AN INVESTIGATION OF CONCRETE CURING PRACTICE IN THE CAPE TOWN AREA

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A project report submitted to the Faculty of Engineering, University of Cape Town, in partial fulfillment of the requirements for the degree of Master of Science in Engineering

Cape Town, 1995

DECLARATION

I declare that this project report is my own, unaided work. It is being submitted for the 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

Andre Krook

15 day of FEBRUARY 1995

ABSTRACT

This project describes the results from the use of durability index tests as a tool for the investigation of the concrete curing practice in the Cape Town area. The object of the tests was to determine the effect environmental conditions have on the physical properties of the outer skin of concrete. The laboratory work involved the exposure of three concrete strengths to various relative humidities. The site work involved testing the cured outer surface of concrete at 28 days on six construction sites.

The oxygen permeability and water sorptivity tests were used to investigate the outer surface of concrete. The laboratory work showed that curing at a relative humidity of 90% had a beneficial effect on the durability index values, while curing at 60% relative humidity was less effective. The permeability and sorptivity of the site results remained constant as the actual strength increased. Furthermore, permeability and sorptivity increased as the average evaporation rate increased.

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NOMENCLATURE

AASHTO	American Association of State Highway and Transport Officials
ACI	American Concrete Institute
Alite	Tricalcium silicate
ASTM	American Society for Testing and Materials
Belite	Dicalcium silicate
C_3A	Tricalcium aluminate
C_4AF	Tetracalcium aluminoferrite
CBD	Central Business District
Dusting	The rising water from bleeding carries with it a considerable amount of finer cement particles that form a layer of laitance on the outer skin of concrete.
FA	Fly Ash
GGBFS	Ground Granulated Blastfurnace Slag
LASRPC	Low-alkali Sulphate-resisting Portland Cement
OPC	Ordinary Portland Cement
Pozzolanic	The reaction of a siliceous or siliceous and aluminous material that combines with lime in the presence of moisture at ordinary temperatures to form compounds possessing cementitious properties
RH	Relative humidity
RMM	Ready Mix Materials
SABS	South African Bureau of Standards
UCT	University of Cape Town
W/B	Water to binder ratio
W/C	Water to cement ratio

CHAPTER 1

INTRODUCTION

Concrete curing involves maintaining adequate moisture and temperature conditions in concrete to encourage cement hydration. The purpose of curing is to ensure that the physical properties of concrete develop to their full potential. The strength and durability properties are mainly determined in the first few days after casting. The advantages to be gained from effectively applied curing are a reduction of shrinkage cracks, improved strength, impermeability and abrasion resistance. Curing is the final stage in the production of good quality concrete.

It is well known that good curing aids early strength development. However, much less appears to be known about the effect of the environmental factors on the durability of concrete. Environmental factors, such as relative humidity, temperature and wind speed, interact together to influence the hydration reaction and the rate of drying of the concrete surface. The Cape Town area experiences hot, dry, windy summers and temperate, wet winters. When curing is neglected it is the outer surface that dries first and is thought to be seriously impaired. This outer layer must resist abrasive forces and aggressive chemicals, and protect the reinforcing steel against corrosion. Special care regarding curing may therefore be required in the Cape Town area.

The current curing practice of the construction industry in the Cape Town area may also be inadequate. There is much concern about the durability of concrete structures in the Cape Town area. The poor service performance and corroding facades on concrete structures may be related to poor or non-existent curing. Factors that may contribute to this state of affairs are specifications that are not adhered to or outdated, ineffective curing methods or materials, inaccurate opinions and a scant understanding of curing by contractors and consultants.

The objectives of this project report are:

1. To determine the effect the environmental conditions in the Cape Town area have on the physical properties of the outer skin of concrete.

2. To assess the effectiveness of on-site curing systems.

3. To determine the opinions, curing practices and levels of understanding of contractors and consultants.

The work for this project is part of a Special Programme, jointly funded by the South African Cement Industry, LTA Construction and the Foundation for Research Development. The programme is concerned with research on concrete materials, with an emphasis on achieving durable and economic construction under South African conditions.

The information on which this research is based was gathered by means of a literature review, laboratory tests, site work and a concrete curing survey. Work done for this project was limited to local materials and concrete mixes used in the Cape Town area. The durability index tests performed were limited to the oxygen permeability and water sorptivity tests and are discussed in more detail in chapter 2.

The following chapter reviews some of the existing theory on concrete curing. Chapter 3 presents and analyses the information gathered in the concrete curing survey. Chapter 4 gives a brief account of the procedures, test methods and findings of the laboratory work. Chapter 5 analyses and discusses the information collected from the construction sites tested. Chapter 6 compares and discusses the site and laboratory results. The conclusions are presented in the final chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The best description of curing found in the literature is cited from Fulton's Concrete Technology (2.1): "Curing is the process of maintaining a satisfactory moisture content and a favourable temperature in concrete during the period immediately following placement so that hydration of the cement may continue until the desired properties are developed to a sufficient degree to meet the requirements of service (2.2)." A vast amount of literature is available on concrete curing. This literature review is primarily concerned with the influence of the environmental conditions on the physical properties of the outer skin of concrete. The philosophy behind durability index tests and the current curing practices in the United Kingdom and United States will also be discussed.

2.2 Methods and Advantages of Curing

A reinforced concrete member can be divided into two zones as illustrated graphically in Figure 2.1. The outer zone is referred to as the covercrete and the inner zone the heartcrete (2.3). The covercrete is the concrete between the external surface of the structure and the reinforcing steel. The covercrete must protect the reinforcing steel while the heartcrete gives the structural member its strength. The exact depth of the covercrete that is affected by curing is not yet known and depends on a host of extrinsic and intrinsic factors. Cather (2.4) used the term "Curing Affected Zone" for the region between the surface and the point internally where the external environment has virtually no effect. The depth of the Curing Affected Zone was estimated to be between 20 and 50 mm. Self-curing takes place at depths greater than the Curing Affected Zone.

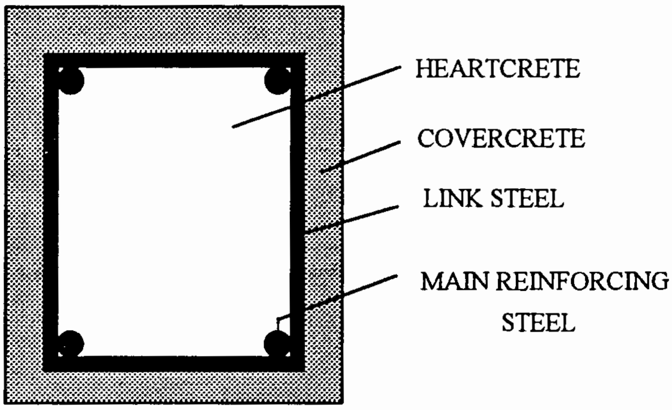

Figure 2.1 Section through a reinforced concrete member (2.3)

Senbetta and Scholer (2.5) tried to determine the depth of the surface concrete that is significantly affected by poor curing conditions. The effect of the different curing conditions on changes in absorptivity with depth are presented in Figure 2.2. The more effective curing methods, such as plastic cover and wet burlap, showed a small change in absorptivity with increasing depth from the concrete surface. The ineffective curing methods, such as the poor quality curing compound, revealed a large change in absorptivity with increasing depth from the concrete surface. Figure 2.2 also indicates that the absorptivity of the surface of poorly cured samples was found to be approximately six times that of well-cured samples.

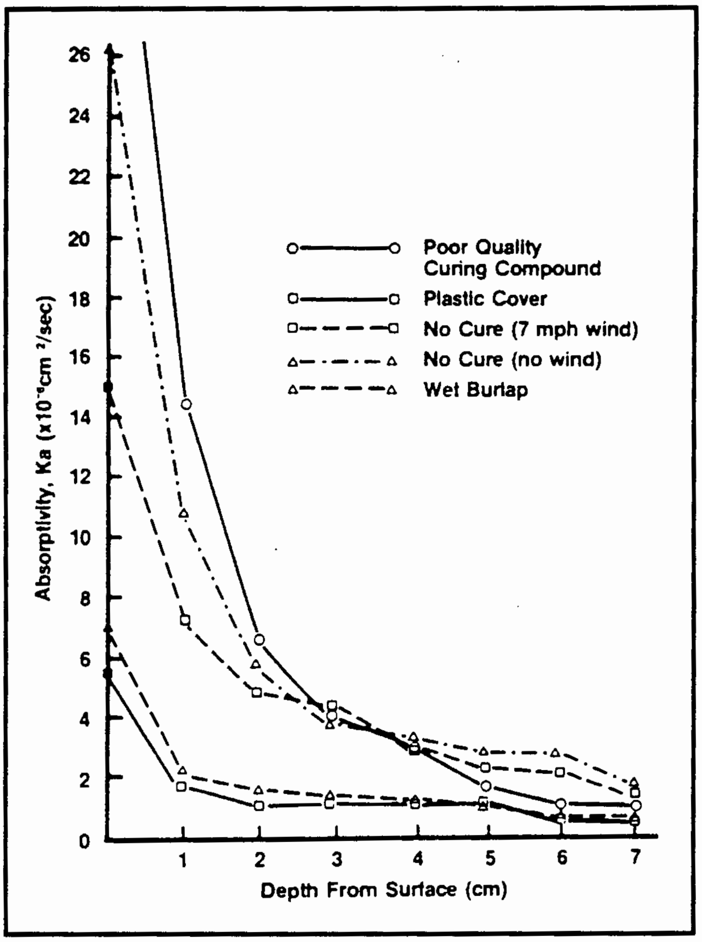

Figure 2.2 Effect of different curing conditions on change in absorptivity with depth for samples made of regular sand and cured at 22% relative humidity for five days (2.5)

Senbetta and Scholer (2.5) also tested the absorptivity of a concrete surface treated with a poor quality curing compound, and cured at three relative humidities. The absorptivity at the concrete surface increased with a decrease in relative humidity as presented in Figure 2.3. Figure 2.2 and Figure 2.3 indicate that the largest changes in absorptivity are found in the outer 30 mm of covercrete. The effects of relative humidity and curing conditions are minimal at depths greater than 50 mm. Thus, Senbetta and Scholer concluded from these results that poor curing affects the exposed surface to a depth of approximately 30 mm for the curing conditions tested in their study.

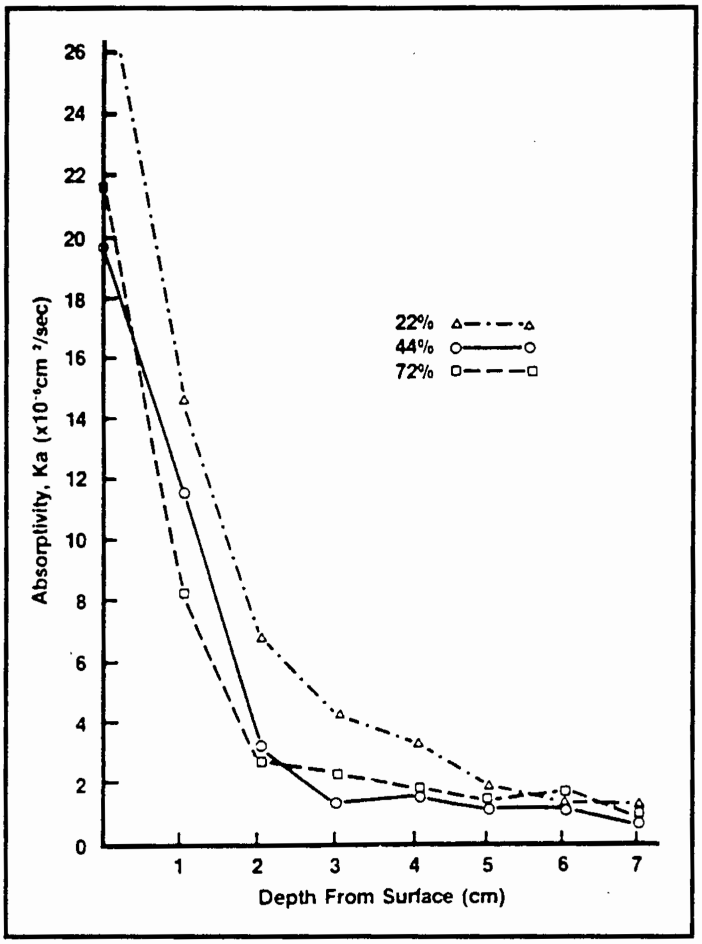

Figure 2.3 Absorptivity test results for samples made of regular sand and cured with poor curing compound at three relative humidities (2.5)

The investigations by Senbetta and Scholer are extremely important as they show the effects of curing at various depths from the exposed surface of concrete. It was decided for this project to test the outer 30 mm of the covercrete, since, as Senbetta and Scholer revealed, the effects of curing on absorptivity and the effects of relative humidity on the covercrete are less marked at depths greater than 30 mm.

2.2.1 Curing methods

Freshly cast concrete must be protected from harmful physical, mechanical and chemical influences. The purpose of curing is to maintain an adequate moisture content and a suitable temperature to promote cement hydration. A variety of curing methods and materials can be used. There are two types of curing methods, namely water curing and sealing (2.3). Water curing includes ponding water on floor slabs, spraying structures with water and covering concrete with damp hessian. Sealing involves placing materials on the concrete surface to reduce evaporation. This includes the application of curing compounds, retaining formwork and covering the concrete in plastic sheets. The curing methods recommended in SABS 1200-G:1982 are listed below (2.6):

(a) ponding the exposed surfaces by means of water;
(b) covering the concrete with sand, or mats made of a moisture retaining material, and keeping the covering continuously wet;
(c) continuously spraying the exposed surface with water;
(d) covering the concrete with waterproof or plastic sheeting firmly anchored at the edges;
(e) using an approved curing compound applied in accordance with the manufacturer's instructions.

Concrete made in the laboratory can be cured in water indefinitely. However, total immersion on site is virtually impossible unless ponding occurs on floor slabs. Furthermore, most curing methods used on construction sites have practical drawbacks. For instance, in the Cape Town area, plastic sheets are difficult to secure in windy conditions. Windy conditions also hinder the application of spray-on curing compounds. The types of curing methods applied to structures in the Cape Town area and the reasons for choosing these methods will be discussed in chapter 3. The curing practices of six construction sites in the Cape Town area will also be reviewed in chapter 5.

2.2.2 Advantages of proper curing

The effects of curing on strength are well known although less is known about the effects of curing on the durability of the covercrete. Fulton's Concrete Technology identifies durability; impermeability; resistance to wear, weathering and chemical attack; and freedom from crazing, shrinkage cracking and warping as benefits of proper curing (2.1). This agrees with the benefits of proper curing quoted by Spears (2.7), listed in Table 2.1. Fulton's Concrete Technology (2.1) cites an ACI report (2.8) that states that the benefits of curing will be increased by prolonging the curing period, and that the benefits of additional curing must be balanced against other factors. These factors may include cost and the availability of curing materials.

Table 2.1 The benefits of proper curing (2.7)

Proper Curing Decreases:	Proper Curing Increases:
Permeability	Strength development
Surface dusting	Abrasion resistance
Thermal-shock effects	Durability
Scaling tendency	Pozzolanic activity
Cracking	Weatherability

The requirements of durable concrete are a low permeability, no macro-voids and defects, adequate cement content and the correct cement type. If reinforcing steel is added then the cover to the steel must also be controlled. Permeability is controlled by the W/C ratio, cement type and, most importantly, curing. Other factors that may affect durability are the choice of aggregate, compaction, control and supervision. Thus good curing is essential in the Cape Town area to produce good quality concrete and to prevent durability problems such as deteriorating infrastructures and impaired serviceability. If curing is applied properly the service life of many reinforced concrete structures may be prolonged. This will prevent expensive repair and maintenance costs, and possibly premature demolition and replacement.

2.3 Concrete Curing Practices

A survey in the United Kingdom found that in 1973 a wide range of opinion existed on the necessity and success of curing (2.9). Many Site Agents felt that curing was important and took steps with varying degrees of adequacy to adhere to the specifications. A few Site Agents expressed doubt whether curing was beneficial to the properties of concrete, while others considered curing only necessary to please the Resident Engineer. In addition, the consensus on curing specifications suggested that the most effective were those that combined simplicity with clarity and were appropriate for the type of structure involved.

The survey concluded that curing of concrete in temperate climates, initially protected by formwork, was necessary only in exceptional circumstances. Furthermore, the survey found that no defects due to a lack of curing, apart from shrinkage cracking in pavements, were observed in the concrete.

In 1992 Cather found that in the United Kingdom the final application of curing measures to concrete was not taken seriously enough by contractors or consultants (2.4). This was possibly due to either a lack of compliance testing or to an absence of penalties for poor curing. Cather suggested a compliance regime to attain a target hydration state or some property closely related to measure curing efficiency. The target could be set by choosing some proportion of the curing achieved in the center of a section. For example, at 15 mm depth the curing efficiency, however defined, shall be 85% of that achieved at 150 mm depth. This compliance regime could either be carried out throughout the contract or in precontract trials.

Cather also stated that contractors and consultants found serious deficiencies in the contract documentation to ensure effective curing. A significant barrier to effective curing on site is that curing is not usually a separately billed item and is therefore not costed. This means that penalties for not curing are difficult to extract. It was recommended that this aspect should be reviewed critically by the industry. There is also a widely held view in the United Kingdom construction industry that the normal environmental conditions encountered, namely average relative humidity greater than 80%, is sufficient to allow the industry to apply no additional curing measures other than those provided for by the weather.

Senbetta conducted a survey of the concrete curing practices of 50 state highway departments in the United States (2.10). The survey found that membrane-forming curing compounds are the most widely used materials for curing pavements, bridge decks and other concrete structures. It was also found that approximately 77 percent of the states used ASTM C156 (2.11), a test procedure that is not entirely reliable, for evaluating the effectiveness of curing compounds (2.10). The imprecision of ASTM C156 was so severe that repeated evaluation of a given curing compound in the same laboratory by a competent technician produced results that make it difficult to conclude whether the curing compound passed or failed the test. The example in Figure 2.4 found that the curing compound passed the test eight times and failed it seven times

The moisture retention test is meant to be an indicator of an acceptable compound, but not its application and therefore its effectiveness in the field. Cather (2.4) stated that there is a fundamental problem with the test methods now used to appraise liquid-applied curing membranes. The tests measure the water loss from a concrete sample and rely on the assumption that the degree of water retention equates to the degree of hydration.

Senbetta (2.10) also concluded that curing practices in the United States need to be standardised and the specifications clarified and written in more meaningful terms. Moreover, the test methods used to evaluate the effectiveness of curing materials also needed improving. One of the objectives of this project was to determine the curing practices of contractors in the Cape Town area. This was accomplished by conducting a concrete curing survey and by recording the curing practices on six construction sites.

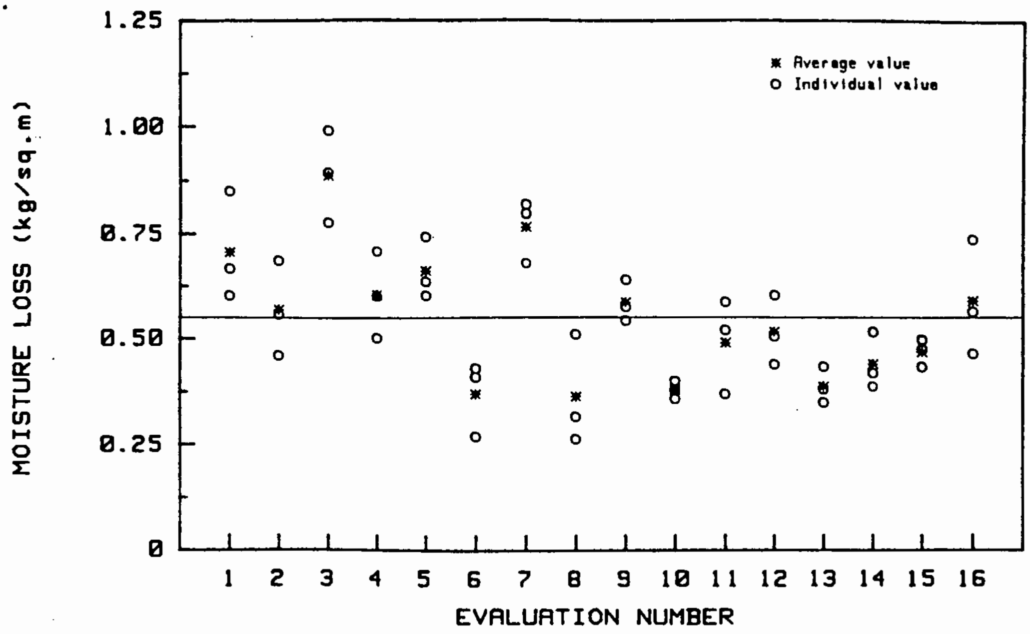

Figure 2.4 ASTM C156 test results (2.10)

2.4 Durability Index Tests

Work at the University of Cape Town and the University of the Witwatersrand is presently being done on the durability characterisation of concrete (2.12, 2.13, 2.14). The durability test methods include early age index testing such as gas permeability and water sorptivity measurements on the covercrete. The early age index tests are performed at 28 days after casting. In addition, work is being carried out on accelerated durability tests such as carbonation, sulphate attack, chloride diffusion and soft water attack. The research concentrates primarily on developing means to predict the long term durability performance of concrete from early age characterisation tests.

There are currently various tests available to determine the rate of water absorption and permeability of the covercrete. The need to test on site led to the development of the Autoclam (2.15), a portable apparatus designed to measure the air and water permeability and sorptivity of concrete surfaces. The ISAT (Initial Surface Absorption Test) (2.16), CAT (Covercrete Absorption Test) (2.17) and Figg air permeability (2.18) tests are examples of other absorption and permeability tests available.

