423	0.92	55.7	2334
42	507	1.11	66.7	2794
56	548	1.20	72.2	3023
84	620	1.35	81.6	3418
112	672	1.47	88.4	3703

Table D5: Creep results for 0.5-CS mix

Age (Days)	Ave Creep Strain (μstrain)	Creep Factor	Specific Creep (μstrain/MPa)	Creep Strain / Unit Stress / Strength Ratio (μstrain)
0	0	0	0	0
0.08	23	0.06	3.1	128
0.17	67	0.16	8.8	366
0.25	92	0.22	12.1	503
1	128	0.31	16.9	704
2	135	0.33	17.8	741
3	157	0.38	20.6	860
4	208	0.50	27.4	1143
5	205	0.49	27.0	1125
6	230	0.55	30.3	1262
7	248	0.60	32.7	1363
10	268	0.65	35.3	1472
14	302	0.73	39.7	1655
21	350	0.84	46.1	1920
28	375	0.90	49.3	2058
42	433	1.04	57.0	2378
56	470	1.13	61.8	2579
84	538	1.30	70.8	2954
112	597	1.44	78.5	3274

Table D6: Creep results for 0.5-BS mix

Age (Days)	Ave Creep Strain (μstrain)	Creep Factor	Specific Creep (μstrain/MPa)	Creep Strain / Unit Stress / Strength Ratio (μstrain)
0	0	0	0	0
0.08	67	0.10	8.8	196
0.17	107	0.16	14.0	313
0.25	128	0.19	16.9	377
1	230	0.34	30.3	675
2	250	0.37	32.9	734
3	297	0.43	39.0	871
4	355	0.52	46.7	1042
5	367	0.54	48.2	1076
6	408	0.60	53.7	1198
7	413	0.60	54.4	1213
10	442	0.65	58.1	1296
14	477	0.70	62.7	1399
21	530	0.77	69.7	1555
28	535	0.78	70.4	1570
42	605	0.88	79.6	1775
56	628	0.92	82.7	1844
84	658	0.96	86.6	1932
112	700	1.02	92.1	2054

Table D7: Creep results for 0.6-CEM I mix

Age (Days)	Ave Creep Strain (μstrain)	Creep Factor	Specific Creep (μstrain/MPa)	Creep Strain / Unit Stress / Strength Ratio (μstrain)
0	0	0	0	0
0.08	117	0.26	15.4	516
0.17	162	0.35	21.3	715
0.25	165	0.36	21.7	729
1	197	0.43	25.9	869
2	257	0.56	33.8	1135
3	313	0.69	41.2	1385
4	327	0.72	43.0	1444
5	340	0.74	44.7	1503
6	365	0.80	48.0	1614
7	373	0.82	49.2	1650
10	443	0.97	58.3	1960
14	495	1.08	65.1	2188
21	587	1.29	77.2	2594
28	657	1.44	86.4	2903
42	752	1.65	98.9	3323
56	808	1.77	106.4	3574
84	907	1.99	119.3	4008
112	948	2.08	124.8	4193

Table D8: Creep results for 0.6-CS mix

Age (Days)	Ave Creep Strain (μstrain)	Creep Factor	Specific Creep (μstrain/MPa)	Creep Strain / Unit Stress / Strength Ratio (μstrain)
0	0	0	0	0
0.08	87	0.19	11.4	375
0.17	145	0.32	19.8	628
0.25	123	0.27	16.2	534
1	142	0.31	18.6	613
2	205	0.45	27.0	887
3	272	0.60	35.7	1176
4	282	0.61	37.1	1219
5	308	0.67	40.6	1335
6	335	0.73	44.1	1450
7	343	0.75	45.2	1486
10	410	0.89	53.9	1775
14	457	0.99	60.1	1977
21	567	1.23	74.6	2453
28	618	1.34	81.4	2677
42	743	1.62	97.8	3218
56	813	1.77	107.0	3521
84	9483	2.06	124.8	4105
112	1040	2.26	136.8	4502

Table D9: Basic creep results for 0.5-CEM I mix

Age (Days)	Ave Creep Strain (μstrain)	Creep Factor	Specific Creep (μstrain/MPa)	Creep Strain / Unit Stress / Strength Ratio (μstrain)
0	0	0	0	0
0.08	87	0.24	11.5	539
0.17	106	0.29	13.9	652
0.25	107	0.29	14.1	662
1	139	0.36	18.3	858
2	152	0.41	20.0	940
3	184	0.50	24.2	1136
4	182	0.49	24.0	1125
5	192	0.52	25.3	1187
6	216	0.58	28.4	1331
7	234	0.63	30.8	1444
10	267	0.72	35.2	1650
14	281	0.76	36.9	1732
21	307	0.83	40.4	1897
28	324	0.87	42.6	1999
42	346	0.93	45.5	2133
56	357	0.96	48.5	2275
84	442	1.19	56.0	2626

Table D10: Basic creep results for 0.5-CS mix

Age (Days)	Ave Creep Strain (μstrain)	Creep Factor	Specific Creep (μstrain/MPa)	Creep Strain / Unit Stress / Strength Ratio (μstrain)
0	0	0	0	0
0.08	24	0.06	3.2	171
0.17	34	0.08	4.5	241
0.25	36	0.09	4.7	253
1	63	0.15	8.2	440
2	63	0.15	8.2	440
3	86	0.21	11.3	603
4	91	0.22	12.0	638
5	98	0.24	12.9	685
6	112	0.27	14.8	790
7	116	0.28	15.3	813
10	121	0.29	15.9	849
14	143	0.35	18.8	1001
21	159	0.39	21.0	1117
28	154	0.37	22.5	1199
42	191	0.46	25.1	1340
56	201	0.49	26.4	1410
84	243	0.59	31.9	1702

Table D11: Basic creep results for 0.5-BS mix

Age (Days)	Ave Creep Strain (μstrain)	Creep Factor	Specific Creep (μstrain/MPa)	Creep Strain / Unit Stress / Strength Ratio (μstrain)
0	0	0	0	0
0.08	191	0.51	25.1	815
0.17	221	0.60	29.0	944
0.25	231	0.62	30.4	986
1	249	0.67	32.8	1065
2	286	0.77	37.6	1222
3	302	0.82	39.8	1293
4	304	0.82	40.0	1300
5	326	0.88	42.9	1393
6	342	0.92	45.0	1464
7	352	0.95	46.4	1507
10	372	1.00	49.0	1592
14	384	1.04	50.5	1642
21	401	1.08	52.7	1713
28	407	1.10	53.6	1742
42	417	1.13	54.9	1785
56	422	1.13	55.4	1799
84	432	1.17	56.9	1849

Table D12: Shrinkage results for all mixes

Age	**Shrinkage Strains (Microstrain)**								
	Water:Binder								
(Days)	**0.4**			**0.5**			**0.6**		
	CEM I	**CS**	**BS**	**CEM I**	**CS**	**BS**	**CEM I**	**CS**	**BS**
0	0	0	0	0	0	0	0	0	0
1	35	47	52	23	28	23	5	17	5
2	60	627	78	37	52	33	18	33	45
3	77	77	100	65	70	42	43	57	71
4	93	88	123	87	83	53	53	62	78
5	112	107	140	93	90	60	57	73	87
6	122	108	145	108	105	68	75	92	93
7	133	128	163	122	120	83	85	95	107
10	165	143	192	152	143	105	108	133	125
14	197	173	228	188	163	137	128	165	155
21	242	202	252	228	198	178	163	213	195
28	282	237	283	265	223	202	198	256	222
42	332	265	312	322	272	238	253	313	260
56	353	278	322	350	282	265	282	345	298
84	398	310	347	408	322	308	353	406	350
112	423	330	365	433	333	330	355	420	365

Table D13: Predicted specific creep results for 0.4 CEM1 mix (μstrain/MPa)

Age (Days)	Measured	ACI	CEB-FIP	RILEM-B3	BSt
0	0	0	0		
0.08	4	1	7	29	
0.17	7	2	9	31	
0.25	9	2	10	33	
1	15	5	15	37	3
2	24	7	18	41	13
3	28	9	20	43	18
4	28	10	22	45	22
5	30	11	24	46	25
6	32	12	25	47	28
7	35	13	26	49	30
10	40	16	29	52	35
14	43	18	32	55	39
21	51	21	36	59	45
28	57	23	39	62	49
42	65	27	44	67	54
56	67	29	47	71	58
84	74	32	52	76	64
112	79	34	56	81	68
1825	113	49	80	124	106

Table D14: Predicted specific creep results for 0.4 CS mix (μstrain/MPa)

Age (Days)	Measured	ACI	CEB-FIP	RILEM-B3	BSt
0	0	0	0		
0.08	4	1	6	27	
0.17	9	2	8	28	
0.25	12	2	9	30	
1	17	5	13	34	3
2	23	7	17	37	13
3	23	9	19	39	18
4	22	10	20	41	22
5	24	11	22	42	25
6	25	12	23	43	28
7	26	13	24	45	30
10	29	15	27	47	35
14	30	18	29	50	39
21	36	20	33	54	45
28	38	23	36	57	49
42	43	26	40	62	54
56	45	28	43	66	58
84	50	31	48	71	63
112	57	34	51	75	67
1825	82	48	73	117	105

Table D15: Predicted specific creep results for 0.4 BS mix (μstrain/MPa)

Age (Days)	Measured	ACI	CEB-FIP	RILEM-B3	BSt
0	0	0	0		
0.08	12	1	8	30	
0.17	14	2	10	32	
0.25	17	3	11	33	
1	23	6	17	38	4
2	37	8	20	42	15
3	41	11	23	44	22
4	43	12	25	46	27
5	45	14	27	47	30
6	47	15	28	49	33
7	51	16	30	50	36
10	57	19	33	53	42
14	59	22	36	56	47
21	65	26	41	60	54
28	68	28	44	64	58
42	72	32	49	69	65
56	74	35	53	73	70
84	76	39	59	79	76
112	80	42	63	834	81
1825	115	60	90	130	126

Table D16: Predicted specific creep results for 0.5 CEM1 mix (μstrain/MPa)

Age (Days)	Measured	ACI	CEB-FIP	RILEM-B3	BSt
0	0	0	0		
0.08	7	1	8	32	
0.17	9	2	10	34	
0.25	12	3	11	35	
1	14	6	17	41	4
2	15	8	21	44	13
3	20	10	24	46	19
4	26	12	26	48	23
5	27	13	28	50	26
6	31	14	29	51	29
7	32	15	31	52	31
10	37	18	34	55	36
14	44	21	38	58	41
21	52	24	42	62	47
28	56	27	46	65	51
42	67	31	51	70	56
56	72	33	55	74	61
84	82	37	61	79	66
112	88	40	65	84	70
1825	127	57	93	128	110

Table D17: Predicted specific creep results for 0.5 CS mix (μstrain/MPa)

Age (Days)	Measured	ACI	CEB-FIP	RILEM-B3	BSt
0	0	0	0		
0.08	3	1	7	28	
0.17	9	2	9	30	
0.25	12	3	10	31	
1	17	6	15	35	4
2	18	9	19	38	14
3	21	11	21	40	20
4	27	12	23	42	24
5	27	14	24	43	27
6	30	15	26	45	30
7	33	16	27	46	32
10	35	19	30	48	38
14	40	22	33	51	43
21	46	25	37	55	49
28	49	28	40	58	53
42	57	31	45	62	59
56	62	34	48	66	63
84	71	38	53	71	69
112	79	41	57	75	73
1825	113	58	82	116	114

Table D18: Predicted specific creep results for 0.5 BS mix (μstrain/MPa)

Age (Days)	Measured	ACI	CEB-FIP	RILEM-B3	BSt
0	0	0	0		
0.08	9	2	9	33	
0.17	14	3	11	35	
0.25	17	4	13	36	
1	30	8	19	42	5
2	33	12	24	45	18
3	39	15	27	47	26
4	47	17	29	49	32
5	48	19	31	51	36
6	54	20	33	52	40
7	54	22	35	53	43
10	58	26	38	56	50
14	63	29	42	60	56
21	70	34	47	64	64
28	70	38	51	67	69
42	80	44	57	72	77
56	83	48	62	76	83
84	87	53	68	82	91
112	92	57	73	87	96
1825	132	81	105	134	150