An index test characterises the covercrete by using parameters related to the deterioration processes acting on the concrete. The surface layer is first affected by curing and then by external deterioration processes. These processes are linked to transport mechanisms such as diffusion, water sorptivity and gas permeability. A series of index tests is necessary to cover the broad range of durability problems; each index test being linked to a transport mechanism relevant to a particular deterioration process.

Alexander and Ballim (2.12) suggested having an item in the Bill of Quantities which stipulates payment as a means of ensuring adequate durability. The item may cover various approaches for achieving durability, such as curing methods, materials selection, mix proportions and coatings. For example, if curing is the desired means of achieving a durable covercrete, and measurement of a suitable index on the finished concrete reveals that curing has not been properly executed, the savings on the particular payment item may be used to provide another measure, such as a suitable coating, to ensure cover quality.

Furthermore, each durability property needs to be specified and appropriately paid for. It is accepted that the initial costs for ensuring durability will be offset by savings on repairs, maintenance and the extended life of the structure. Life-cycle costing may also soon show that paying for initial durability is a financially viable long-term investment.

Much work still needs to be done to accumulate a database of index values, to correlate the index values with each other and with other important parameters, and to draw up suitable specifications and acceptance criteria for concrete durability. This project will help to collect durability index values from concrete cast and cured in the laboratory and on construction sites in the Cape Town area. The oxygen permeability and water sorptivity tests are used as durability index tests for this project, and are discussed in more detail in chapter 4.

2.5 Influence of the Environment

The hydration of cement and the micro-structure of the covercrete are influenced by environmental factors such as temperature, relative humidity and wind speed (2.3, 2.19, 2.20). These environmental factors could cause a rapid withdrawal of moisture from freshly cast concrete and may result in early age shrinkage and severe cracking (2.1). The effects of these environmental factors in the Cape Town area on the physical properties of the covercrete are not yet well known. It is expected that the covercrete cured in summer conditions will be less durable than the covercrete cured in winter conditions.

An indication of the influence of the environmental factors can be obtained from Figures 2.5 to 2.8. These figures present a graphic method for estimating the average evaporation rate from the concrete surface. It must be stressed that these figures strictly refer only to the evaporation of water from concrete soon after placing, i.e., approximately 3 hours. However, for the purposes of this project, the average evaporation rate will be used as a guide to show the effects of the environment on the durability index values.

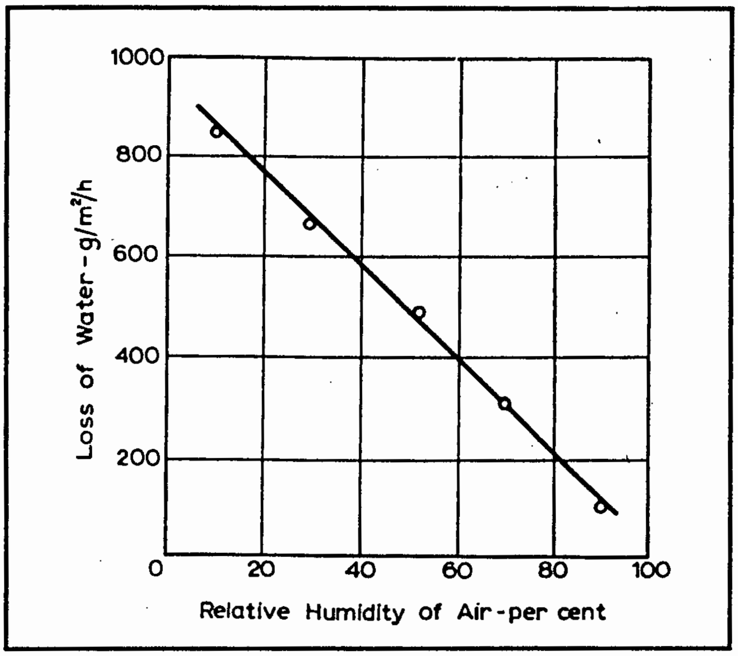

Figure 2.5 Influence of air relative humidity on the water loss from concrete in the early stages after placing (air temperature 21°C, wind velocity 4,5 m/s) (2.21)

The average evaporation rate will be calculated from Figure 2.8 by using the graphic method shown. Moisture in the gel and capillary pores permeates through the concrete by capillary action. The rate at which moisture is lost to the surface of the concrete is fairly slow in comparison to the rate of evaporation. Wind affects only the rate of evaporation and not the rate at which moisture permeates through the concrete. Consequently, the average evaporation rate will be calculatted from Figure 2.8 and will be used in chapters 5 and 6.

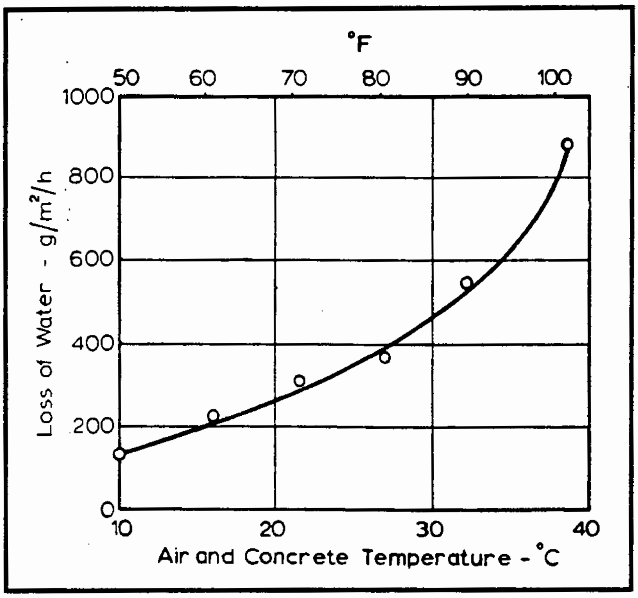

Figure 2.6 Influence of air temperature on the water loss from concrete in the early stages after placing (air relative humidity 70%, wind velocity 4,5 m/s) (2.21)

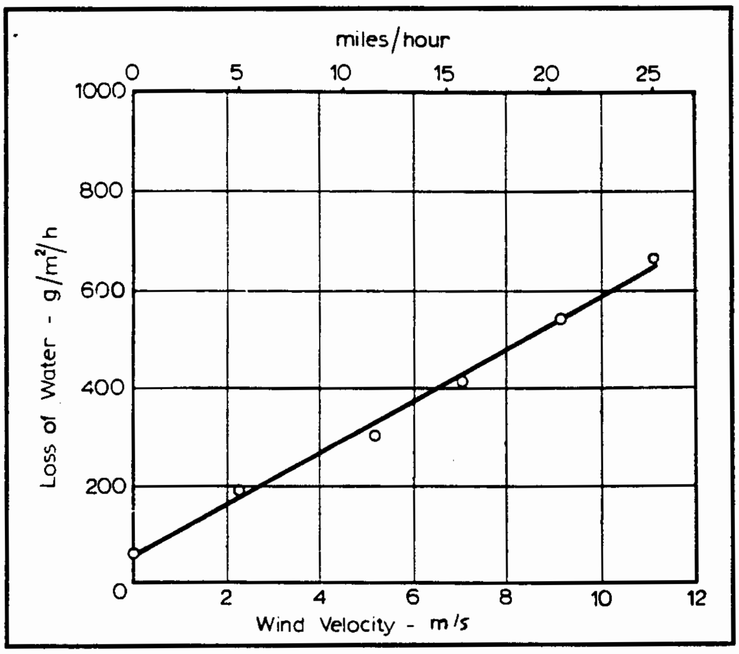

Figure 2.7 Influence of wind velocity on the water loss from concrete in the early stages after placing (air relative humidity 70%, temperature 21°C) (2.21)

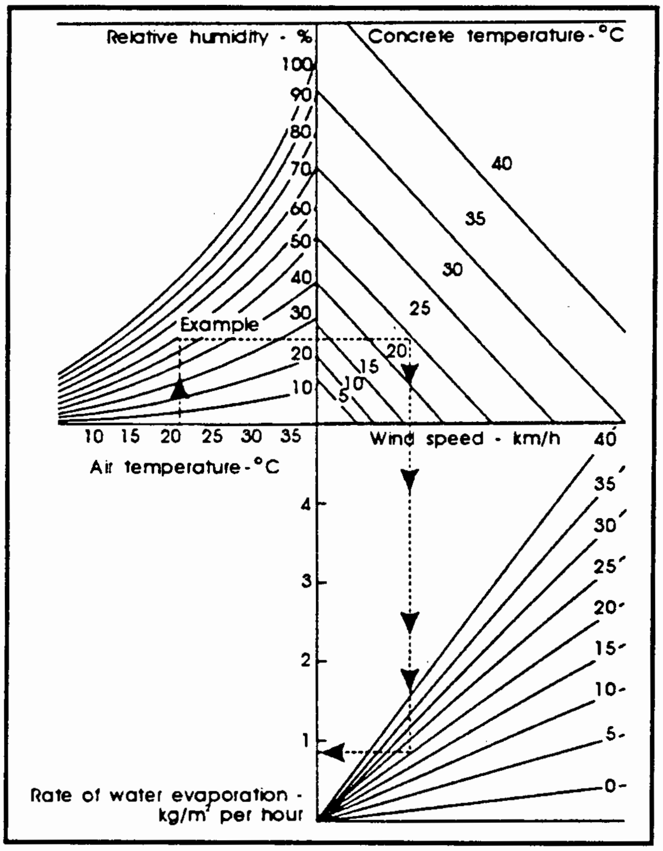

Figure 2.8 A graphic method for determining the rate of evaporation of moisture from the surface of concrete (2.3)

2.5.1 Cape Town area climate

The Cape Town area has a Mediterranean climate of hot, dry summers and temperate, wet winters. Concrete cured in summer will often be exposed to severe drying due to high temperatures, low relative humidities and strong winds. The prevailing wind in summer is south south-east, while in winter it is a rain-bearing northwesterly. The average climatic conditions in the Cape Town area are shown in Figures 2.9, 2.10 and 2.11 (2.22). Figure 2.9 reveals that the mean of the daily relative humidities in winter may be as high as 90% and may drop to as low as 52% in summer. The mean of the daily temperatures in the Cape Town area, as shown in Figure 2.10, may vary between a minimum of 7°C in winter and a maximum of 27°C in summer.

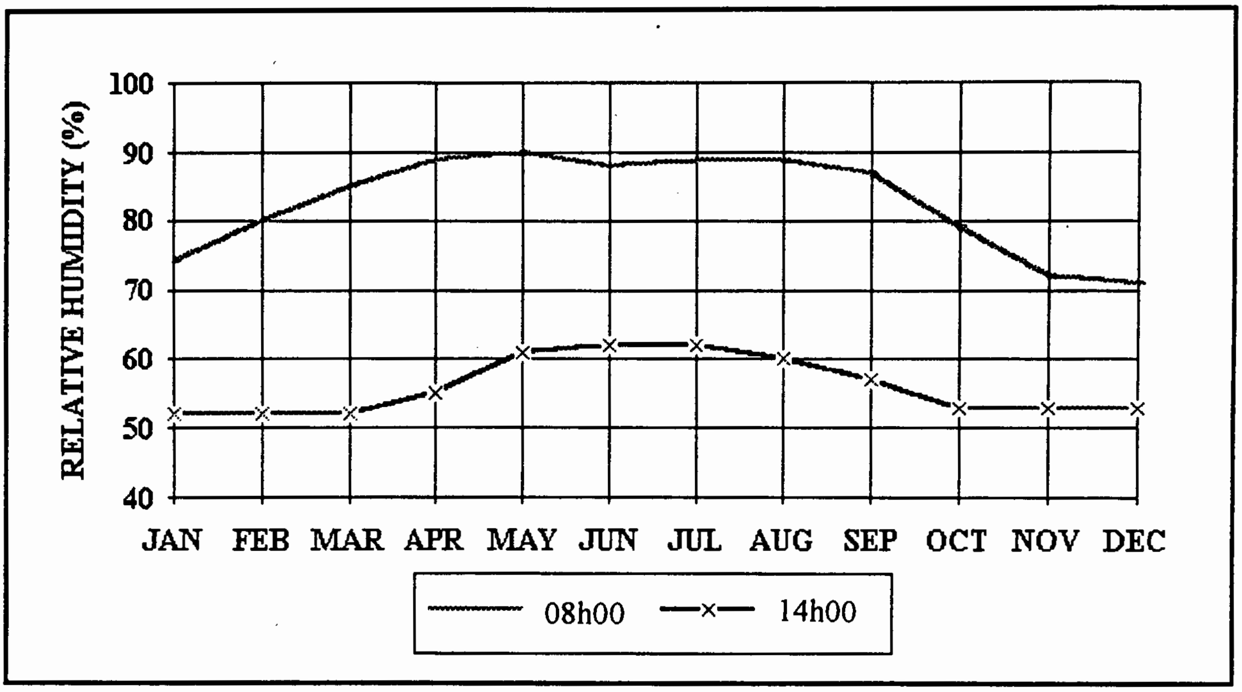

Figure 2.9 Mean daily relative humidity at 0800 and 1400 hours in Cape Town (2.22)

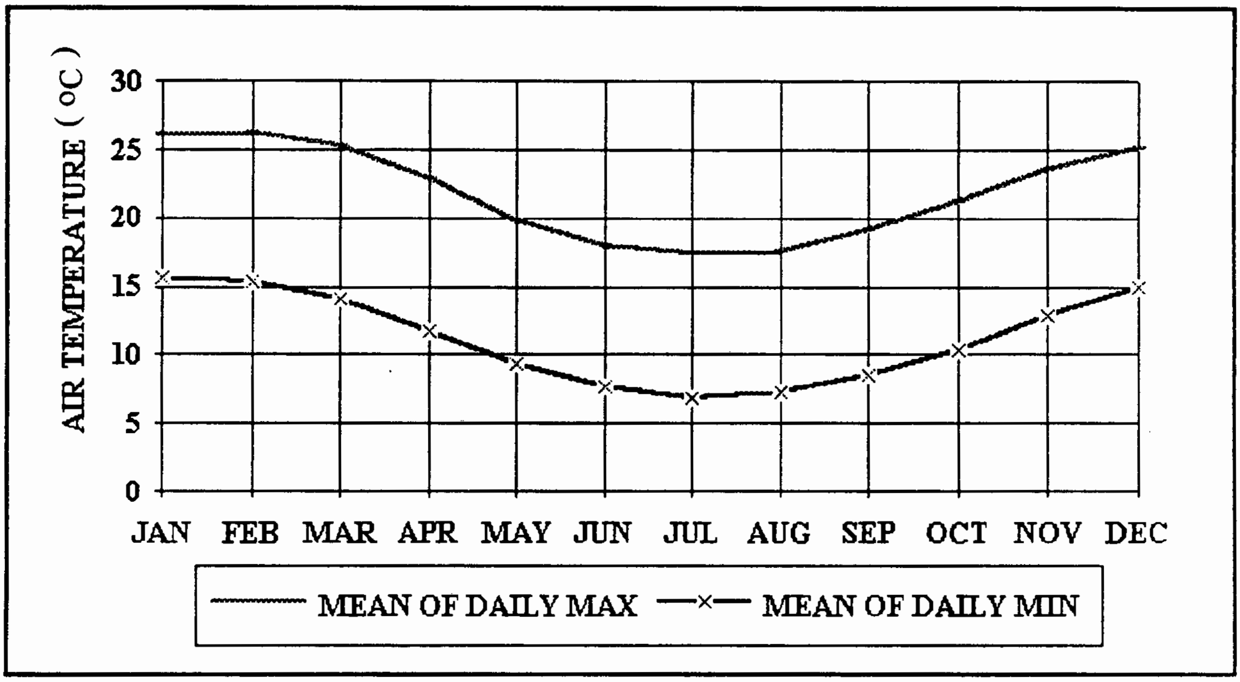

Figure 2.10 Mean of the daily maximum and minimum air temperatures in Cape Town (2.22)

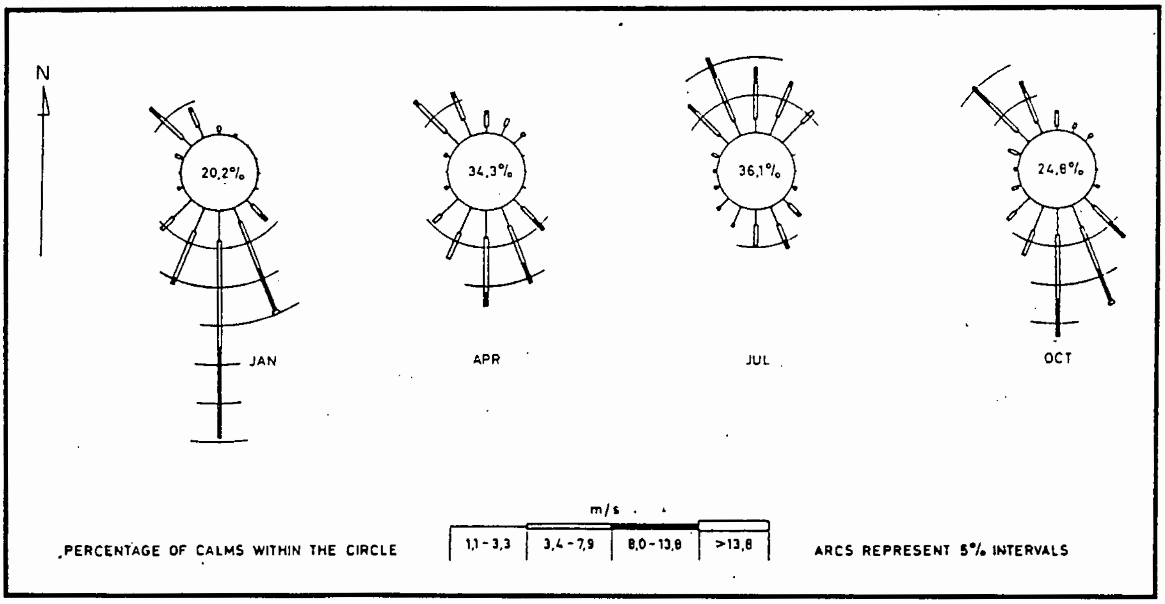

Figure 2.11 Wind direction frequencies in percentage for selected wind speed intervals (2.22)

The average monthly wind directions and wind speeds recorded at Cape Town Airport are shown in Figure 2.11 for January, April, July and October (2.22). The wind direction is mainly south or south southeast in January and north or north northwest in July. July had the highest percentage of calm periods (36,1%), while January had the lowest percentage of calm periods (20,2%). The average monthly wind speeds are shown in detail in Figure 2.11. Wind speeds may be greater than 13,8 m/s (50 km/h) in January and October.

2.5.2 Effect of relative humidity on hydration and pore structure

The hydration of cement will cease first at the exposed surface and then at increasing depths if the relative humidity of the surrounding air is low enough (2.23). In the outer surface layer the cement will continue to hydrate with the residual pore water at a reduced rate. The lower the relative humidity of the surrounding air, the faster drying and the slower the rate of hydration. Hence, drying can cause gradients of cement hydration which are more severe when early drying has occurred.

Parrott, Killoh and Patel (2.23) investigated cement hydration under partially saturated curing conditions. The effect of relative humidity during curing upon OPC hydration at 90 days can be observed in Figure 2.12. The graph reveals a marked increase in hydration above a curing relative humidity of approximately 80%, while below approximately 80% there is a slight long-term hydration.

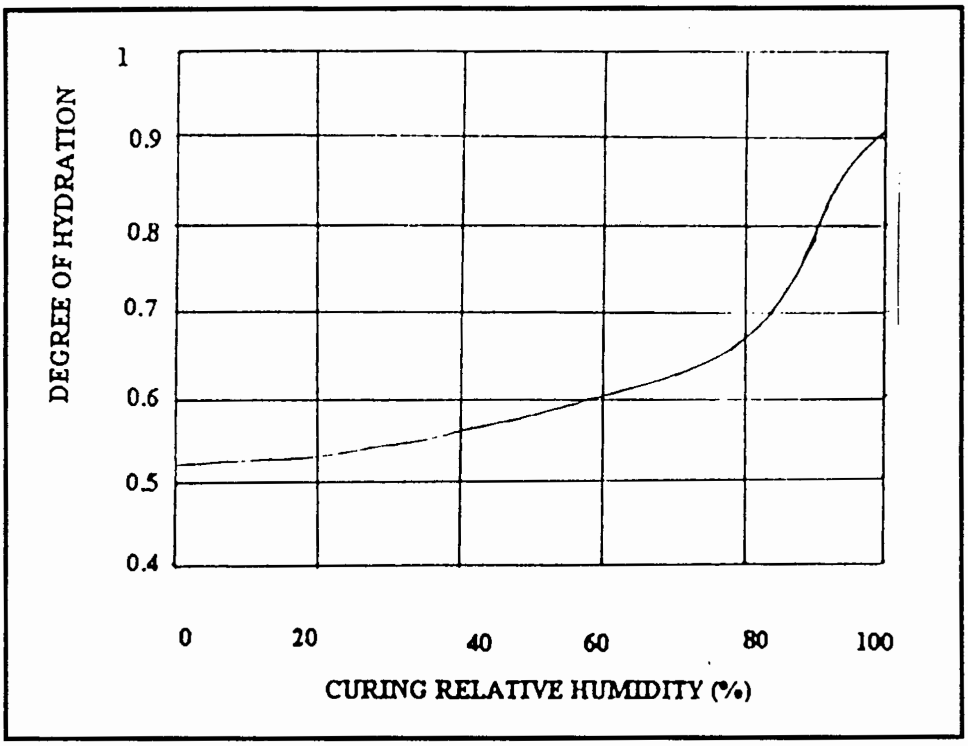

Figure 2.12 Hydration versus curing relative humidity at 90 days (2.23)

More recent work by Patel, Killoh, Parrott and Gutteridge (2.24) revealed that the relative humidity of curing affects the hydration rate of the main compounds of OPC, namely Alite, Belite, C_3A and C_4AF. The OPC paste was cured for two days and then exposed to controlled relative humidity environments. The relationship between the relative humidity maintained beyond two days and the fractions of Alite and Belite reacted are presented in Figure 2.13. From about 30% to 80% relative humidity, hydration shows only a small increase. Above 80% relative humidity there are substantial increases in hydration. The 14 and 90 day results emphasize the benefit of the increased hydration achieved at high humidities.