Table D19: Predicted specific creep results for 0.6 CEM1 mix (μstrain/MPa)

Age (Days)	Measured	ACI	CEB-FIP	RILEM-B3	BSt
0	0	0	0		
0.08	15	2	9	33	
0.17	21	3	11	35	
0.25	22	3	12	37	
1	26	7	18	42	4
2	34	10	23	45	15
3	41	12	26	47	21
4	43	14	28	49	26
5	45	16	30	51	29
6	48	17	31	52	32
7	49	19	33	53	35
10	58	22	36	56	40
14	65	25	40	59	45
21	77	29	45	63	52
28	86	32	49	66	56
42	99	37	55	71	63
56	106	40	59	74	67
84	119	45	65	80	74
112	125	48	70	84	78
1825	179	69	100	129	122

Table D20: Predicted specific creep results for 0.6 CS mix (μstrain/MPa)

Age (Days)	Measured	ACI	CEB-FIP	RILEM-B3	BSt
0	0	0	0		
0.08	11	2	8	31	
0.17	19	3	10	33	
0.25	16	3	12	34	
1	19	7	17	40	4
2	27	11	21	43	15
3	36	13	24	45	22
4	37	15	26	47	26
5	41	17	28	48	30
6	44	19	30	49	33
7	45	20	31	50	35
10	54	23	34	53	41
14	60	27	38	56	47
21	75	31	43	60	53
28	81	35	46	63	58
42	98	40	52	68	64
56	107	43	56	71	69
84	125	48	62	76	75
112	137	51	66	80	80
1825	197	74	95	123	125

Table D21: Predicted shrinkage results for 0.4 CEM1 mix (μstrain)

Age (Days)	Measured	ACI	CEB-FIP	RILEM	BSt
0	0	0	0	0	0
1	35	14	45	45	10
2	60	28	63	64	19
3	77	40	77	78	28
4	93	53	89	90	36
5	112	64	99	101	44
6	122	76	108	111	51
7	133	86	116	120	59
10	165	115	136	143	78
14	197	148	158	169	101
21	242	194	187	206	132
28	282	230	209	237	157
42	332	283	242	286	193
56	353	319	265	324	218
84	398	366	297	380	251
112	423	395	318	418	271
1825	561	508	415	566	350

Table D22: Predicted shrinkage results for 0.4 CS mix (μstrain)

Age (Days)	Measured	ACI	CEB-FIP	RILEM	BSt
0	0	0	0	0	0
1	47	14	42	45	10
2	62	28	59	64	19
3	77	40	72	78	28
4	88	52	82	90	36
5	107	64	92	101	44
6	108	75	100	110	51
7	128	85	107	119	59
10	143	113	126	142	78
14	173	146	146	168	101
21	202	191	173	205	132
28	237	226	194	236	157
42	265	278	224	285	193
56	278	313	246	322	218
84	310	360	276	377	251
112	330	388	295	414	271
1825	457	500	385	556	350

Table D23: Predicted shrinkage results for 0.4 BS (μstrain)

Age (Days)	Measured	ACI	CEB-FIP	RILEM	BSt
0	0	0	0	0	0
1	52	14	40	45	10
2	78	28	57	64	19
3	100	41	69	78	28
4	123	53	79	91	36
5	140	64	88	101	44
6	145	75	96	111	51
7	163	86	103	120	59
10	192	114	121	143	78
14	228	147	141	169	101
21	252	193	167	206	132
28	283	228	186	237	157
42	312	280	216	286	193
56	322	316	237	324	218
84	347	363	265	380	251
112	365	391	284	418	271
1825	483	504	370	567	350

Table D24: Predicted shrinkage results for 0.5 CEM1 mix (μstrain)

Age (Days)	Measured	ACI	CEB-FIP	RILEM	BSt
0	0	0	0	0	0
1	23	14	50	46	10
2	37	28	70	64	19
3	65	41	85	79	28
4	87	53	98	91	36
5	93	64	109	102	44
6	108	75	119	111	51
7	122	86	128	120	59
10	152	114	150	144	78
14	188	147	174	170	101
21	228	193	206	207	132
28	265	229	231	238	157
42	322	281	267	288	193
56	350	317	293	327	218
84	408	363	328	385	251
112	433	392	351	424	271
1825	583	505	458	582	350

Table D25: Predicted shrinkage results for 0.5 CS mix (µstrain)

Age (Days)	Measured	ACI	CEB-FIP	RILEM	BSt
0	0	0	0	0	0
1	28	14	46	45	10
2	52	28	64	64	19
3	70	41	78	78	28
4	83	53	90	91	36
5	90	65	100	101	44
6	105	75	109	111	51
7	120	86	117	120	59
10	143	115	138	143	78
14	163	147	160	169	101
21	198	193	189	206	132
28	223	229	212	237	157
42	272	281	245	286	193
56	282	317	269	325	218
84	322	364	301	380	251
112	333	393	323	419	271
1825	469	506	421	568	350

Table D26: Predicted shrinkage results for 0.5 BS mix (µstrain)

Age (Days)	Measured	ACI	CEB-FIP	RILEM	BSt
0	0	0	0	0	0
1	23	15	44	46	10
2	33	28	62	64	19
3	42	41	75	79	28
4	53	54	87	91	36
5	60	66	96	102	44
6	68	77	105	111	51
7	83	87	113	120	59
10	105	117	133	144	78
14	137	150	154	170	101
21	178	197	182	207	132
28	202	233	204	238	157
42	238	286	236	288	193
56	265	323	258	327	218
84	308	370	290	385	251
112	330	400	310	425	271
1825	477	515	404	583	350

Table D27: Predicted shrinkage results for 0.6 CEM1 mix (µstrain)

Age (Days)	Measured	ACI	CEB-FIP	RILEM	BSt
0	0	0	0	0	0
1	5	15	52	46	10
2	18	29	73	65	19
3	43	42	88	79	28
4	53	54	101	91	36
5	57	66	113	102	44
6	75	77	123	112	51
7	85	88	132	121	59
10	108	117	155	144	78
14	128	151	180	170	101
21	163	198	213	208	132
28	198	235	239	239	157
42	253	288	276	289	193
56	282	325	303	328	218
84	353	373	340	387	251
112	373	402	364	427	271
1825	515	518	474	589	350

Table D28: Predicted shrinkage results for 0.6 CS mix (µstrain)

Age (Days)	Measured	ACI	CEB-FIP	RILEM	BSt
0	0	0	0	0	0
1	17	15	50	46	10
2	33	30	71	64	19
3	57	43	86	79	28
4	62	56	99	91	36
5	73	69	110	102	44
6	92	80	119	111	51
7	95	91	128	120	59
10	133	122	151	144	78
14	165	157	175	170	101
21	213	206	208	207	132
28	257	244	232	238	157
42	313	299	269	288	193
56	345	337	295	327	218
84	407	387	330	385	251
112	420	418	353	424	271
1825	570	538	461	583	350

Table D29: Predicted shrinkage results for 0.6 BS mix (μstrain)

Age (Days)	Measured	ACI	CEB-FIP	RILEM	BSt
0	0	0	0	0	0
1	5	15	46	46	10
2	45	29	65	64	19
3	72	43	80	79	28
4	78	55	91	92	36
5	87	67	102	102	44
6	93	79	111	112	51
7	107	90	119	121	59
10	125	120	140	145	78
14	155	154	162	171	101
21	195	202	192	209	132
28	222	240	215	240	157
42	260	294	249	290	193
56	298	332	273	330	218
84	350	381	306	389	251
112	365	411	327	430	271
1825	514	530	427	596	350

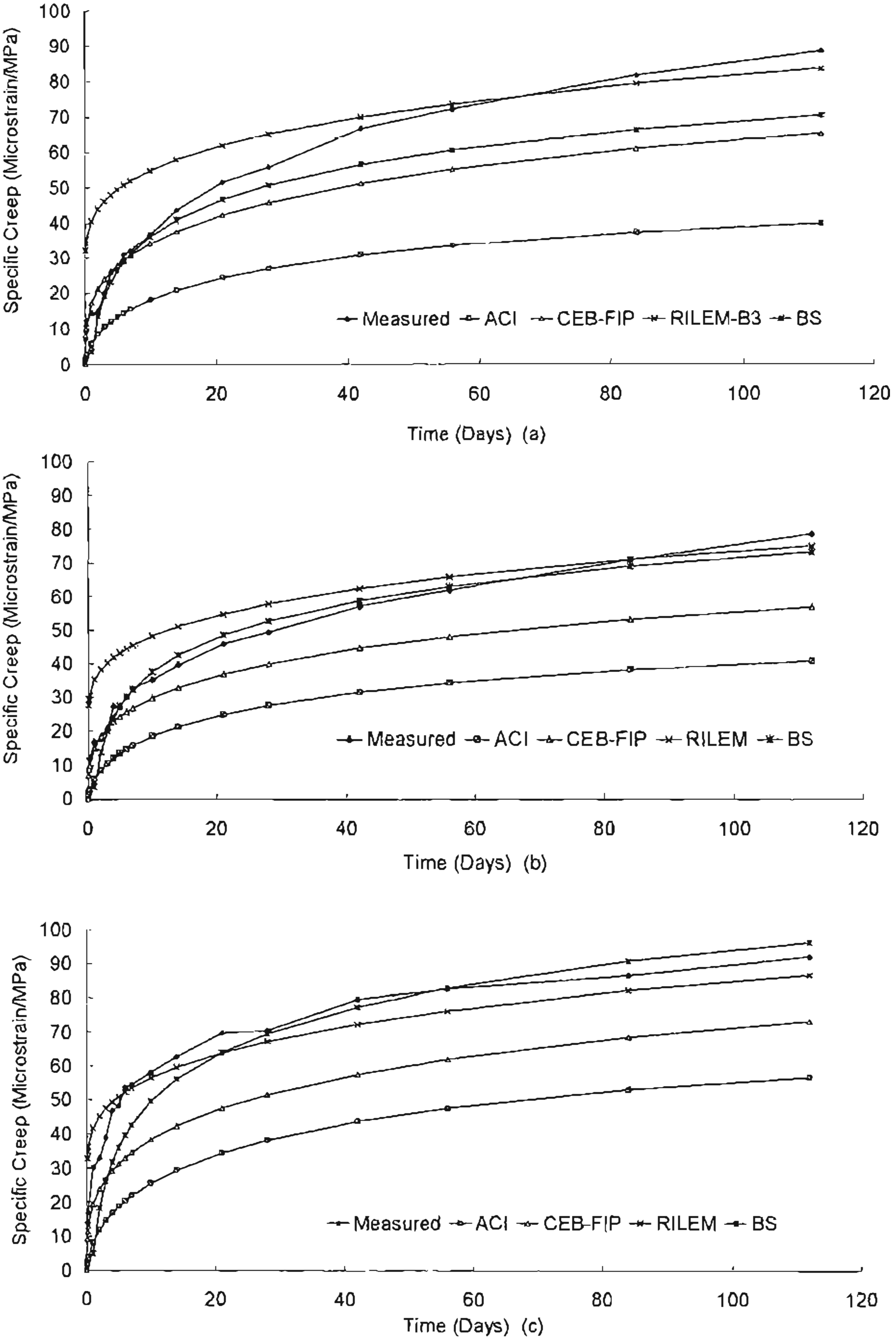

Fig. D1: Predicted specific creep for (a) CEM I (b) CS (c) BS concretes for having a water:binder ratio of 0.5