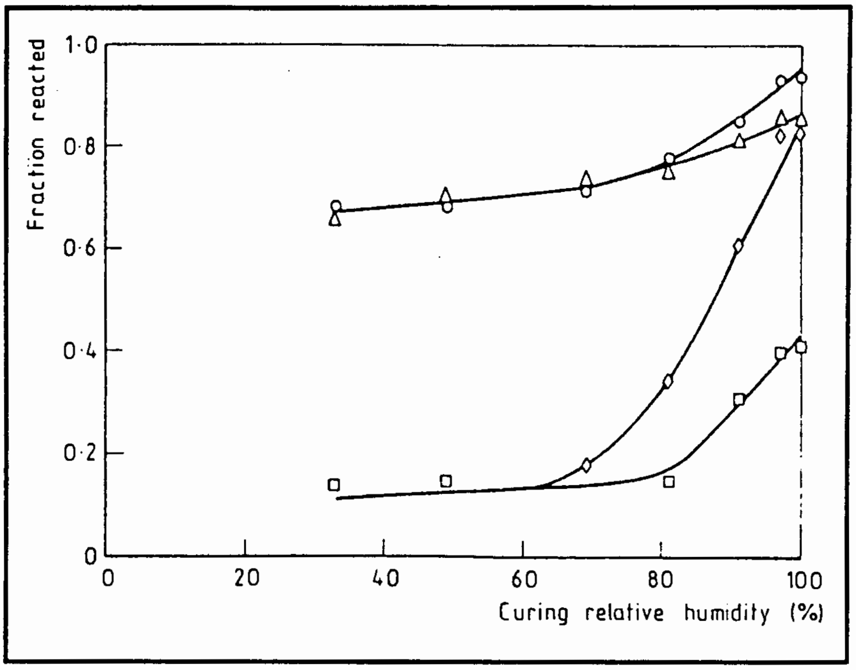

Figure 2.13 Alite and belite hydration against curing relative humidity: (Δ) alite 14 days; (o) alite 90 days; (□) belite 14 days; (◊) belite 90 days (2.24)

The work of Parrott, Killoh and Patel (2.23) and Patel, Killoh, Parrott and Gutteridge (2.24) used a combination of thermogravimetric analysis, quantitative X-ray diffraction and loss on ignition techniques to estimate the degree of hydration. Note that only the top 3 mm of the covercrete was tested while the top 30 mm was tested for the present work. Figure 2.12 and Figure 2.13 show the importance of curing at relative humidities greater than 80%.

Patel, Killoh, Parrott and Gutteridge (2.24) also showed that the relative volume of pores smaller than 4 nm and smaller than 37 nm decreased with a reduction in the relative humidity due to the effects of drying and reduced hydration. The 37 nm pore size was chosen because the filling of 37 nm pores in silica glass was easily detected by a substantial increase in weight. Therefore, it was assumed that pores of the same size in the paste slices were also filled at this stage. Furthermore, previous adsorption studies with porous glass enabled the stage where 4 nm pores were filled to be identified.

The reduction in the volume of small pores due to drying was accompanied by a corresponding increase in the volume of large pores. The high porosity values observed at relative humidities below 80% for pores wider than 37 nm are thought to be of practical significance, since they could adversely affect the durability of in-situ concrete. The increase in large porosity with a decrease in curing relative humidity is shown in Figure 2.14. Note that a reduction in large porosity with time is only observed at relative humidities above 95%. Thus prematurely dried concrete will have a low degree of hydration, many large diameter pores, and will offer less protection to the underlying concrete and steel reinforcement.

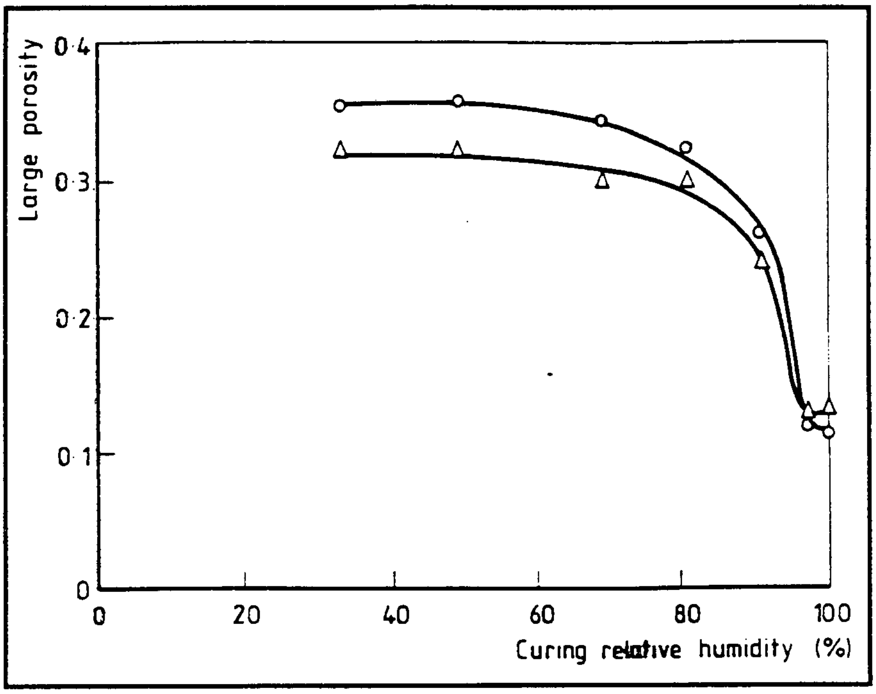

Figure 2.14 Large porosity against curing relative humidity: (o) 90 days; (Δ) 14 days (2.24)

The effects of relative humidity on the covercrete are extremely important to the present work. Relative humidity is expected to play a large role in determining the physical properties of surface concrete. Thus it was decided for the laboratory tests to compare the effects of three curing regimes on the physical properties of concrete. The first curing regime immersed concrete in water to simulate ideal curing conditions. The second curing regime exposed concrete to 80% relative humidity to simulate good curing conditions. The third curing regime exposed concrete to 50% relative humidity to simulate poor curing conditions. The laboratory tests are discussed in more detail in chapter 4.

2.5.3 Effect of hot weather and wind

Hot weather introduces many problems to the manufacturing, placing and curing of concrete and may affect the properties of hardened concrete. The rate of water evaporation increases with an increase in air temperature. For example, as the temperature increases from 10°C to 20°C, the rate of evaporation from the concrete will double (2.19). High ambient temperatures can also raise the temperature of concrete materials to an unacceptable level. On mixing, the concrete temperature will be high enough to reduce the workability of the concrete, thus preventing satisfactory compaction which may result in a porous permeable concrete.

Wind is another factor that creates many problems when concreting in hot dry weather (2.19, 2.20). The rate of evaporation increases substantially in windy conditions, and could reach serious proportions if wind speeds exceed 15 km/h. In the Cape Town area wind can reach speeds of up to 50 km/h (2.22). These winds are often coupled with high temperatures and low humidities and cause rapid drying of the concrete. Rapid drying occurs especially when casting thin sections with a high surface area to volume ratio, such as floor slabs. The drying of concrete through rapid water loss could seriously impair durability, particularly if moisture loss occurs at a very early age, and may lead to shrinkage cracks.

The environmental conditions affect the rate and amount of evaporation of water from fresh concrete, which in turn affect the properties of concrete. It was thus decided to record all environmental conditions that the laboratory and site tests were exposed to as this would help to determine the effects the environmental conditions in the Cape Town area have on the physical properties of the covercrete.

2.6 Effect of Curing on Permeability and Sorptivity

Dhir, Hewlett and Chan (2.25) found that the intrinsic permeability of concrete can be characterised by using the air permeability test. The intrinsic permeability of concrete relates to the internal structure of concrete and is independent of the properties of the migrating fluid. Thus, a sample tested with any liquid or gas should yield the same intrinsic permeability value. Dhir, Hewlett and Chan also revealed that the permeability of the covercrete is very sensitive to small changes in the W/C ratio and the duration of initial moist curing. The effect of the W/C ratio and initial moist curing on the air permeability of the covercrete is illustrated in Figure 2.15. It can be seen that permeability increases almost exponentially with increasing W/C ratio. The results show that to produce a low permeability concrete it is as essential to ensure adequate curing as to specify a low W/C ratio.

The rate at which water is absorbed into concrete by capillary suction can also provide useful information relating to the pore structure and permeability of the covercrete. Parrott (2.26) revealed that the water absorption after a given wetting time increased with an increase in the W/C ratio, see Figure 2.16. Ballim (2.14) found that moist curing of concrete at early ages reduces the permeability and sorptivity of the covercrete, see Figures 2.17 and Figure 2.18. Furthermore, increasing the degree of moist curing at early ages appears to be a more efficient way of improving potential durability than decreasing the W/C ratio.

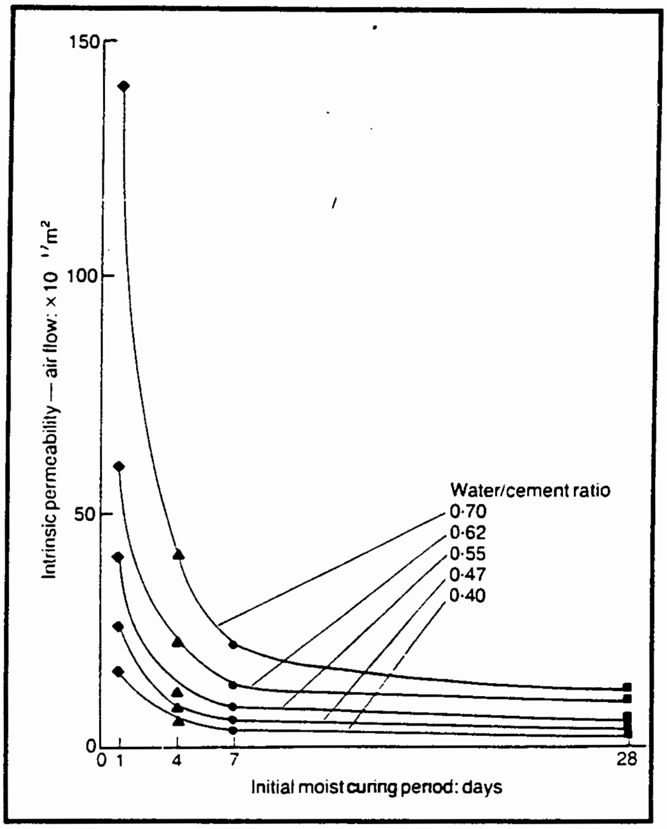

Figure 2.15 Effect of initial moist curing period and W/C ratio on intrinsic permeability of concrete (2.25)

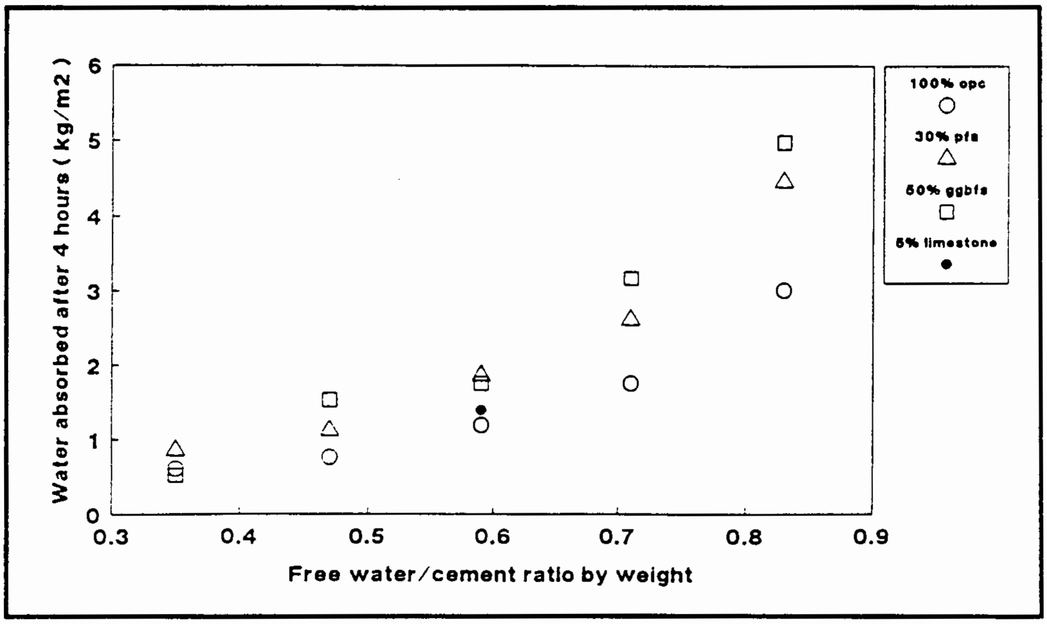

Figure 2.16 Effect of W/C ratio and cement type upon water absorption after 18 months of laboratory exposure (three days moist curing) (2.26)

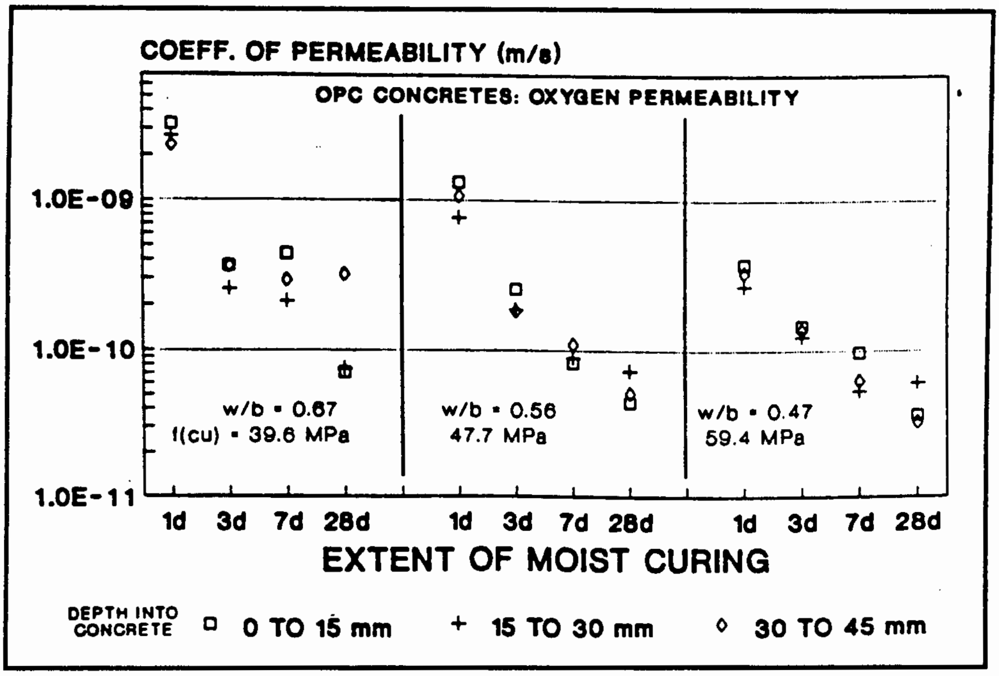

Figure 2.17 Oxygen permeability results for the OPC concretes (2.14)

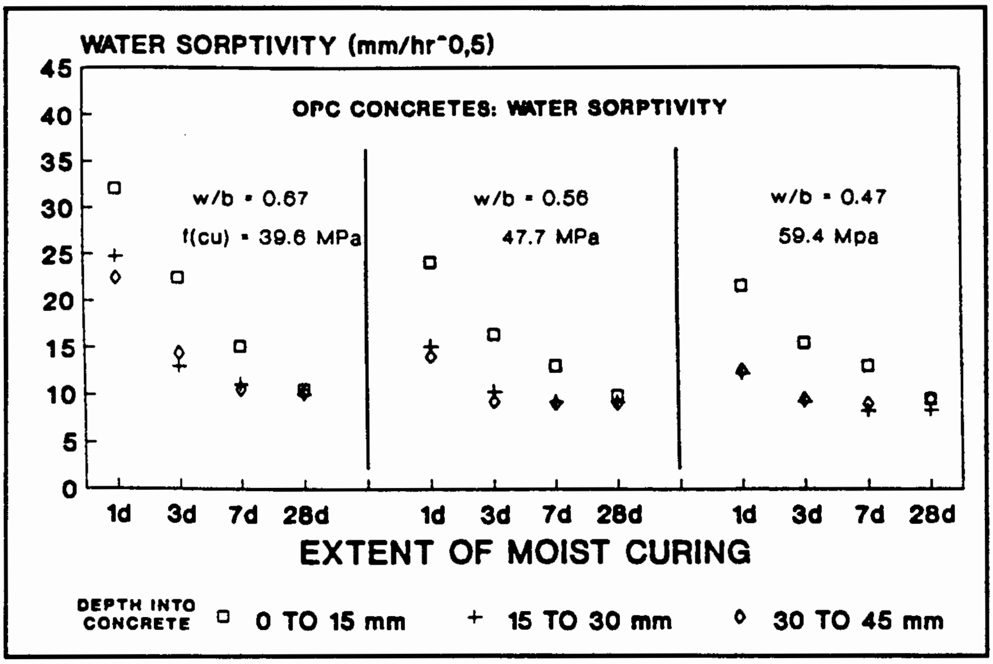

Figure 2.18 Water sorptivity results for the OPC concretes (2.14)

The results in Figures 2.17 and 2.18 also show that permeability and sorptivity are influenced by the duration of moist curing and the W/C ratio. Therefore, the oxygen permeability and water sorptivity durability index tests were used to determine the effects of environmental conditions on the physical properties of the covercrete. The durability index tests were also used to assess the effectiveness of on-site curing systems. The test methods used to calculate oxygen permeability and water sorptivity for the present work will be explained in chapter 4.

2.7 Summary

Relative humidity affects the porosity and rate of hydration of the covercrete. The hydration rate of cement increases markedly above a curing relative humidity of about 80%, while below 80% relative humidity, hydration proceeds at a much slower rate. In addition, the high porosity values observed at relative humidities below 80%, for large diameter pores, could seriously affect the durability of in-situ concrete. This shows that the environmental conditions in the Cape Town area affect the physical properties of the outer skin of concrete. Therefore, it is important to cure properly in the Cape Town area, especially during summer, to produce durable concrete.

Poor or non-existent curing has a large effect on the top 30 mm of the covercrete. At depths greater than 30 mm the effects of relative humidity and curing methods are less significant. Self-curing takes place at depths greater than 50 mm. Furthermore, permeability and sorptivity are sensitive to changes in the W/C ratio and initial moist curing. Good curing is as influential in decreasing the permeability and sorptivity of the concrete, as decreasing the W/C ratio. Accordingly, the permeability and sorptivity of the top 30 mm of the covercrete will be tested to assess the effectiveness of on-site curing systems and the effects relative humidity and temperature have on the covercrete durability.

Literature reviewed from the United Kingdom and United States revealed that there was much uncertainty about the importance of curing, and that the final application of curing measures to concrete was not taken seriously enough by contractors or consultants. Moreover, membrane-forming cring compounds were widely used even though the test method for evaluating them was not entirely reliable. A few Site Agents expressed doubts about whether curing was beneficial to the properties of concrete, while others considered curing only necessary to please the Resident Engineer. The Cape Town area may experience similar trends and the following chapter will attempt to determine the opinions, curing practices and levels of understanding of contractors and consultants towards curing.

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CHAPTER 3

CONCRETE CURING SURVEY

3.1 Introduction

A questionnaire was posted out in January 1994 to all the members of the Concrete Society of Southern Africa in the Cape Town area. The members were all contractors and consultants in the civil and building industries. The format of the questionnaire, accompanying and response letters are shown in Appendix A. Responses were received from 54 of the 230 questionnaires posted out, i.e., a return of 23%. The questionnaire was intended to obtain data on the opinions, curing practices and levels of understanding of contractors and consultants in the Cape Town area. The following analysis was based on information obtained from the returned questionnaires.

3.2 Discussion of Results

The survey consisted of the following eleven questions:

Question 1

In which sector have you mainly worked in the last five years?

The first question was intended to determine in which sector the respondent had worked in the last five years. Of the questionnaires returned, 41% were from the construction field, 52% from the consulting field and 7% from either concrete technology or material suppliers.

Question 2

What do you understand by the phrase: "concrete curing"?

This question was answered similarly by contractors and consultants. A few examples of replies are listed below:

- "The protection and treatment of freshly cast concrete to ensure proper strength gain and the prevention of shrinkage cracks."
- "The retention of sufficient moisture within the concrete to ensure that hydration of the cement proceeds at an adequate rate and the protection of the concrete from temperature extremes during the early curing period."
- "The protection of concrete in the early stages against extremes of temperature and wind to retain moisture for hydration."
- "The provision and maintenance of conditions conducive to maximum rate of hydration of the cement paste for as long as practicably and economically possible after the concrete has set."

Some respondents stated that curing increased concrete strength and improved durability. Other respondents stated that curing was the protection of freshly cast concrete against harsh environmental conditions. To most contractors and consultants concrete curing simply meant maintaining sufficient water in concrete to complete the hydration reaction. The replies also agreed with the curing definitions quoted in the literature.

Question 3

How important do you think curing is for developing the strength and durability properties of concrete?

Figures 3.1 and 3.2 showed that contractors and consultants felt curing was more beneficial to developing the durability properties than the strength properties of concrete. Strength was rated as being very important while durability was rated as being extremely important. Figure 3.1 found that contractors and consultants rated curing for developing strength as very important. Figure 3.2 showed that consultants rated curing as more important for developing the durability properties of concrete than contractors. Consultants thought that durability was extremely important (75% of respondents), while for contractors the percentage was much lower (39%).