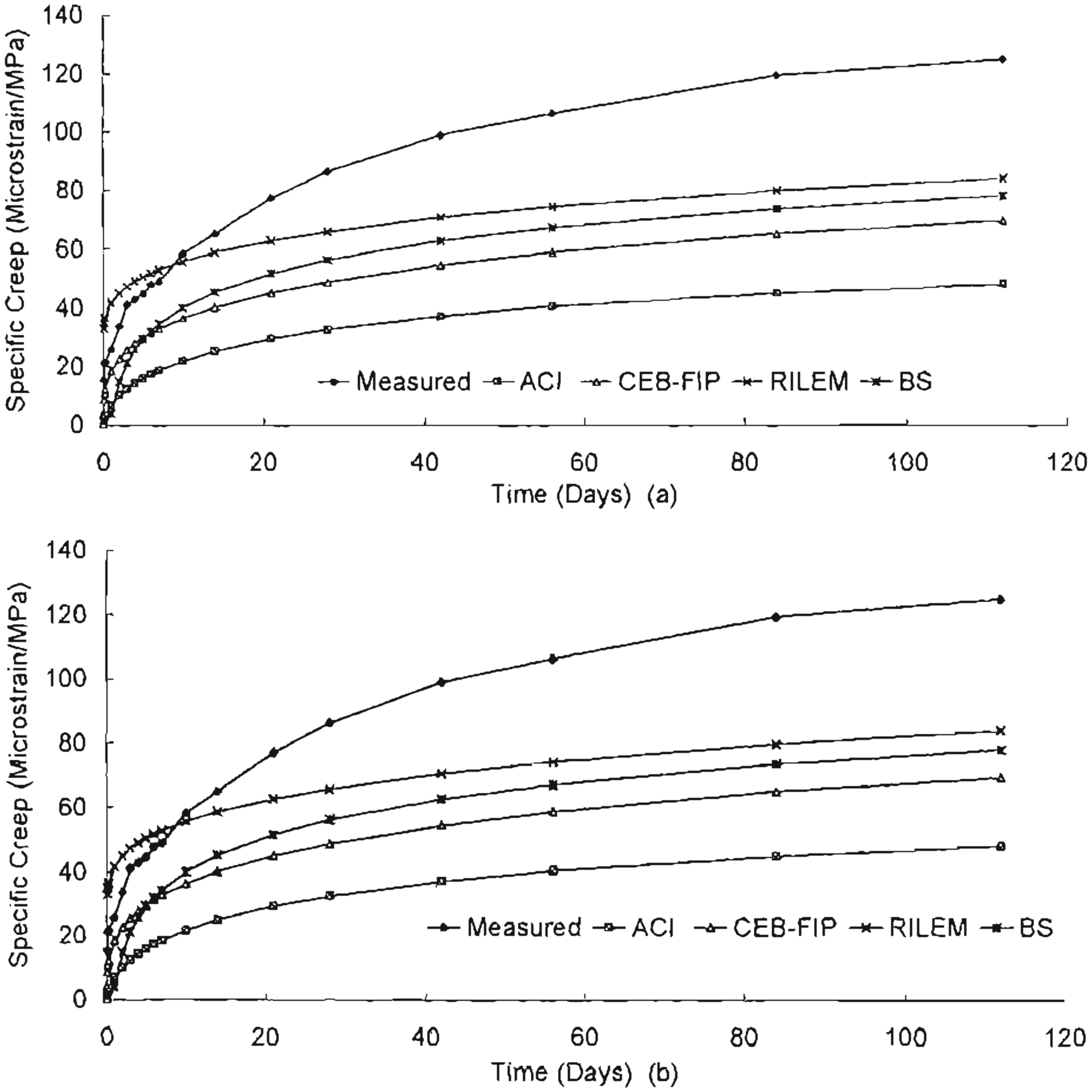

Fig. D2: Predicted specific creep for (a) CEM I (b) CS concretes having a water:binder ratio of 0.6