Note that this question does not clearly differentiate between early and long-term strength, nor whether the strength referred to be of the heartcrete or the covercrete. Some respondents stated that the importance of curing for strength depends mainly on the size of the member. For instance, in massive members, such as pile caps, the effect of curing on strength is not very important while in thin precast members it is extremely important. The findings showed that contractors and consultants rated curing more beneficial to developing the durability properties than the strength properties of concrete. Furthermore, a higher percentage of consultants than contractors rated durability as extremely important.

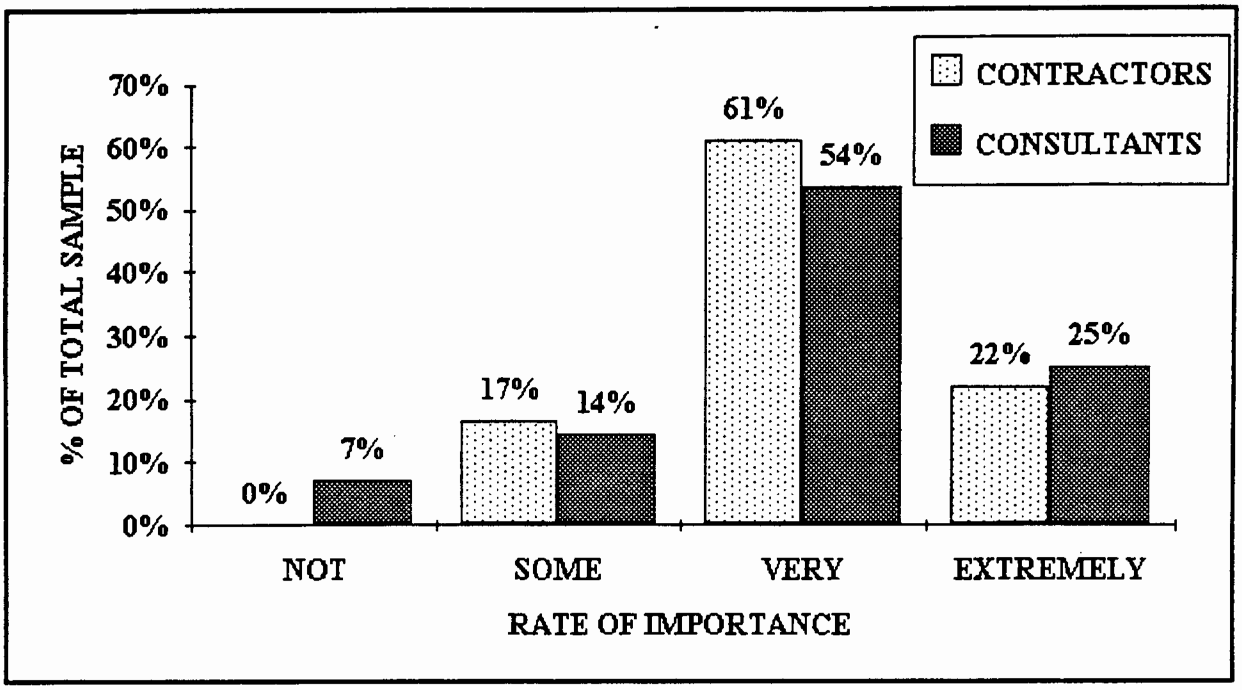


Figure 3.1 How important do you think curing is for developing the strength properties of concrete?

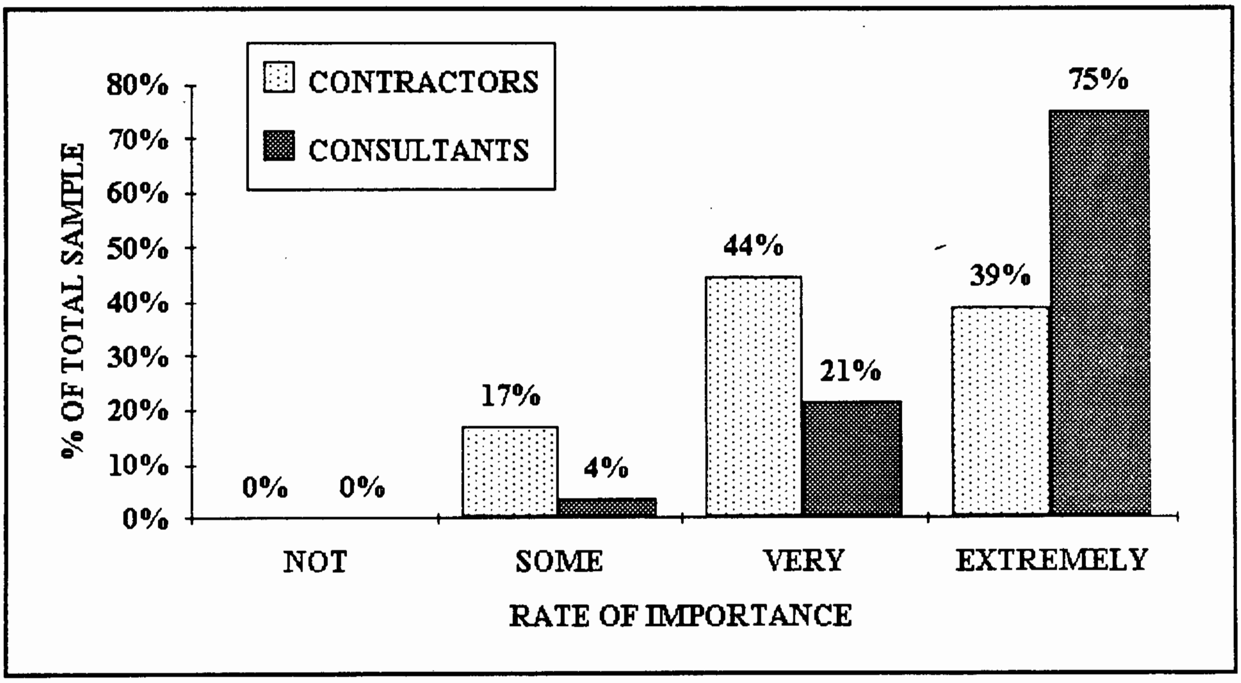


Figure 3.2 How important do you think curing is for developing the durability properties of concrete?

Question 4(a)

What type of curing method would you apply or specify for the following structural members?

The results in Figure 3.3 revealed that curing compounds are the most frequently applied or specified method for curing columns. The consultants reported that they favoured specifying curing compounds (41% of respondents) and damp hessian (22%) for columns. The contractors reported that they favoured applying curing compounds (38%) and plastic sheets (29%) for columns. The results in Figure 3.4 clearly show the popularity of applying or specifying curing compounds to beams. The contractors reported that they preferred applying curing compounds (68%) and damp hessian (16%) for beams. The consultants reported that they preferred specifying applying curing compounds (57%) and retention of formwork (25%) for beams.

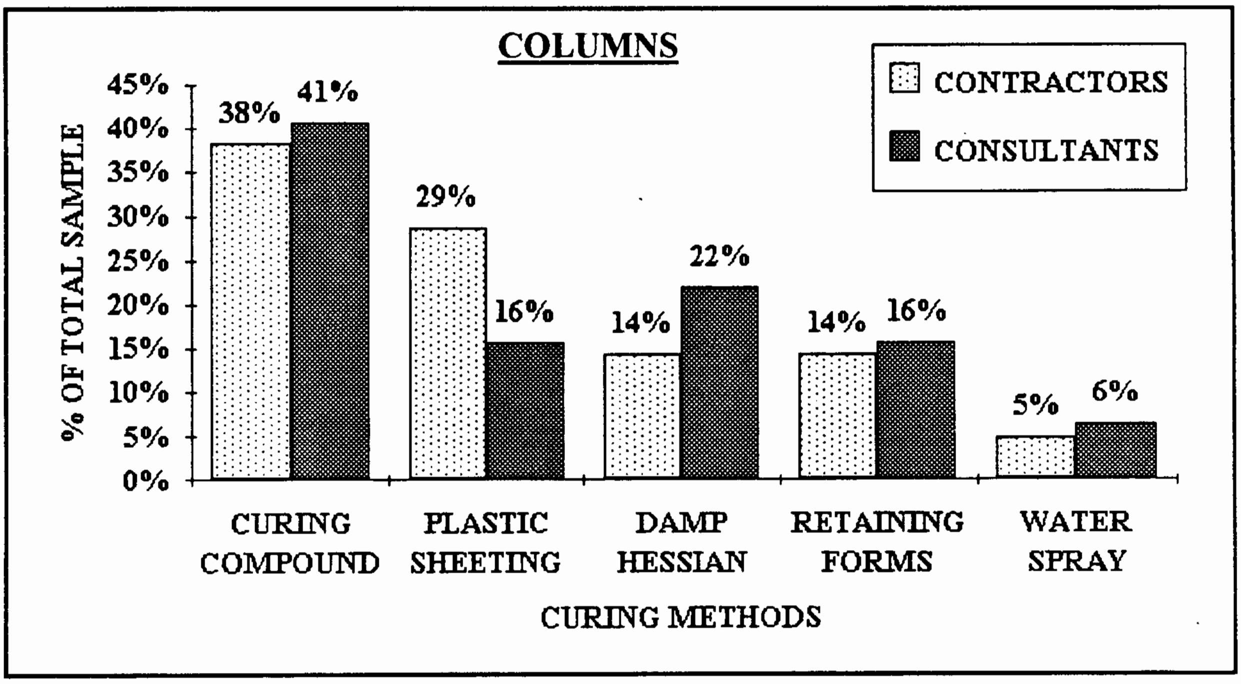


Figure 3.3 The type of curing method applied or specified for columns

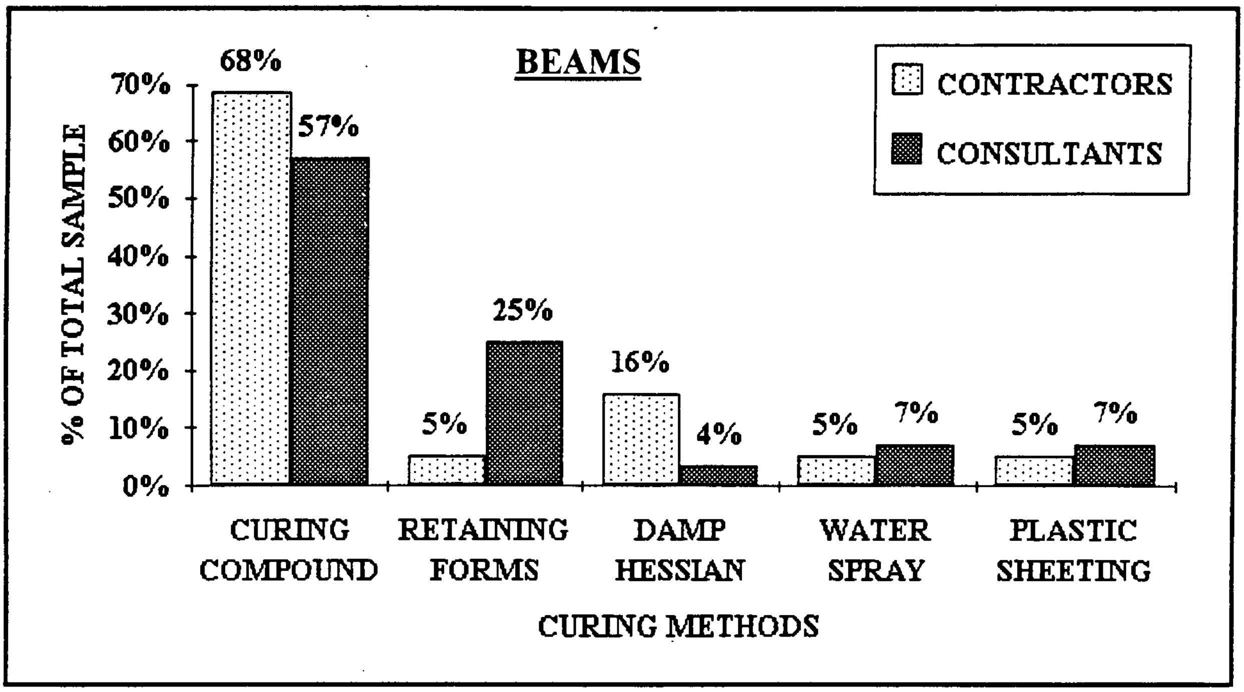


Figure 3.4 The type of curing method applied or specified for beams

The results in Figure 3.5 showed that ponding was the most frequently applied or specified method for curing slabs. Contractors reported that they preferred applying ponding of water on slabs (33% of respondents). Consultants reported that they preferred applying ponding of water on slabs (39% of respondents). Other techniques used to cure slabs included curing compounds, wet sand, water spray and damp hessian. The reasons why contractors and consultants chose these particular curing methods are discussed in question 4(b).

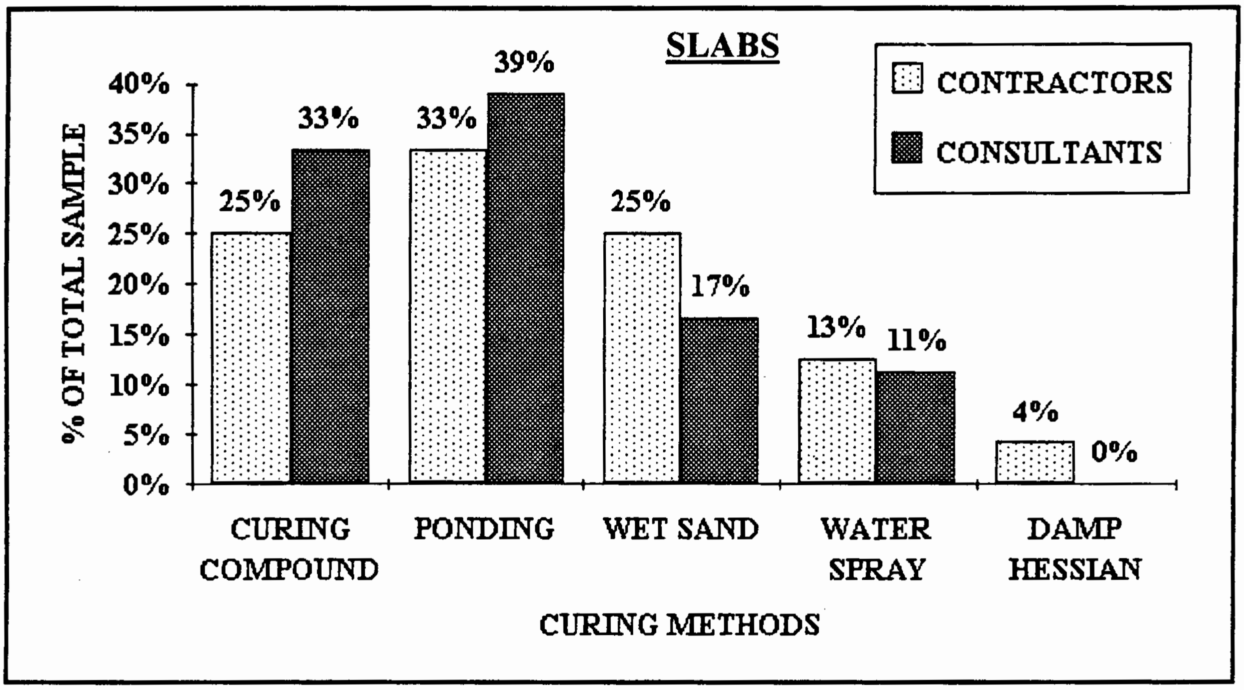


Figure 3.5 The type of curing method applied or specified for slabs

Question 4(b)

Why would you choose this type of curing method for the following structural members?

Figures 3.6 and 3.7 revealed that curing methods for columns, beams and slabs were chosen predominantly for their ease of application rather than lower costs or proven efficiency of curing. The only exception was for slabs where consultants reported that they specified a given curing method for proven efficiency (53% of respondents) rather than practical ease of application (42%). However, the irony is that there are presently no on-site tests available for determining the efficiency of curing. Thus it is very difficult for contractors and consultants to know which curing methods are the most efficient to apply or specify.

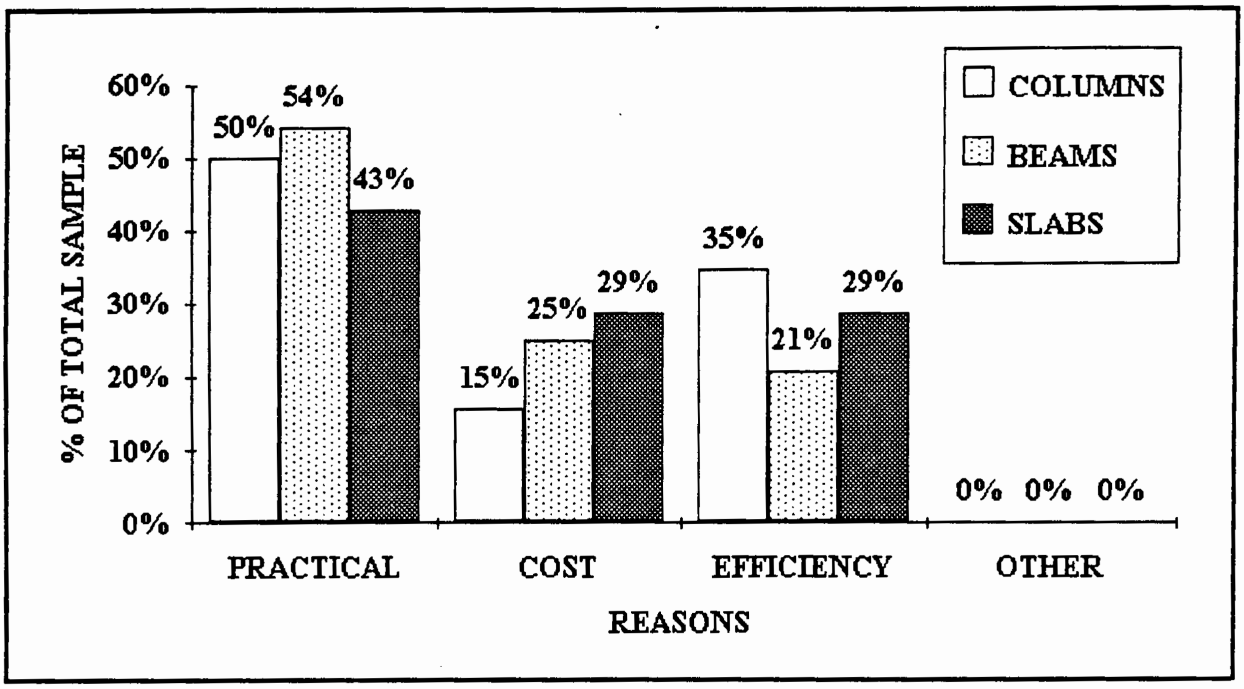


Figure 3.6 The reasons contractors applied curing methods

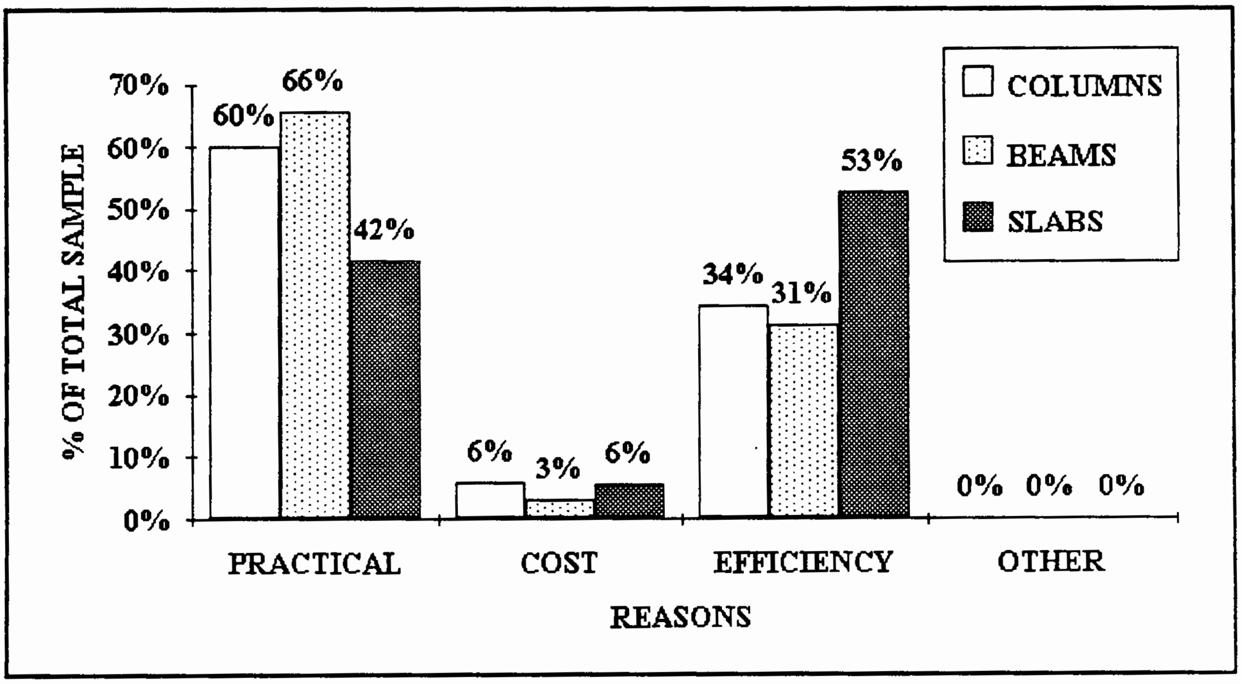


Figure 3.7 The reasons consultants specified curing methods

Consultants chose the most practical curing method for columns and beams (60% for columns and 66% for beams). Contractors also chose the most practical curing method for columns and beams (50% for columns and 54% for beams). Cost played a significant role for contractors in deciding which curing method to choose (29% for slabs and 25% for beams). Cost played a small role for consultants (6% for slabs and 3% for beams). In contrast, the proven efficiency of curing played a large role for consultants (53% for slabs and 31% for beams) and a small role for contractors (29% for slabs and 21% for beams). Furthermore, no additional reasons for curing apart from those listed in the questionnaire were given by any of the respondents.

A few comments made by consultants and contractors are listed below:

- "If not monitored properly the norm is that no curing will take place. This is why curing compounds are popular, as one does not have to constantly check to see if fresh concrete is being kept moist."

- "We normally specify the full range of curing methods in the specifications. The contractors then usually prefer to use a curing compound which we permit."

- "When contractors use a curing compound, drying still takes place. It is also important to balance practicability, theory and finance."

- "Although I believe that using a curing compound is not the most effective curing method, it is often accepted that one is at least assured of some curing."

- "Immersion in water, or ponding the top surface of a slab, is the best method of curing. Leaving the shutters in place is a good second best because shutters prevent evaporation largely due to the mould oil that creates a seal. Curing membranes are third choice."

The findings indicate the enormous popularity of applying and specifying curing compounds especially for columns and beams. Furthermore, contractors clearly chose the most practical curing method available, curing compounds, rather than consider cost or curing efficiency. The preceding examples showed that contractors and consultants are aware that curing compounds may not be the most effective curing method, but for practical and cost reasons they prefer to specify or apply curing compounds. Consultants may specify or permit curing compounds to at least assure some curing.

Question 5

What do you think are the benefits of good curing?

One consultant stated that good curing produces durable concrete with an extended life that minimises future maintenance costs. Figures 3.8 and 3.9 indicate the number of times each benefit was reported, given as a percentage. Interestingly, contractors thought that good curing increased strength (34% of contractors) more often than improved durability (29%). The consultants thought that good curing improved durability (33% of consultants) and increased strength (24%). Other benefits of good curing reported were less shrinkage cracks, low permeability, high abrasion resistance and a greater resistance to chemical attack. Note that the combined effect of these factors on concrete is extremely difficult to quantify.

There is also a domineering concern by contractors and consultants with strength in Figures 3.8 and 3.9. This conflicts with question 3 where contractors and consultants rated curing more beneficial to developing the durability properties than the strength properties of concrete. However, the improved durability percentages in Figures 3.8 and 3.9 would be higher if the other durability related benefits were included, such as low permeability, less shrinkage cracks, high abrasion resistance and resistance to chemical attack.

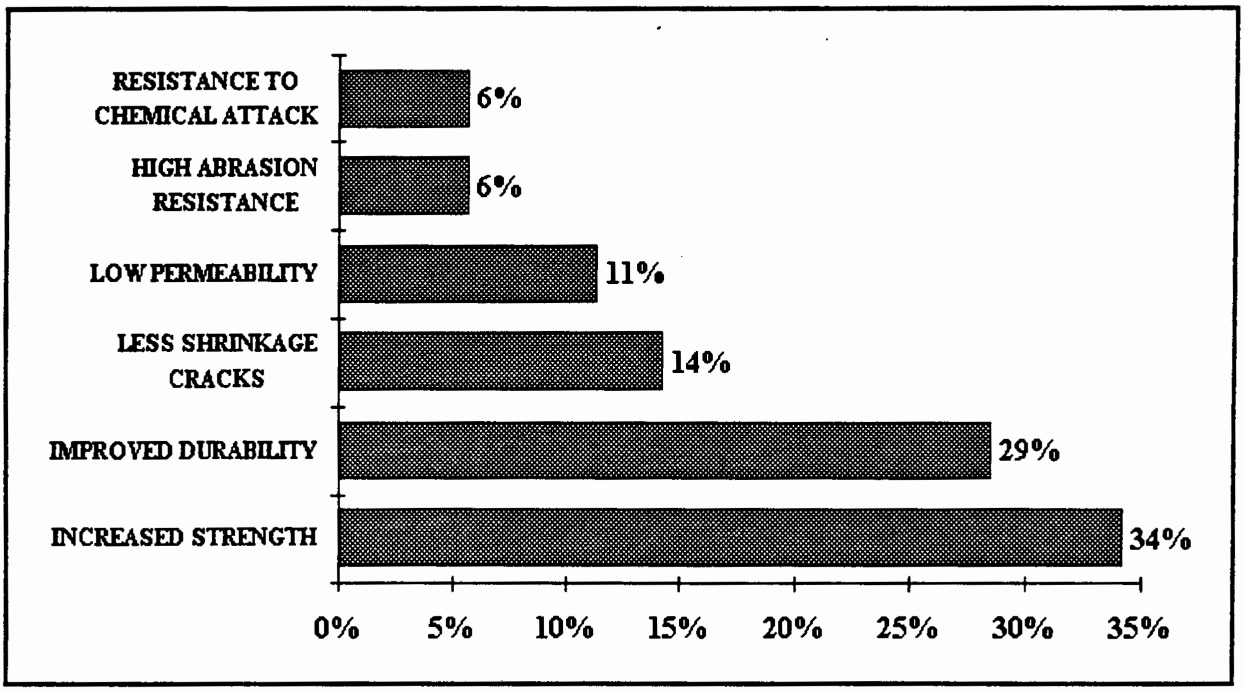


Figure 3.8 What contractors think are the benefits of good curing

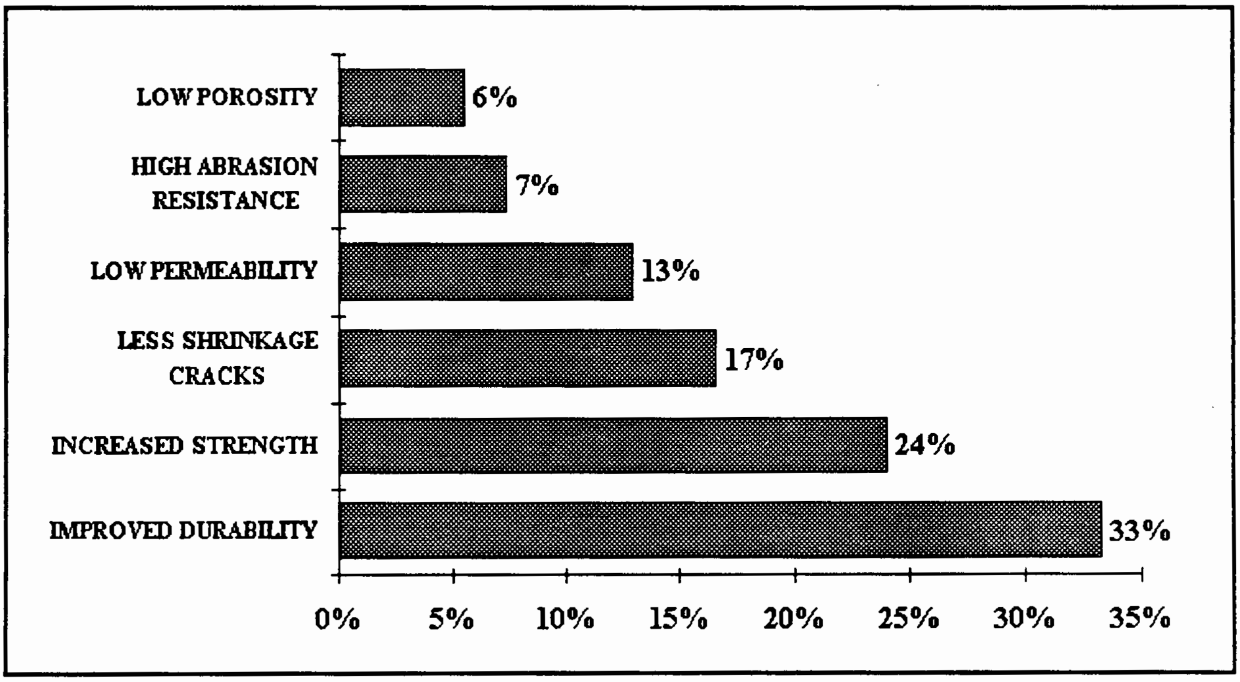


Figure 3.9 What consultants think are the benefits of good curing

The benefits reported in the survey agreed with the benefits reviewed in the literature. Warping and freedom from crazing were the only benefits mentioned in the literature that were not identified in the survey. The findings reveal that, generally, contractors and consultants have a good understanding of the benefits of curing. This is a significant outcome and a positive aspect, since it means that now the construction industry can more easily be persuaded to move towards performance-based curing specifications.

Question 6

In your opinion and experience, what quality (strength & durability) of concrete is usually achieved on construction sites for the following structural members?

Figure 3.10 revealed that contractors thought the quality of concrete achieved for columns (50% of contractors) and slabs (69%) was adequate. Contractors believed that the quality of concrete achieved for beams (50% of contractors) was good. Figure 3.11 found that the quality of concrete achieved for columns (63% of consultants), beams (52%) and slabs (43%) was good.

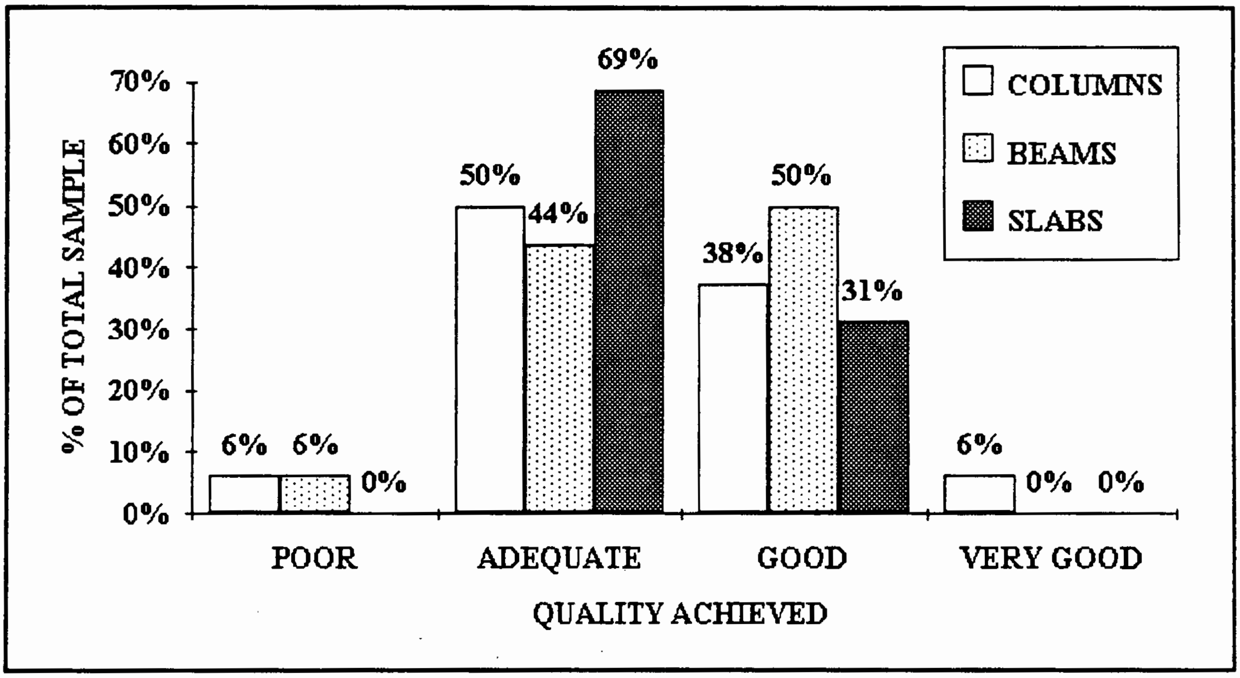


Figure 3.10 The quality of concrete that contractors thought was achieved for columns, beams and slabs

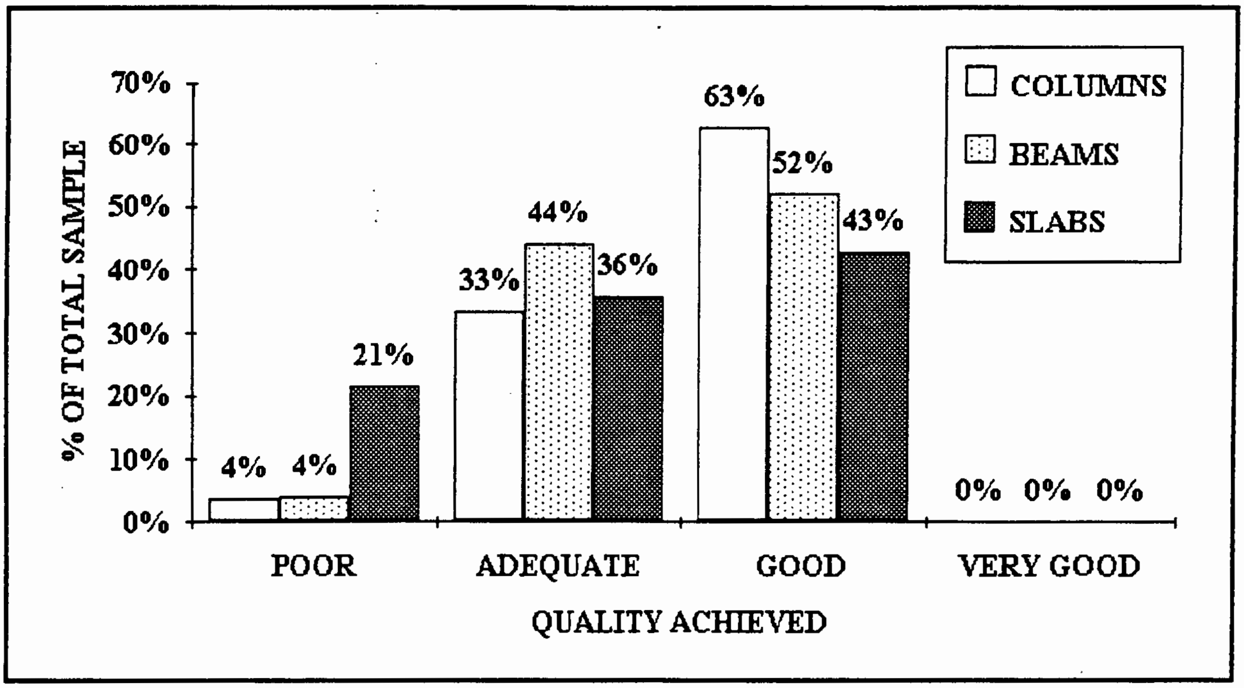


Figure 3.11 The quality of concrete that consultants thought was achieved for columns, beams and slabs

A few comments made by consultants and contractors on the quality of concrete achieved on construction sites are listed below:

- "If control exists then a good quality of concrete will be achieved, but in the norm, especially if the inspector is not on top of things, little or no curing will take place."
- "The choice of fine aggregate dictates the quality of concrete. Concrete made in the Cape Town area with Dune Sand and Malmesbury Shale will only produce poor quality concrete."
- "Quality not only varies between construction companies but also between individual construction sites. There is also a large difference in the quality of concrete produced on civil and building sites."

- "I believe consultants and contractors should spend less time and effort debating the pros and cons of curing, and concentrate on improving the quality of concrete. The main criteria at the moment is strength and not quality. I believe more emphasis should be put on the quality of aggregate used in the production of concrete, and stop relying on high cement contents and admixtures to obtain the required strength. In doing so the durability problem encountered in concrete would be generally overcome."

The above comments were all made by respondents that thought the quality of concrete achieved on site was poor. They suggested that the quality of concrete in the Cape Town area could be improved by either using higher quality materials or enforcing curing. It was also suggested that there may be differences in the quality of concrete achieved on civil and building sites. These differences may be due to more stringent curing control on civil sites than building sites.

Surprisingly, contractors considered that the quality of concrete achieved on construction projects was generally adequate while consultants felt that the quality achieved was good. It was expected that consultants would be less content with the quality achieved than contractors. Note that defining quality is difficult and subjective as there are currently no on-site tests to measure quality. Furthermore, contractors or consultants may also be referring to the compressive strength or surface appearance of concrete rather than the quality of concrete.

Question 7

What are the adverse effects you have noticed that may be caused by poor or non-existent curing?

Figures 3.12 and 3.13 showed that contractors and consultants believed shrinkage cracks and low strengths are the most common adverse effects of poor or non-existent curing. Note that shrinkage cracks and low strengths are easily measurable, or at least observable aspects of poor or non-existent curing. Other aspects of durability, such as high permeability, are not easily measurable and do therefore not feature as prominently.

Contractors felt that poor or non-existent curing resulted in shrinkage cracks (44% of contractors), low strengths (20%) and low abrasion resistance (12%). Other adverse effects identified by contractors included dusting, high permeability and brittleness. Consultants believed that poor or non-existent curing resulted in shrinkage cracks (31% of consultants), low strengths (15%), dusting (13%) and high permeability (13%). Other adverse effects identified by consultants included surface and edge spalling, corrosion of steel and low abrasion resistance.

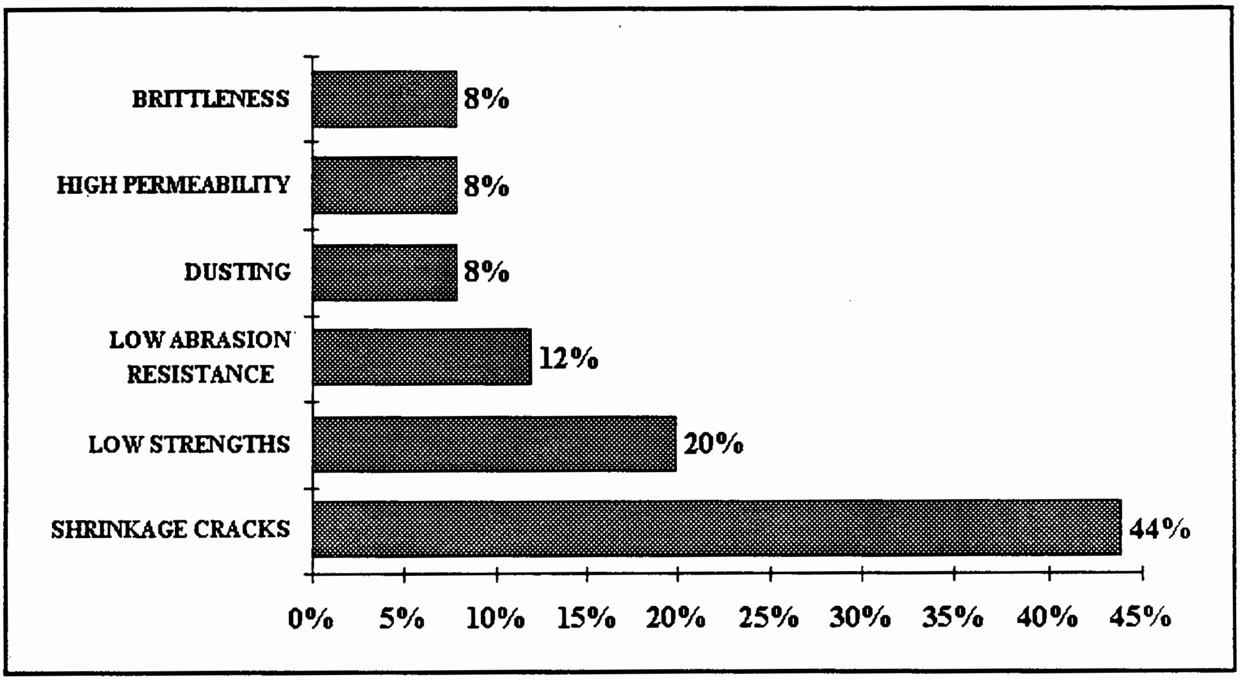


Figure 3.12 What contractors think are the adverse effects of poor or non-existent curing

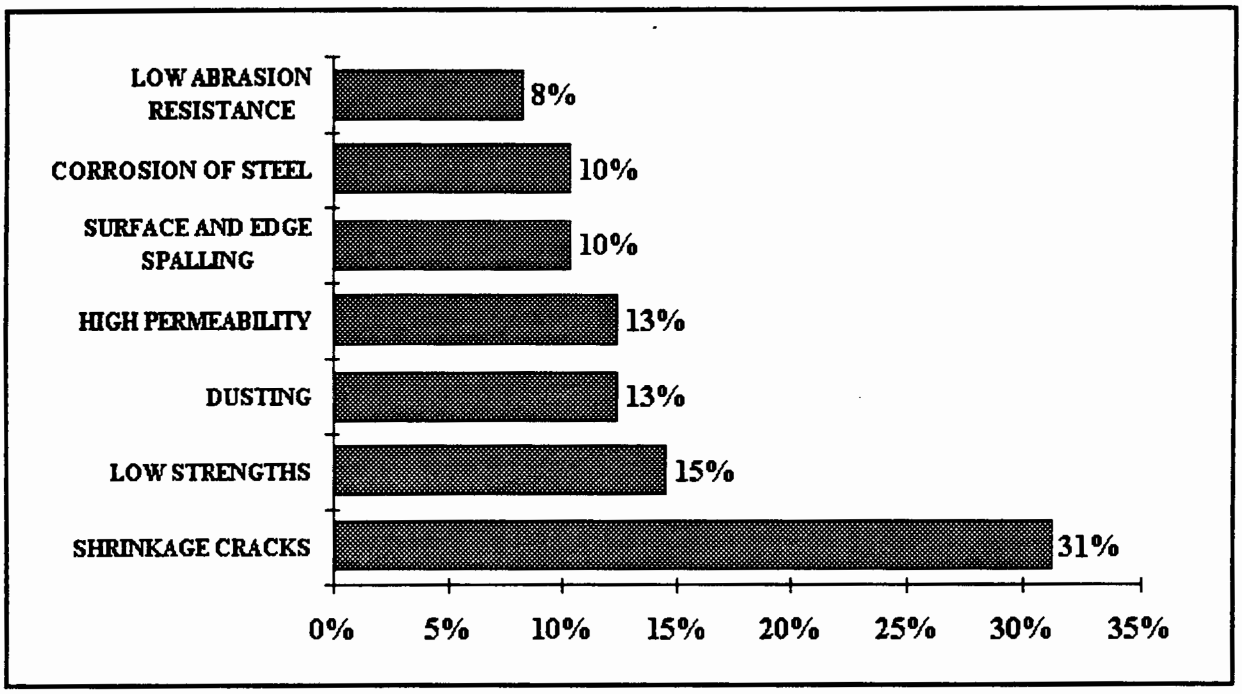


Figure 3.13 What consultants think are the adverse effects of poor or non-existent curing

Two comments made by consultants and contractors on the effects of poor curing are listed below:

- "The adverse effects of poor curing are not normally noticed in the short term. In construction one seldom has the opportunity to observe the long term effects of good or bad curing. Spalling is often encountered on older buildings in Cape Town and this is probably due to bad cover and poor curing."