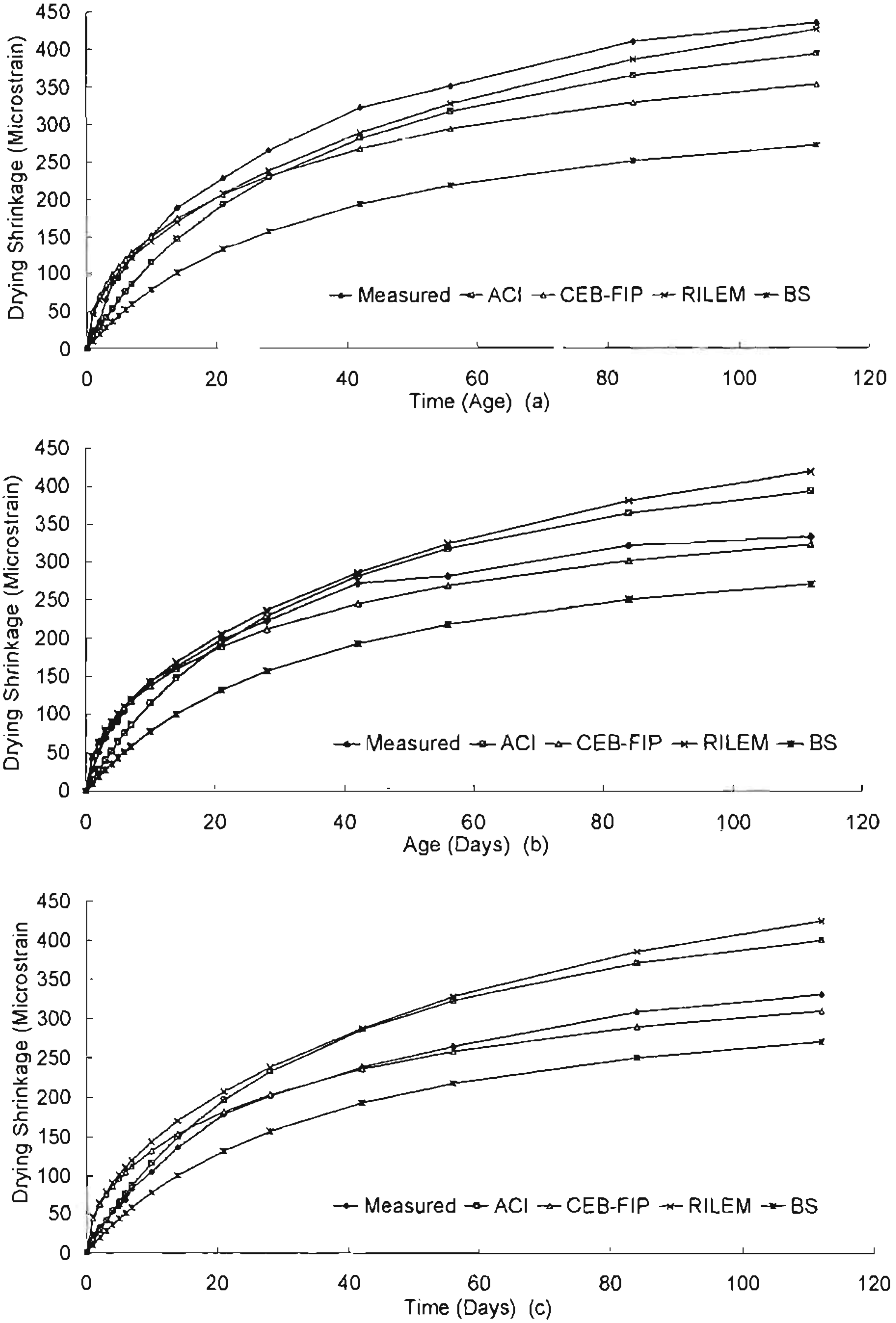

Fig. D3: Predicted drying shrinkage for (a) CEM I (b) CS (c) BS concretes having a water:binder ratio of 0.5

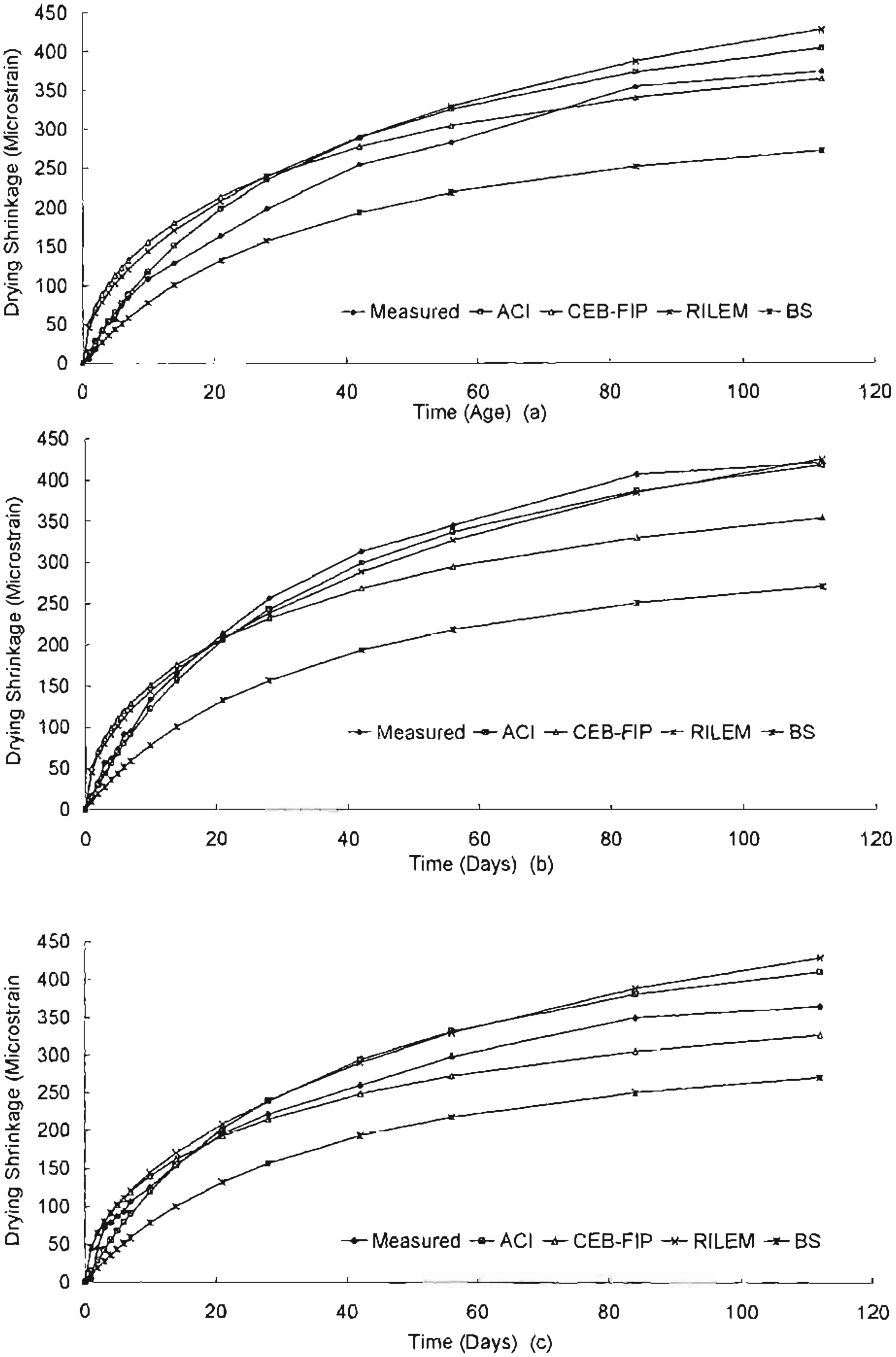

Fig. D4: Predicted drying shrinkage for (a) CEM I (b) CS (c) BS concretes having a water:binder ratio of 0.6