- "On hot windy days evaporation takes place, especially in slabs, in the top 50 mm layer of covercrete. This quick drying out of the concrete then inhibits the hydration process and results in shrinkage cracks forming 2 to 4 hours after the removal of formwork."

These results are not entirely consistent with the benefits of proper curing presented in Figures 3.8 and 3.9. The most frequently mentioned benefit of proper curing in Figures 3.8 and 3.9 was improved durability and not less shrinkage cracks as shown in Figure 3.12 and 3.13. However, improved durability in Figure 3.8 and 3.9 could also have referred to less shrinkage cracks. This may explain the higher percentage for shrinkage cracks in Figure 3.12 and 3.13 than in Figure 3.8 and 3.9.

Contractors and consultants felt that the adverse effects of bad curing were shrinkage cracks, low strengths, dusting, low abrasion resistance, high permeability, brittleness, spalling and corrosion. Shrinkage cracks were the most frequently identified adverse effect. Furthermore, plastic shrinkage cracks may appear, especially in slabs, on hot windy days. Plastic shrinkage cracks normally appear within 2 to 4 hours of placing the concrete, long before the formwork is removed. They sometimes extend considerably deeper than 50 mm.

Question 8

Can you make any suggestions for a site-based test to determine the effectiveness of curing methods used on construction projects?

This question was poorly answered and not completed by most respondents. The suggestions made for a site-based test are listed below.

- "Perhaps a modified abrasion resistance or surface hardness test, calibrated against a control specimen could give a qualitative indication of the effectiveness of curing."

- "A possible test could be to cast a batch of cubes on site. Some samples from the batch could be wet cured and used as control samples. The rest of the cubes could be cured in the same way as the structure being cured and left in close proximity to that member."

- "The only way to test reliably would be to measure the permeability of the concrete on site and compare if with a control specimen. However, this would not be a practical, routine method."

- "A dye that reacts differently to fully and partially hydrated cement."

- "The provision of core samples from an extra piece of beam or slab cast, and later broken off."

One contractor remarked that it is difficult to test only the effectiveness of the curing method. Good quality concrete depends not only on good curing but also on the mix design, materials used, water quality and compaction. Few suggestions were given for a site-based test and the only new suggestion was a dye that reacts differently to fully and partially hydrated cement.

Question 9

What is your opinion of the usefulness and practicality of the current curing specifications in SABS 1200-G:1982 (3.1) and SABS 0100-Part 2:1992 (3.2)?

A range of opinion exists among contractors and consultants on the usefulness and practicality of the specifications. A few comments made by consultants and contractors on the specifications are listed below:

- "The codes provide an adequate guideline for curing and should not be specific thereby allowing the contractors to choose a method that suits them best."

- "SABS 1200-G:1982 allows for an open and wide variety of methods, but the method of application is often too vague. Furthermore, more information is needed on say curing in dry strong winds in summer."

- "The specifications are too rigid and do not allow for any other curing method to be used or for further development in the mix design, e.g., higher cement contents, to overcome curing problems."

- "Fast track contracts do not allow for the extended curing periods specified unless a curing compound is used. Most curing compounds available in South Africa do not comply with the required standards and so have limited effectiveness."

- "The specifications set out good practice because they protect the specifiers and form the basis for legal action by owners that have been short changed by careless contractors."

- "The specifications basically set out what is required but do not adequately emphasize the importance of curing."

- "Curing is important and should therefore be enforced and standardised with no alternatives. The engineer should specify exactly what curing he wants."

- "The specifications are fine, but the real problem is trying to enforce curing in practice because the specifications are not taken seriously enough by contractors and consultants. The situation would be acceptable if the specifications were adhered to and more stringent specifications would probably still be ignored."

The findings show that there is much scope for changing the specifications. The comments suggest that the specifications need more information on curing in dry, strong winds in summer. The method of application of curing techniques is too vague. The specifications could allow for higher cement contents to overcome curing problems and emphasize the importance of curing. On fast track contracts, the extended curing periods specified cannot be attained unless curing compounds are applied. Curing compounds may also be ineffective. Some respondents thought that changing the specifications may still not be enough to enforce curing in practice.

Question 10

Consulting Engineers: How would you ensure that concrete curing on site complies with the Specification?

The most commonly mentioned technique for ensuring curing complies with the specifications was regular inspection or full-time supervision by the Resident Engineer. One consultant stated that they only appointed contractors with a proven record of ability to cure and employed Resident Engineers who insisted on curing. Comment was also made that contractors are often reluctant to cure because curing costs money. Curing methods should be agreed upon at the start of the contract. A few techniques suggested by consulting engineers to ensure that curing complies with the specifications are listed below:

- "Specify that say 10 or 15% of the concrete price be retained and paid if adequate curing carried out."

- "Payment for curing be based on say 25% of the concrete rate. The contractor will only get full payment for concrete if the specified curing is applied correctly."

- "The engineer should have curing as a measurable pay item in the Bill of Quantities. He could then specify the curing method and the measure to pay for it. This payment item would then give the on-site engineer more leverage to enforce proper curing. If the contractors put in a very low rate for curing then their curing method may be ineffective."

The findings reveal that the only way to ensure curing complies with the specifications is through regular inspections or full-time supervision. Consultants suggested that they would like to see curing become a measurable pay item in the Bill of Quantities. Curing could also be based on retaining part of the concrete price. The contractor will only get full payment if the specified curing method is carried out correctly. Hence the need to develop and stipulate a site-based test to measure the effectiveness of curing.

Question 11

Contracting Engineers: How would you like to see that concrete curing on site is correctly achieved according to the Specification?

Presently, contractors suggested that curing can only be achieved according to specifications by regular inspections and stringent Resident Engineer control. Contractors believed that the consultant and contractor should discuss and lay the ground rules for effective curing at the start of the contract. The curing method chosen by the engineer must be practically achievable, capable of attaining the required finish and, if possible, be designed into the job. Thus, if the engineer has attended to these aspects, the specifications should be easily achievable by the contractor. A few suggestions to ensure curing is correctly achieved are listed below:

- "To educate all the site personnel that would include the Site Agent, foreman, artisans and labourers at some appropriate technical level."

- "Any implementation has to be generated from the site management down."
- "The general foreman has to understand the full importance of adequate curing while still maintaining the same productivity on site."
- "A dedicated person or team must be given the responsibility for curing."

Some contractors felt that competitive tendering and short construction periods work against good curing. Furthermore, the opportunity cost of time is often higher for curing properly than merely adding cement and not curing. Thus some contractors thought that curing was a basic waste of resources. One contractor even suggested that only the minimum necessary expense and delay must be incurred to achieve, but not exceed, the specification.

The findings showed that contractors felt that the current curing practice could be greatly improved by educating all site personnel and this could start from the site management down. A dedicated person or team must be given the responsibility for curing.

3.3 Summary

Contractors and consultants felt that curing was more beneficial to developing the durability properties than the strength properties of concrete. Furthermore, a higher percentage of consultants than contractors thought that durability was extremely important. Curing compounds were the most frequently applied or specified curing method for columns and beams. Ponding was the most frequently applied or specified curing method for slabs. The curing methods chosen for columns, beams and slabs were predominantly applied for their practical ease of application. Cost and proven efficiency of curing were of low priority when choosing a curing method.

are
The benefits of curing suggested by contractors and consultants were increased strength, improved durability, less shrinkage cracks, low permeability and high resistance to abrasion and chemical attack. The most frequently identified benefit of curing by contractors was increased strength and improved durability by consultants. The adverse effects of poor or non-existent curing are shrinkage cracks, low strengths, dusting, low abrasion resistance, higher permeability, brittleness, surface and edge spalling and corrosion of steel. Shrinkage cracks were the most frequently identified adverse effect. Contractors believed that the quality of concrete achieved on construction projects was adequate while consultants thought the quality achieved was good.

The following comments were made on the current curing specifications. More information is needed on curing in dry, strong winds in summer. The method of application of curing techniques is too vague. Higher cement contents should be allowed to overcome curing problems. The importance of curing must be emphasized in the specifications. The extended curing periods specified on fast track contracts cannot be achieved unless curing compounds are applied. However, curing compounds may be ineffective. Changing the specifications may still not be enough to enforce curing in practice.

Consultants suggested that they would like to see curing become a measurable pay item in the Bill of Quantities. Curing could also be based on retaining part of the concrete price. The contractor will only get full payment if the specified curing method is carried out correctly. Hence the need to develop and stipulate a site-based test to measure the effectiveness of curing. The only new suggestion for a site-based test was a dye that reacts differently to fully and partially hydrated cement. Contractors suggested that the current curing practice could be greatly improved by educating all site personnel and this could start from the site management down. Furthermore, a dedicated person or team must be given the responsibility for curing.

The following chapter will attempt to determine the effects of three curing regimes and W/C ratios on the transport properties of concretes. The effects of five curing methods on the transport properties of concrete will also be compared.

3.4 Conclusions

The main objective of the concrete curing survey was to determine the opinions, curing practices and level of understanding of contractors and consultants towards curing. The following conclusions were drawn from the survey:

1. The survey showed that contractors and consultants have a good understanding of the benefits of proper curing and the adverse effects of poor or non-existent curing. This is a positive aspect, since it means that the construction industry can now take steps to move towards performance-based curing specifications. The curing benefits identified in the survey correlated well with the benefits found in the literature.

2. Contractors and consultants were of the opinion that curing was more beneficial to developing the durability properties than the strength properties of concrete. Contractors were of the opinion that the quality of concrete achieved on construction projects was generally adequate while consultants thought the quality achieved was good.

3. The curing specifications in SABS 1200-G:1982 and SABS 0100-Part 2:1992 need to be reviewed and updated. The curing specifications could be enforced by making curing a measurable pay item in the Bill of Quantities or by retaining part of the concrete price.

4. Curing compounds are the most commonly applied curing method to columns and beams. Furthermore, curing methods are predominantly chosen for their practical ease of application rather than their proven efficiency of curing. The effectiveness of curing compounds as a curing method needs to be reviewed critically.

5. The current curing practice could be greatly improved by educating all site personnel and this could start from the site management down. Furthermore, a dedicated person or team must be given the responsibility for curing.

6. The only new suggestion for a site-based test was a dye that reacts differently depending on the degree of hydration. More research work is needed to find an acceptable site-based test to determine the effectiveness of curing methods used on site.

3.5 References

3.1 South African Bureau of Standards, Standard Specification for Civil Engineering Construction, SABS 1200-G:1982.

3.2 South African Bureau of Standards, Materials and Execution of Work, SABS 0100-Part 2:1992.

CHAPTER 4

LABORATORY WORK

4.1 Introduction

Before starting research on site concrete, three sets of laboratory tests was performed, namely Sets 1, 2 and 3. The laboratory work aimed to determine the effect of three curing regimes and W/C ratios on the transport properties of the covercrete. Moreover, the effects of five different curing methods on the transport properties of concrete were also compared. The oxygen permeability and water sorptivity durability index tests were used to investigate the durability of the covercrete. Set 1 was initially cured in the laboratory and then exposed to the natural environment. Set 2 was exposed to a controlled environment. A concrete wall was cast outside the laboratory to compare different curing methods for Set 3. All the results of the oxygen permeability and water sorptivity tests are illustrated graphically and discussed at the end of this chapter.

4.2 Durability Index Tests

Durability is the ability of concrete to resist deterioration by environmental forces. A physically measurable property is required as a direct indication of the potential durability of a particular concrete. The fluid transport properties of oxygen permeability and water sorptivity are used in this project to characterise the potential durability of the covercrete, and tests for these properties are named "durability index tests." The test samples for the oxygen permeability and water sorptivity tests were drilled from cubes, concrete blocks or median barriers.

4.2.1 Oxygen permeability test

The permeameter chosen for this work was developed at the University of the Witwatersrand. It derives the D'Arcy coefficient of permeability by monitoring a falling pressure head, using oxygen as the permeating medium (4.1). Permeability primarily controls the rate at which aggressive agents may enter the concrete and cause deterioration. Permeability indicates the degree of interconnection between the pores. The test apparatus, method and calculations for the oxygen permeability test are given below.

a) Test apparatus and method

The main cylinder is manufactured from a segment of mild steel water piping with a 106 mm nominal internal diameter. The pressure gauge ranges from 0 to 150 kPa and pressure can be read to an accuracy of 0,5 kPa. Figure 4.1 shows a schematic arrangement of the permeameter (4.2). The concrete sample is inserted into the silicone rubber collar, then positioned on the top plate of the permeameter cell and compressed against the perforated cover plate using a single clamping bolt.

The inlet and outlet valves are then opened and the pressure cylinder is purged by allowing the test gas to flow through the cylinder for a minute. Once purging is complete, the outlet valve is shut and the pressure is allowed to increase to approximately 100 kPa. On shutting the inlet valve, the time and pressure are recorded. Pressure decay with time is then monitored by taking pressure readings at regular time intervals down to 50 kPa.

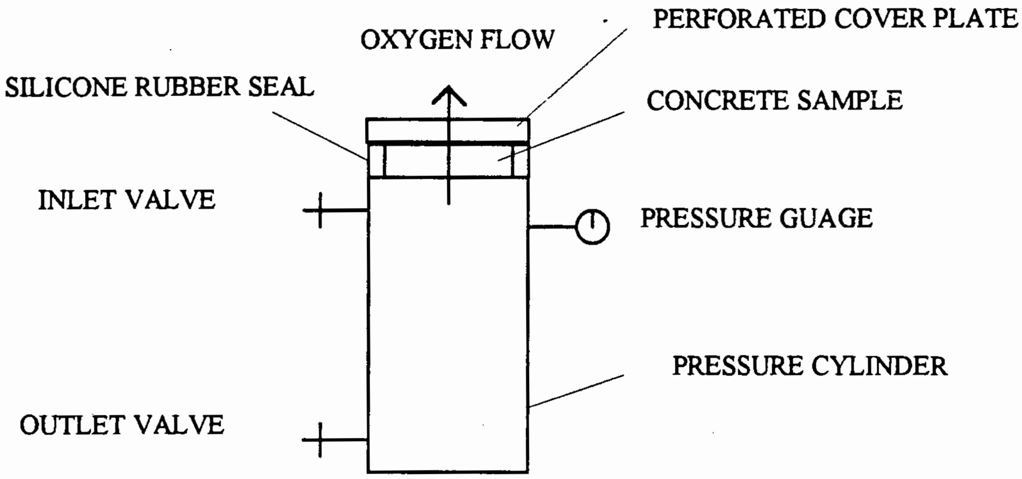


Figure 4.1 Schematic arrangement of the falling-head permeameter (4.2)

Immediately after the cores were drilled and sliced, they were transferred to an air-ventilated oven, controlled at a temperature of 50°C. All samples were dried in this manner for seven days before testing. On the day of testing, the samples were allowed to cool for one hour before being tested for oxygen permeability. The time required for testing depends on the permeability and thickness of the sample. A 30 mm thick sample of a low strength, poorly cured concrete requires approximately 30 minutes to test. A high strength concrete sample of the same thickness requires approximately 12 hours to test.

b) Calculation of oxygen permeability

The equation below gives the relationship governing the operation of the falling head permeameter.

Oxygen Permeability Index $= -(\log_{10} . k)$ (1)

where:

$$k = (w.V.g.d.\ln\frac{P_o}{P})/(R.A.q.t) \qquad (2)$$

k = coefficient of permeability (m/s)
w = molecular mass of permeating air (kg/mol)
V = the volume of air under pressure (m^3)
g = acceleration due to gravity (m/s^2)
R = universal gas constant = 8313 $(Nm/K\,mol)$
A = superficial cross sectional area of the sample (m^2)
d = sample thickness (m)
q = absolute temperature (K)
t = time for pressure to decrease from P_o to P (s)
P_o = pressure at beginning of test (kPa)
P = pressure at end of test (kPa)

It can be seen from Equation 2 that the logarithm of the ratio of pressure heads for the same sample should be directly proportional to the time required for the pressure decrease. The apparatus was tested to check the applicability of this theory to gas flow through concrete. An example of an oxygen permeability index test result is shown in Figure 4.2. The sample used was control 1 from laboratory Set 3. The details of the sample and test procedure are given in section 4.4.3. The derivation of equation 2 and further theoretical considerations are discussed in detail by Ballim (4.1).

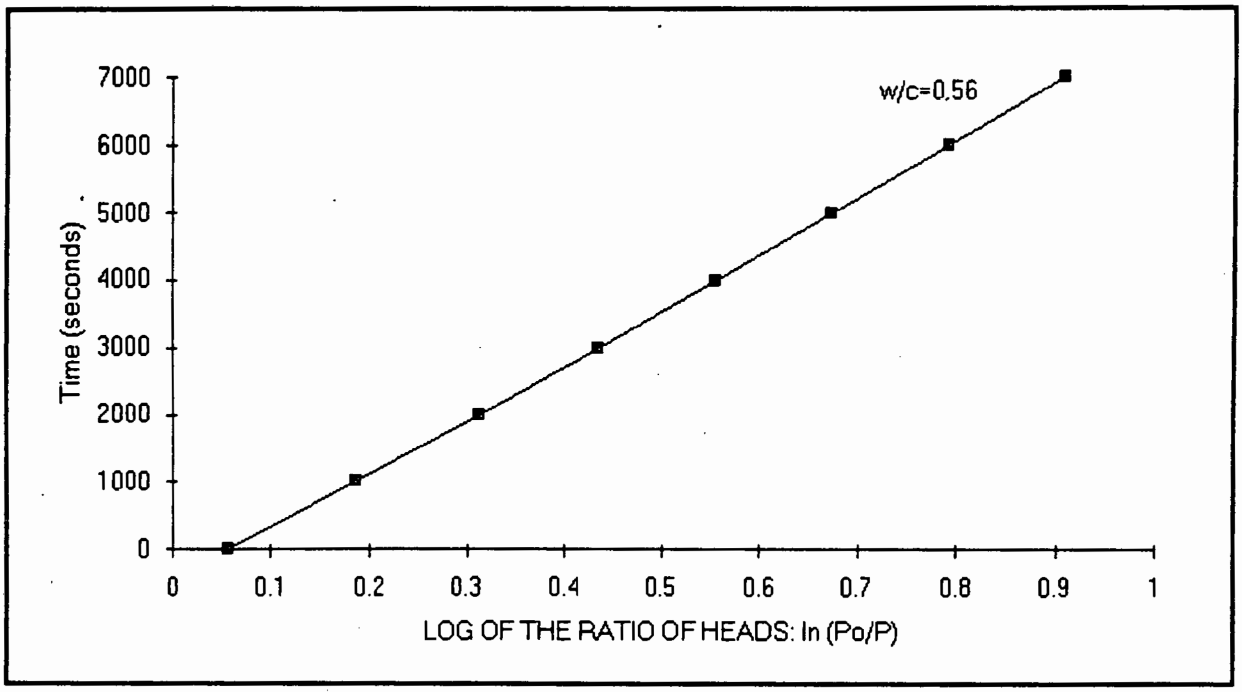


Figure 4.2 Example of an oxygen permeability index test result

4.2.2 Water sorptivity test

Water sorptivity is a material constant that determines the rate of water penetration into an unsaturated concrete (4.3). The effective porosity is the relative mass of water required to saturate the concrete. Sorptivity depends on the permeability and porosity of the concrete, and on the strength of capillary forces. Sorptivity provides a useful indication of the pore structure of the concrete surface layer. The sample preparation, test method and calculations for the water sorptivity test are given below.

a) Sample preparation and test method

Upon completion of the oxygen permeability test, the same samples were returned to the drying oven for 12 hours. The samples were allowed to cool before the edges were sealed with plastic tape, as illustrated schematically in Figure 4.3 (4.4). After determining the dry mass of the sample, a layer of water approximately 3 mm thick was placed on the surface. The mass of the sample was then measured at regular intervals up to 64 minutes. When weighing the sample, water was removed and the surface wiped with a cloth. The sample was saturated in water for 24 hours and then vacuum saturated in water for a further two hours, to determine the apparent porosity. From these results a value of sorptivity (4.3), a measure of the initial rate of water absorption, was calculated for each sample.

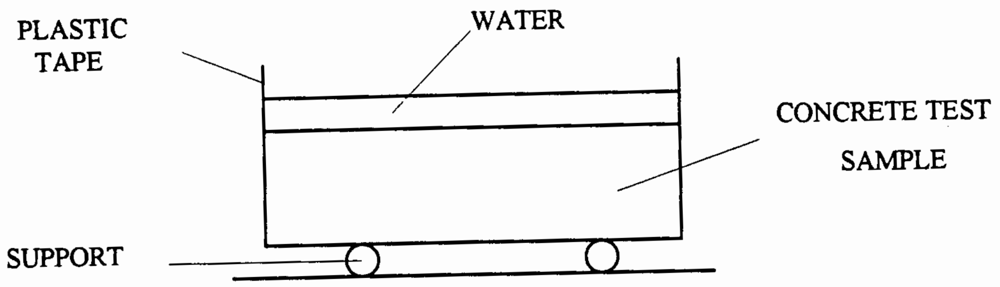


Figure 4.3 Schematic diagram showing water sorptivity test arrangement (4.4)

b) Calculation of water sorptivity

From D'Arcy's law for fluid flow through a porous medium, it can be shown that the depth of penetration of water into unsaturated concrete is proportional to the square root of time. The equation below gives the relationship governing the water sorptivity test (4.3).

$$S = (M(t) - M(0)) / (A \cdot z \cdot \sigma_w \cdot t^{\frac{1}{2}}) \qquad (3)$$

where:

S = sorptivity $(m / s^{\frac{1}{2}})$
$M(t)$ = mass of the concrete cylinder at time t (g)
$M(0)$ = initial mass of the concrete cylinder (g)
$M(sat)$ = mass of the saturated concrete cylinder (g)
A = cross-sectional area of flow (m^2)
z = effective porosity $(\% \ v / v)$
σ_w = density of fluid (kg / m^3)
t = time from contact of water with sample (s)
l = length of sample (m)

The porosity is obtained from the difference between the dry and the saturated masses and is given by the equation :

$$z = (M(sat) - M(0)) / Al\sigma_w \qquad (4)$$

Once porosity has been calculated, sorptivity can be calculated from the slope of the plot of mass versus square root of time. An example of a water sorptivity test result is presented in Figure 4.4. The sample tested was control 1 from laboratory Set 3. All the details for the sample and test procedure are given in section 4.4.3. The result shows that the weight gain over the whole period of absorption is initially rapid. No more water will be absorbed once saturation is complete. The derivations of equations 3 and 4 are discussed in detail by Kelham (4.3).

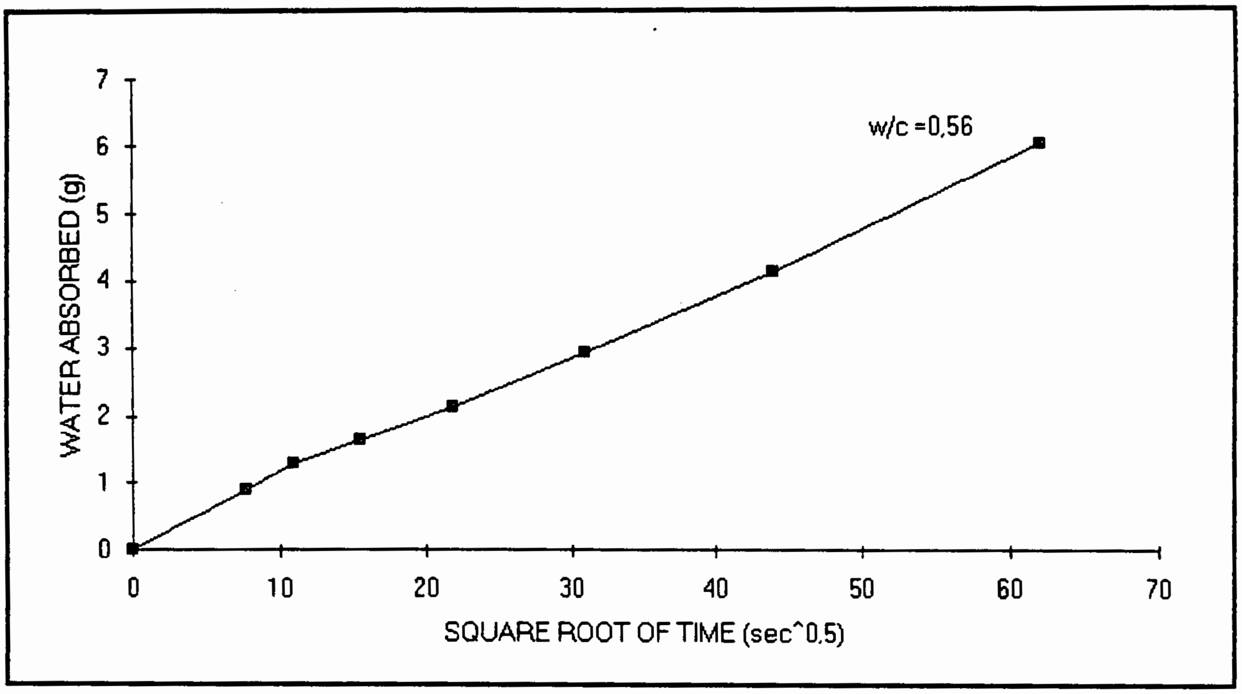


Figure 4.4 Example of a water sorptivity test result

4.3 Mix Materials

The mix materials used in this research were Cape Flats Dune Sand as the fine aggregate, Greywacke as the course aggregate, and OPC from the Pretoria Portland Cement plant at Riebeek West as binder. Three sets of laboratory tests were conducted, namely Set 1, Set 2 and Set 3. Sets 1 and 2 were made from three concrete mixes, namely a 20, 40 and 60 MPa strength mix. Set 3 was made from a 40 MPa strength mix. The mix details of the three strengths of concrete are listed in Table 4.1.

Table 4.1 The concrete mix design for 20, 40 and 60 MPa strength concretes

Mix Details	All Quantities per m^3		
Target 28 day strength	20 MPa	40 MPa	60 MPa
BINDER: OPC Riebeek West	240 kg	386 kg	515 kg
SAND: Cape Flats Dune Sand	862 kg	794 kg	637 kg
STONE: Greywacke 19 mm	1050 kg	1050 kg	1050 kg
Water content	200 l/m^3	192 l/m^3	198 l/m^3
W/C	0,83	0,56	0,38

4.4 Laboratory Procedure

Three sets of laboratory tests were performed. Set 1 was cured in the laboratory and then exposed to the natural environment. The specimens were placed outside the concrete laboratory at the University of Cape Town. The samples were exposed to rain, wind and cold for three months, August to October 1993. Set 2 was exposed to a controlled environment for 28 days in August 1994. The relative humidity and temperature were controlled for the full duration of the exposure. Sets 1 and 2 were used to determine the effects of three different curing regimes and different W/C ratios on the physical properties of the covercrete.

Set 3 compared the effects of five different curing methods on the transport properties of concrete. A 40 MPa strength OPC concrete mix was used. The laboratory results present typical values and trends for concrete cured in the laboratory and will be compared with the site results in chapter 6.

4.4.1 Set 1: Natural environment exposure tests

Three curing regimes were used to determine the effect of relative humidity on the transport properties of OPC. The curing regimes were applied to 20, 40 and 60 MPa strength concrete blocks, the details of which are shown in Figure 4.5. The moulds for the blocks and cubes were removed after 24 hours. The moulds for the blocks were made of wood. The three curing regimes were as follows:

(a) immersed in water at a temperature of 22 ± 1°C for 28 and 90 days.
(b) cured in air at a temperature of 19°C ± 1°C and a relative humidity of 80% ± 3% for six days before being placed in the natural environment for 83 days.
(c) cured in air at a temperature of 26°C ± 1°C and a relative humidity of 50% ± 2% for six days before being placed in the natural environment for 83 days.

The blocks were exposed for three months, August to October 1993. The average relative humidity and average temperature experienced by the blocks in the natural environment was approximately 78% and 15°C respectively. These values were calculated from the mean values of daily relative humidity and temperature readings obtained from the Cape Town Airport weather bureau (4.5).

The three curing regimes were applied to 20, 40 and 60 MPa strength concrete mixes. Two blocks and eight 100 mm cubes were cast for each strength of concrete. The two blocks were exposed to curing regimes (b) and (c) while the cubes were exposed to curing regime (a). Cores were drilled perpendicular to one face of each block as illustrated in Figure 4.6. Three 68 mm diameter cores were drilled at each of 28 and 90 days. The outer 30 mm of each core was sliced off and used as a test sample as illustrated in Figure 4.6. A high speed, water-cooled diamond saw blade was used to slice each core. All the samples were immediately transferred to an air-ventilated oven, controlled at a constant temperature of 50°C, in preparation for the oxygen permeability and water sorptivity tests.

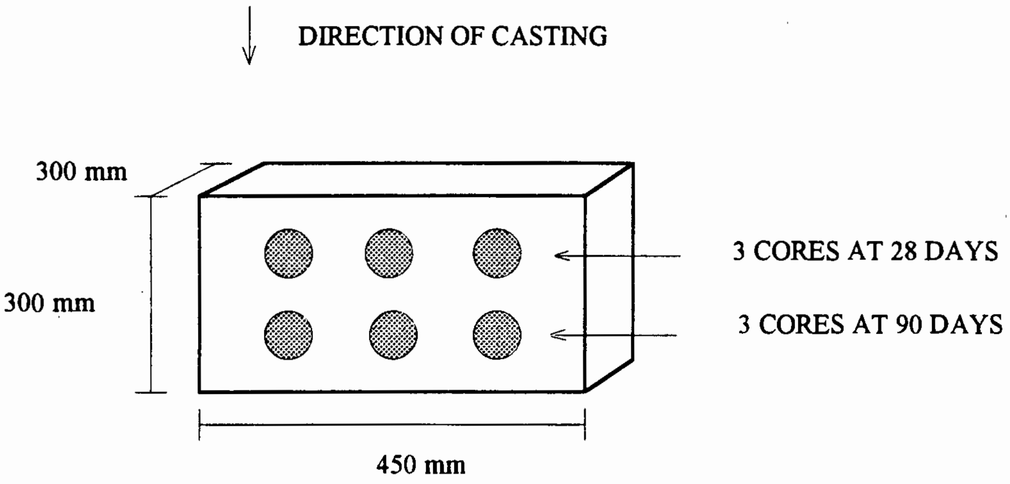


Figure 4.5 Position of cores on one face of block

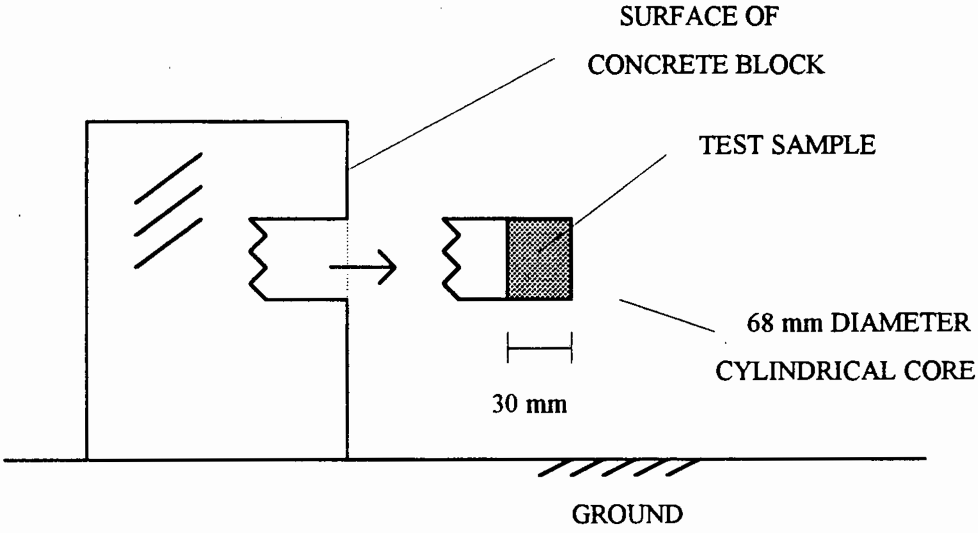
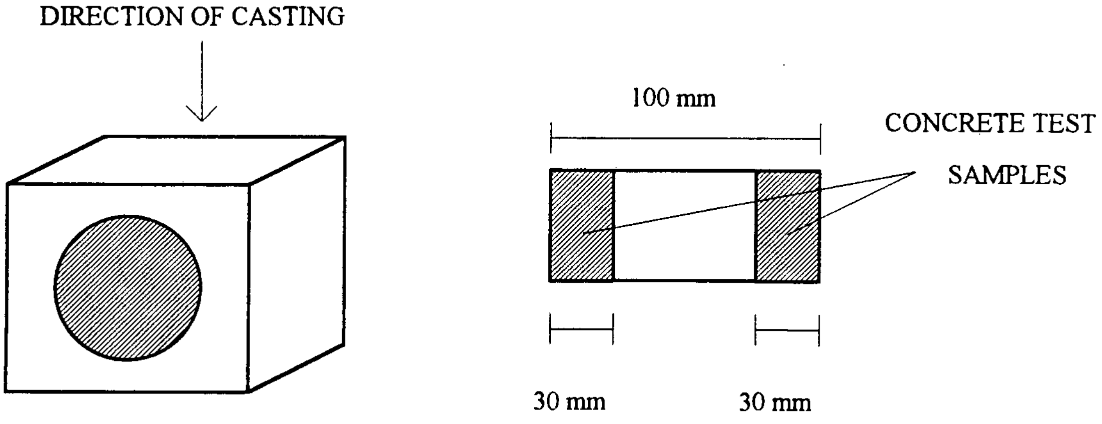


Figure 4.6 Method of coring and slicing block to obtain test sample

Three cubes were used to determine the compressive strength of concrete at each of 28 and 90 days. The compressive strength tests were done according to SABS 863 (4.6). The two remaining cubes were used as control samples for the oxygen permeability and water sorptivity tests. One cube was cored at each of 28 and 90 days. Figure 4.7 illustrates the coring and slicing of the cube in relation to the direction of casting. All the samples were immediately transferred to an air-ventilated oven, controlled at a constant temperature of 50°C, in preparation for the oxygen permeability and water sorptivity tests.



100 mm CUBE

CYLINDRICAL CORE

Figure 4.7 Method of coring and slicing cube to obtain test samples

4.4.2 Set 2: Controlled environment exposure tests

Set 2 was cast in August 1994. Three curing regimes were used to determine the effect of relative humidity on the transport properties of OPC. The curing regimes were applied to cubes and all the moulds were removed after 24 hours. The three curing regimes were as follows:

(a) immersed in water at a temperature of 22 ± 1°C for 28 days.
(b) cured in air at a temperature of 22 ± 2°C and a relative humidity of 90 ± 2% for 28 days.
(c) cured in air at a temperature of 22 ± 2°C and a relative humidity of 60 ± 2% for 28 days.

The three curing regimes were applied to 20, 40 and 60 MPa strength concrete mixes. For each strength of concrete nine 100 mm cubes were cast. Three cubes were immersed in water and tested for strength at 28 days. Two cubes were exposed to each of curing regimes (a), (b) and (c). The six cubes exposed to curing regimes (a), (b) and (c) were cored and sliced at 28 days as illustrated in Figure 4.7. All the samples were immediately transferred to an air-ventilated oven, controlled at a constant temperature of 50°C, in preparation for the oxygen permeability and water sorptivity tests.

4.4.3 Set 3: Comparison of curing methods

Five curing methods were used to compare the effects of different curing methods on the transport properties of covercrete. A concrete wall of 3 x 0,3 x 0,2 m dimensions was cast outside the laboratory at UCT and exposed to the natural environment. The details of the concrete wall are shown in Figure 4.8. A 40 MPa strength OPC concrete mix was used for Set 3, being a typical strength poured on site. Details of the concrete mix design are listed in Table 4.1. Two steel shutters of 3 x 0,45 m dimensions were used as formwork.

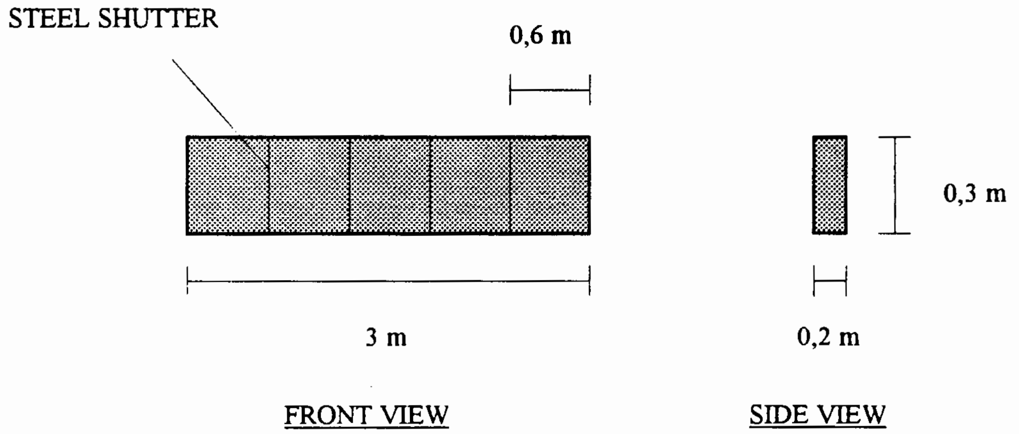
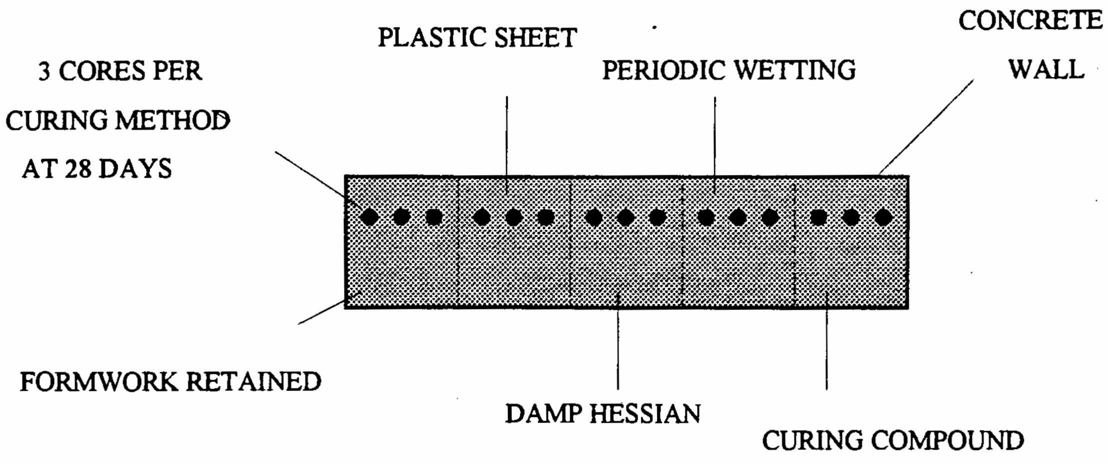


Figure 4.8 Details of the concrete wall

Set 3 was cast on 18 November 1994. Two batches of material were used to make the 40 MPa strength mix. Variations between batches were prevented by weighing the same quantity of materials, mixing for the same period and wetting the mixer before mixing. The wall was divided into five sections by pieces of shutterboard. The following curing methods were applied to the north face of the wall.

(a) seven days in formwork with no subsequent curing; cored at 28 days.
(b) 24 hours in formwork and curing compound applied immediately after formwork was removed; cored at 28 days.
(c) 24 hours in formwork and wetted twice per day for six days with a bucket of water; cored at 28 days.
(d) 24 hours in formwork; 6 days wrapped in damp hessian; cored at 28 days.
(e) 24 hours in formwork; 6 days wrapped in plastic sheets; cored at 28 days.

The Nitobond HAR curing compound, manufactured by Fosroc, was applied with a brush at a coverage rate of 5 m^2 per litre. The positions of cores and their curing methods on the concrete wall are illustrated in Figure 4.9. All the samples were cored and sliced from the north face of the wall at 28 days. Five 100 mm cubes were also cast and immersed in water at a temperature of 22 ± 1°C for 28 days. These were used as control cubes for the compressive strength and durability index test samples. Three control cubes were tested for compressive strength at 28 days. Two control cubes were cored and sliced as shown in Figure 4.7. All the samples were immediately transferred to an air-ventilated oven, controlled at a constant temperature of 50°C, in preparation for the oxygen permeability and water sorptivity tests.



FRONT VIEW

Figure 4.9 Position of each curing method and cores on the concrete wall

4.5 Discussion of Results: Set 1 and Set 2

All the individual results of the oxygen permeability, water sorptivity and compressive strength tests are listed in Appendix B; Tables B.1 to B.14. The standard deviations and coefficients of variation for all the individual results were calculated.

According to the 1977 Building Code of the American Concrete Institute (4.7), at least 30 tests are needed for an adequate estimate of the standard deviation of concrete strength. This is mainly due to inherent variables in the concrete, and non-uniformities caused by outside factors such as bleeding and segregation, entrapped and entrained air, and different shapes and sizes of aggregate (4.8). Experimental or testing errors also add to the variation of the test results. Note that although every effort should be made to produce uniform results, uniform results are not necessarily accurate results.

The standard deviation of the oxygen permeability index and water sorptivity results was only calculated from three measurements. In future, a typical permeability and sorptivity laboratory test should involve approximately 30 measurements of the same test. This is to ensure that a meaningful, reliable and more accurate standard deviation is obtained before any statistical analysis.

According to ASTM C670 (4.8), when three measurements are averaged to obtain a test result, the range of the individual measurements may be examined. This is to determine whether they meet the criterion of being valid individual measurements under the conditions of the test method. The maximum acceptable range, that is the difference between the highest and lowest value allowed in ASTM C670, for three individual measurements is obtained by multiplying the standard deviation by a factor of 3.3. However, since the standard deviation used for the present work was only calculated from three measurements, the maximum acceptable range would not be accurate.

Certain individual measurements were concealing trends. The variability in a group of three results may sometimes be ascribed to a single anomalous result in the group. The rejection of data is difficult and subjective when the decision is based on only three measurements. If one individual value did not significantly influence the average for this project then all the individual values were used. Only two individual values were discarded from all the oxygen permeability index and water sorptivity values. No values were excluded in the calculation of the compressive strength test results.

4.5.1 Compressive strength at 28 and 90 days

The average compressive strength test results for all the mixes at 28 and 90 days are listed in Table 4.2. Each value listed in Table 4.2 represents the average of three individual cube compression tests. The individual results of all the compressive strength tests are presented in Appendix B; Tables B.7 and B.14.

The mixes were designed for 28 day target strengths of 20, 40 and 60 MPa. Given these target strengths, Test 1: 40 MPa and Test 2: 60 MPa were both overdesigned. The strength gain of concrete is due to a chemical reaction between the cement and water. The reaction is rapid at early ages and provided sufficient water is always present it will continue, though increasingly slowly, for several years.