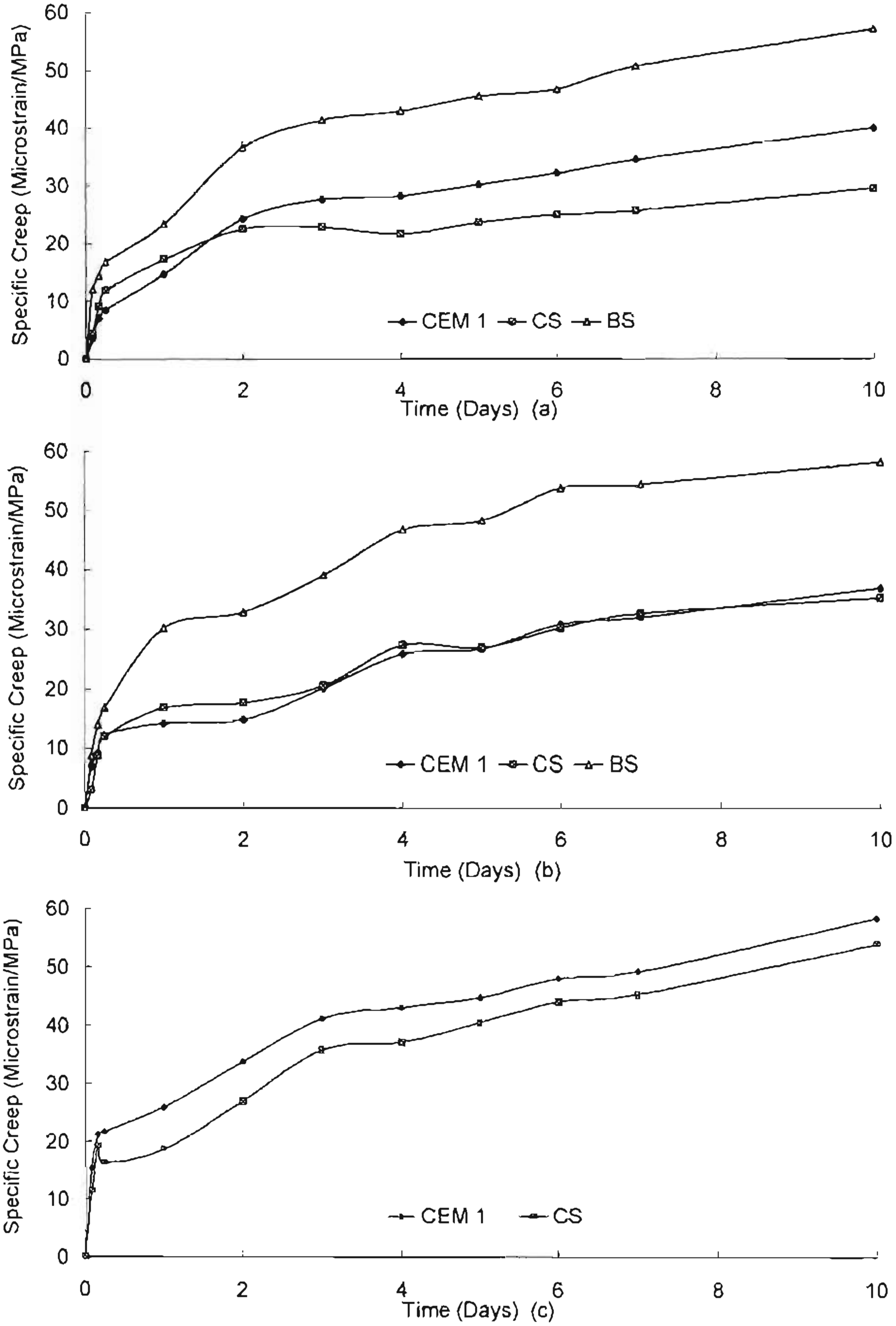

Fig. D 5: Early age specific creep of concrete having water:binder ratios of (a) 0.4 (b) 0.5 (c) 0.6

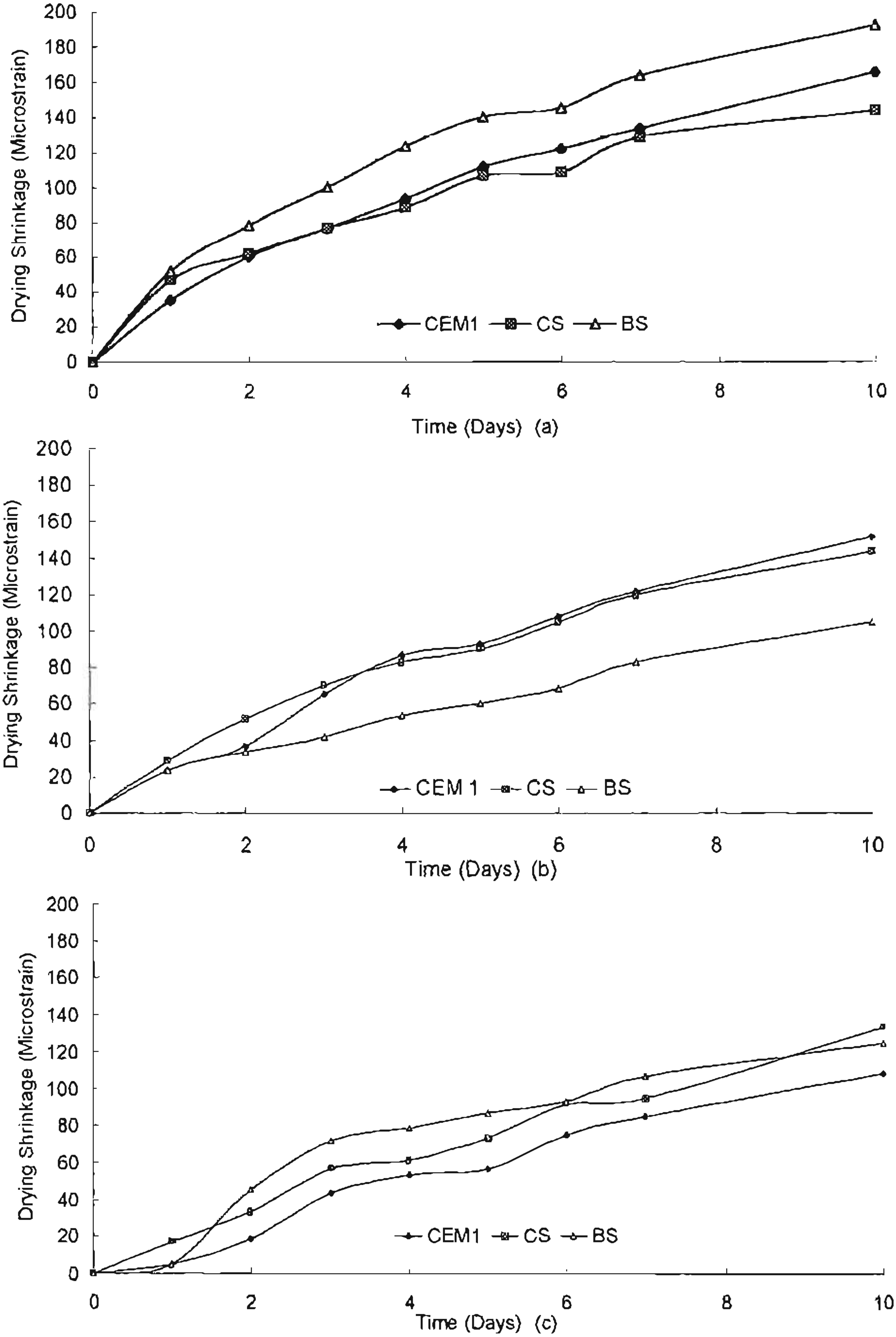

Fig. D6: Early age drying shrinkage of concrete having water:binder ratios of (a) 0.4 (b) 0.5 (c) 0.6

APPENDIX E – SCHEMATICS OF DURABILITY INDEX TESTS

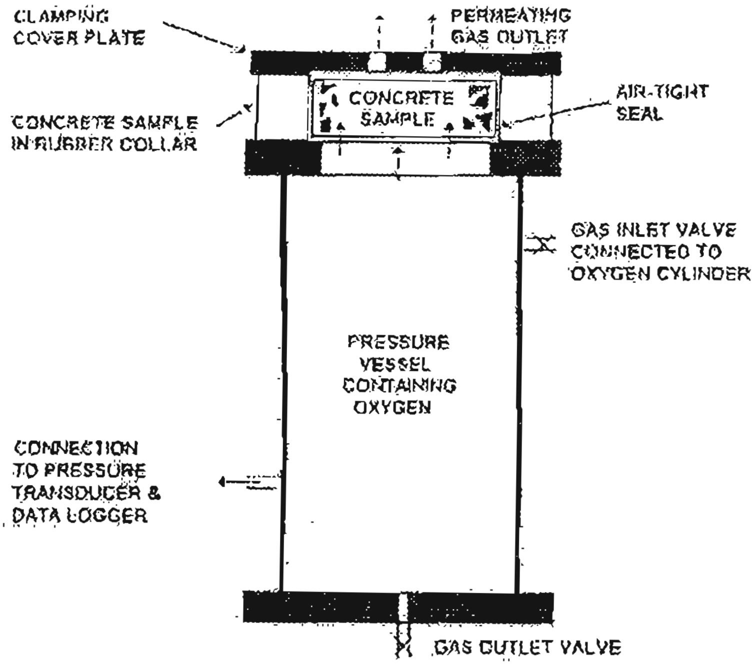

Fig. E1: Oxygen permeability apparatus

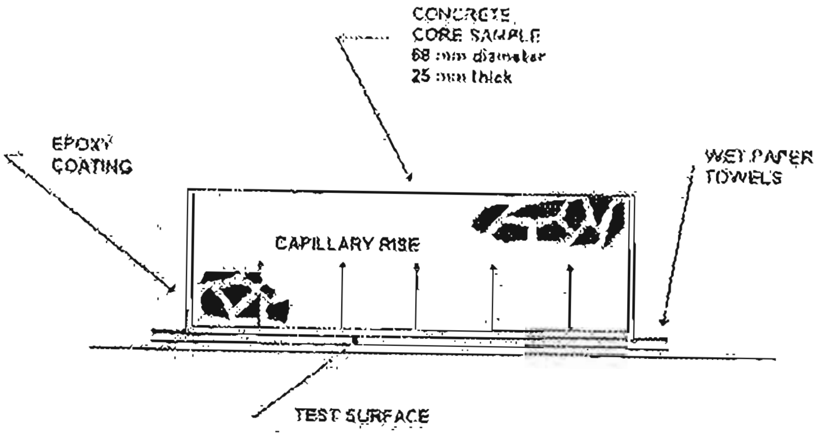

Fig. E2 Water sorptivity test

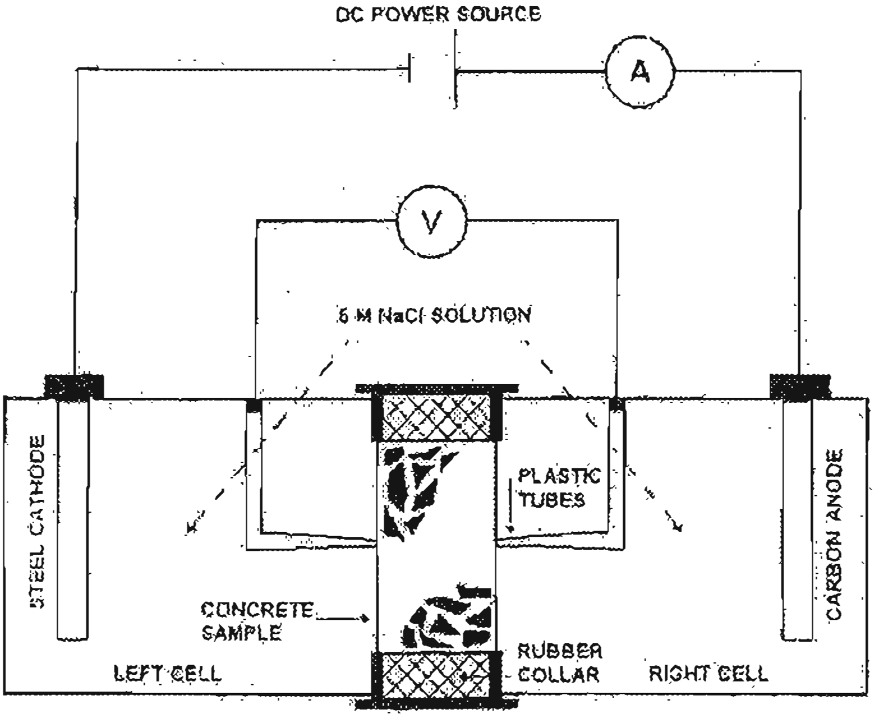

Fig. E3: Chloride conductivity apparatus