Table 4.2 shows the gain in compressive strength for Test 1 from 28 to 90 days. High strength mixes gain strength more rapidly than low strength mixes (4.9). This is because the cement grains are closer together and a continuous system of hydrates from various compounds is established more rapidly. However, the rate of strength gain from 28 to 90 days was slightly higher for Test 1: 20 MPa than Test 1: 40 MPa. This could be explained by the high coefficient of variation of the 90 day Test 1: 20 MPa result as listed in Appendix B, Table B7. The high coefficient of variation was influenced by the 20 MPa 6 sample. If this result is excluded then the results are more realistic.

Table 4.2 Average compressive strength results at 28 and 90 days

Test No. and Target Strength	Binder	W/C Ratio	Average Compressive Strength at 28 days (MPa)	Average Compressive Strength at 90 days (MPa)
Test 1: 20 MPa	OPC	0,83	20,0	22,6
Test 1: 40 MPa	OPC	0,56	44,0	46,5
Test 1: 60 MPa	OPC	0,38	61,7	66,1
Test 2: 20 MPa	OPC	0,83	20,9	*
Test 2: 40 MPa	OPC	0,56	42,2	*
Test 2: 60 MPa	OPC	0,38	68,5	*
Test 3: 40 MPa	OPC	0,56	40,1	*

* Result not taken

4.5.2 Oxygen permeability at 28 and 90 days

All the individual results of the oxygen permeability index tests for the various concretes are presented in Appendix B. The oxygen permeability index values are calculated to two decimal places. The results for the natural environment exposure tests are illustrated graphically in Figure 4.10 (Set 1). The results for the controlled environment exposure tests are illustrated graphically in Figure 4.11 (Set 2).

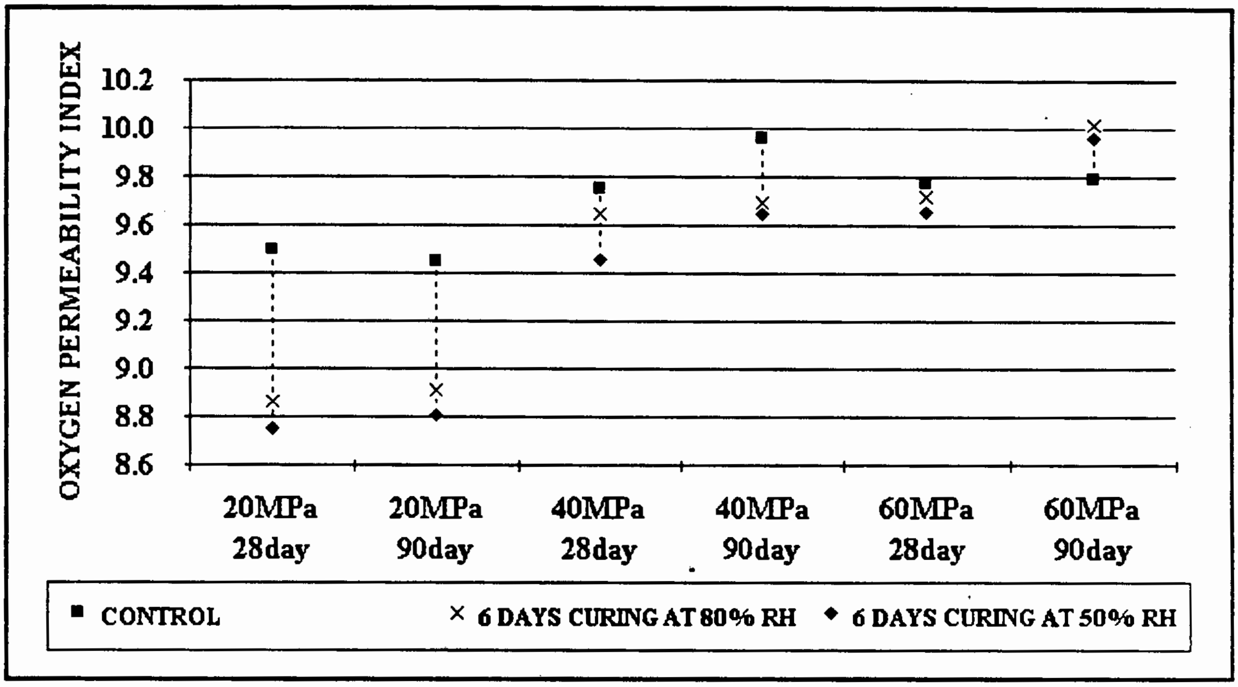


Figure 4.10 Oxygen permeability index results for natural environment exposure Set 1

The oxygen permeability index results are the average values calculated from three samples. At the time Set 1 was undertaken the problem of the variability of the permeability index measurements was not fully appreciated. As a result, the control values for Set 1 represent the average of only two measurements. As soon as it was recognised that two control samples were inadequate, three control samples were used for the remaining laboratory work.

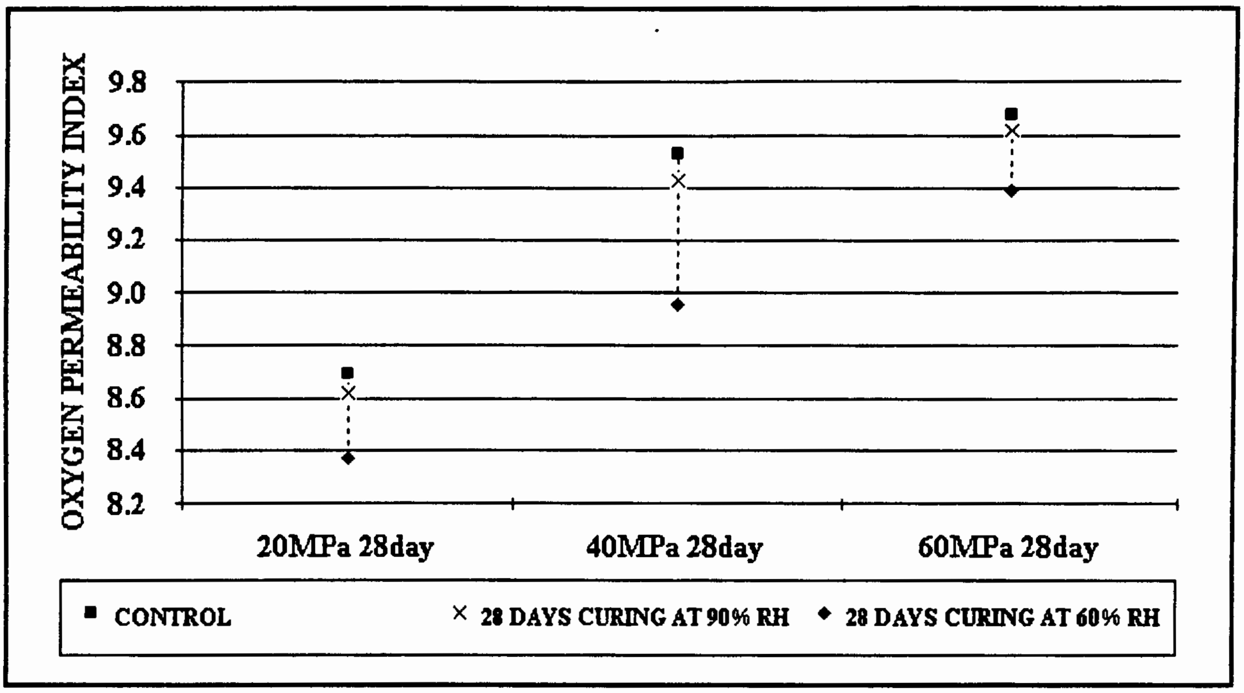


Figure 4.11 Oxygen permeability index results for controlled environment exposure Set 2

It is evident from Set 1 that permeability generally decreased from 28 to 90 days. This is because the products of hydration are deposited in the pores, and permeability is reduced by decreasing pore size and the lower degree of interconnection between pores. There is a noticeable decrease in permeability as the concrete strength increases in Sets 1 and 2. This decrease becomes less marked as the strength grade increases.

Set 1 revealed that there is a large difference in permeability between wet curing and curing at 80% relative humidity for six days. There is little difference in permeability between curing at 80% and 50% relative humidity for six days. Set 2 showed that a 40 MPa concrete cured at 90% relative humidity was less permeable than a 60 MPa concrete cured at 60% relative humidity for 28 days.

The results of Set 1 must be treated with caution and as a preliminary set of proving trials. The oxygen pressure was read off a pressure gauge at regular intervals for Set 1. However, for Set 2 the pressure readings were recorded by computer using electronic pressure transducers. Thus it is probable that more accurate readings were obtained for Set 2 than Set 1. The samples in Set 1 were not always cored and sliced perpendicular to the concrete surface. However, with repeated use of the core drilling machine and saw, the coring and slicing improved. Consequently, the test samples for Set 2 were considered to be better than Set 1.

The low quality results for Set 1 show the importance of using correct and consistent testing techniques. These results suffered from poor experimental techniques and will not be used subsequently. The results of Set 2 are considered to be better than Set 1 and will be used in chapter 6 for further analysis.

4.5.3 Water sorptivity at 28 and 90 days

All the individual results of the water sorptivity tests for the various concretes are presented in Appendix B. The water sorptivity values are calculated to two decimal places. The results for the natural environment exposure tests are illustrated graphically in Figure 4.12 (Set 1). The results for the controlled environment exposure tests are illustrated graphically in Figure 4.13 (Set 2).

The water sorptivity results are the average values calculated from three samples. As with the permeability index measurements, the problem of variability of the sorptivity measurements was not fully appreciated at the time Set 1 laboratory results were undertaken. As a result, the sorptivity control values for Set 1 represent the average of only two measurements. As soon as it was recognised that two control samples were inadequate, three control samples were used for the remaining laboratory work.

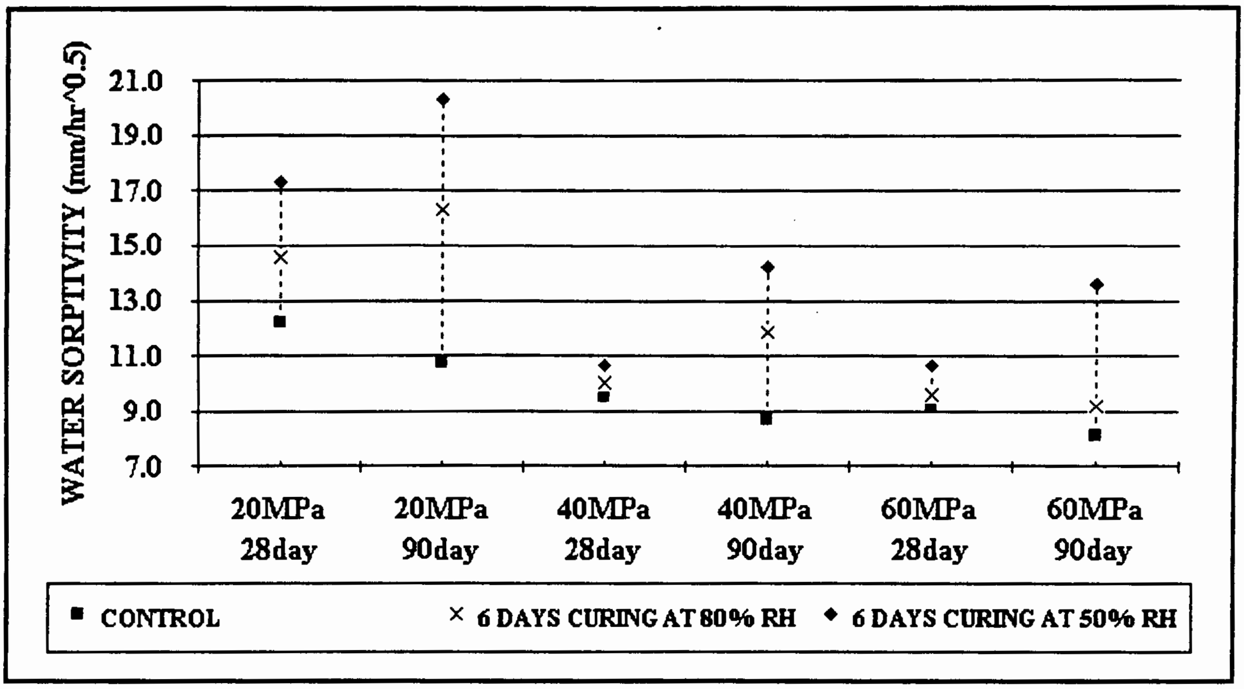


Figure 4.12 Water sorptivity results for natural environment exposure Set 1

The results of Set 1 are a preliminary set of proving trials. These results are suspect and must be treated with caution due to the poor experimental techniques in the sample preparation. The edges of the test samples were not sealed correctly. The plastic tape did not cover the side of the test sample completely. Air may thus have escaped and influenced the sorptivity value. In addition, water may also have been absorbed between the plastic tape and the side of the test sample, influencing the sorptivity value.

The same test samples were used for the water sorptivity test as the oxygen permeability test. As explained in section 5.4.2, the test samples for Set 2 were cored and sliced better than Set 1. Furthermore, whilst the samples for Set 1 were only saturated in water for 24 hours to calculate effective porosity, the samples for Set 2 were saturated in water for 24 hours and then vacuum saturated in water for a further two hours.

Set 1 provided the sorptivity results from 28 to 90 days. The sorptivity of the control samples generally decreased with age while that of the exposed samples increased with age. This phenomenon is difficult to explain since the permeability values for the same samples decreased with age. The reason may be that sorptivity decreases as the covercrete draws water from the interior of the concrete, i.e., self curing takes place. Once self curing has ceased, the covercrete dries quickly and hydration ceases, resulting in a porous surface layer. The sorptivity of the control samples decreased with age as they were completely submerged in water, thus prohibiting any drying of the surface layer.

The rate at which drying occurs in the covercrete may be influenced by the temperature, relative humidity and strength of concrete. The relationship between the durability index values, strength, relative humidity and temperature will be discussed in more detail in chapter 6. That the sorptivity of the exposed samples increased with age must be treated with caution, given the poor experimental techniques for Set 1. Chapter 5 will further test the sorptivity of site concrete at 28 and 90 days. Note that after 90 days the effects of carbonation may begin to influence the sorptivity results.

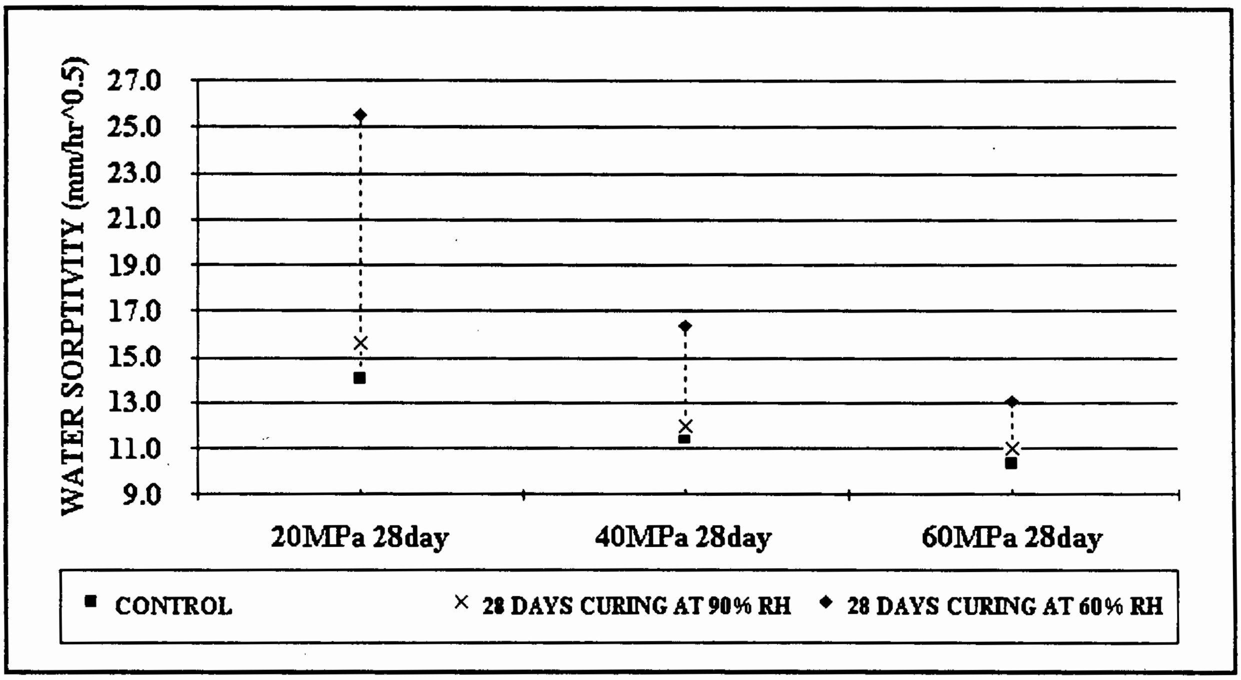


Figure 4.13 Water sorptivity results for controlled environment exposure Set 2

There is a noticeable decrease in sorptivity as the concrete strength increases. This decrease becomes less marked as concrete strength increases due to a smaller proportion of water-filled spaces, or pores, between the cement particles. The smaller spaces are therefore more easily and effectively sealed off by the hydration products of the cement (4.10).

It is evident from Set 2 that sorptivity decreased as the relative humidity increased. There is a large difference in sorptivity for concrete cured at 60% and 90% relative humidity. Curing concrete for 28 days at 90% relative humidity has a beneficial effect on sorptivity whilst curing at 60% relative humidity is much less effective. The results also revealed that the effect of relative humidity on lower strength concretes is more marked.

The results of Set 2 showed that a 40 MPa concrete cured at 90% relative humidity produces a lower sorptivity value than 60 MPa concrete cured at 60% relative humidity for 28 days. A lower sorptivity was achieved for a 20 MPa strength concrete cured at 90% relative humidity than a 40 MPa concrete cured at 60%. However, a lower permeability was not achieved for a 20 MPa strength concrete cured at 90% relative humidity than a 40 MPa concrete cured at 60%.

The results of Set 1 suffered from poor and inconsistent experimental techniques and will not be used subsequently. These poor results reflect the importance of using correct and consistent testing techniques. The results of Set 2 were considered to be better than Set 1 and will be used in chapter 6.

4.6 Discussion of Results: Set 3

All the individual results of the oxygen permeability, water sorptivity and compressive strength tests are listed in Appendix B; Tables B.15 to B.17. The standard deviations and coefficients of variation for all the individual results were calculated. The average compressive strength for Set 3 was 40,2 MPa. The oxygen permeability and water sorptivity results for Set 3 are shown in Figures 4.14 and 4.15.

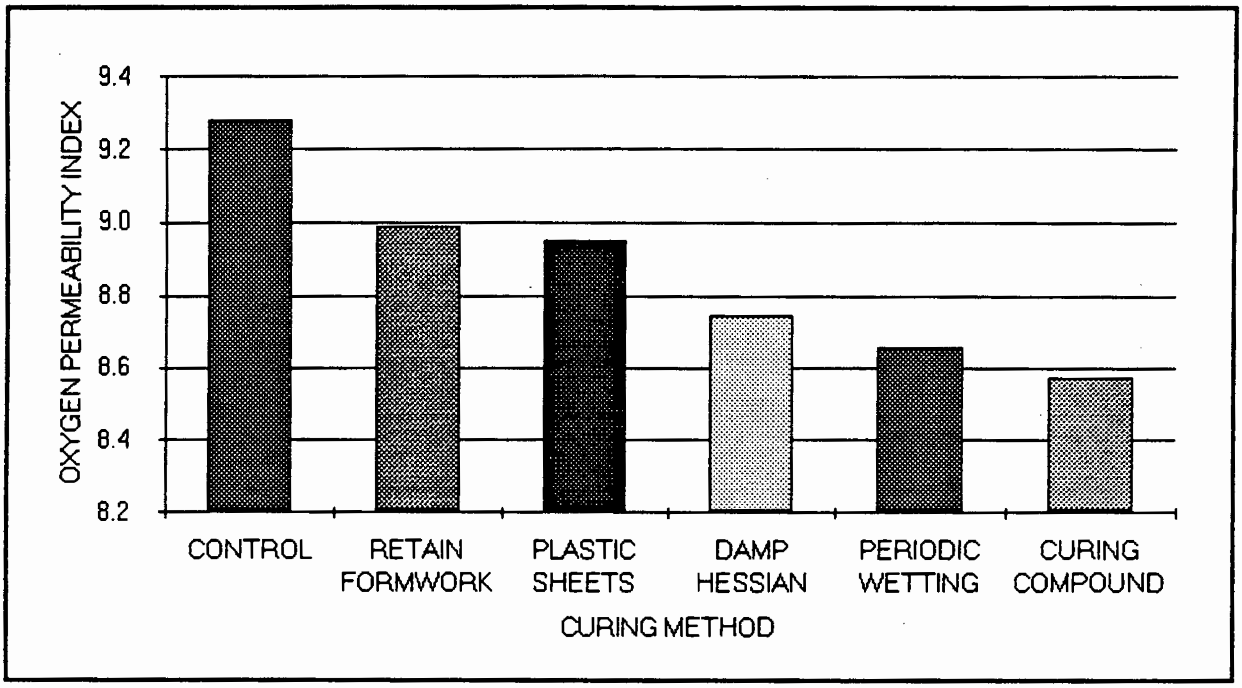


Figure 4.14 Oxygen permeability index results for comparison of curing methods Set 3

The environmental conditions experienced for the first few days after casting are extremely important. The average environmental conditions for the first seven days after casting are listed in Table 4.3 (4.5). Rain on day 1 after stripping may have aided the hydration of the covercrete for the damp hessian and periodic wetting curing methods. The retained formwork, plastic sheet and curing compound methods would have benefited little or not at all from the additional moisture.

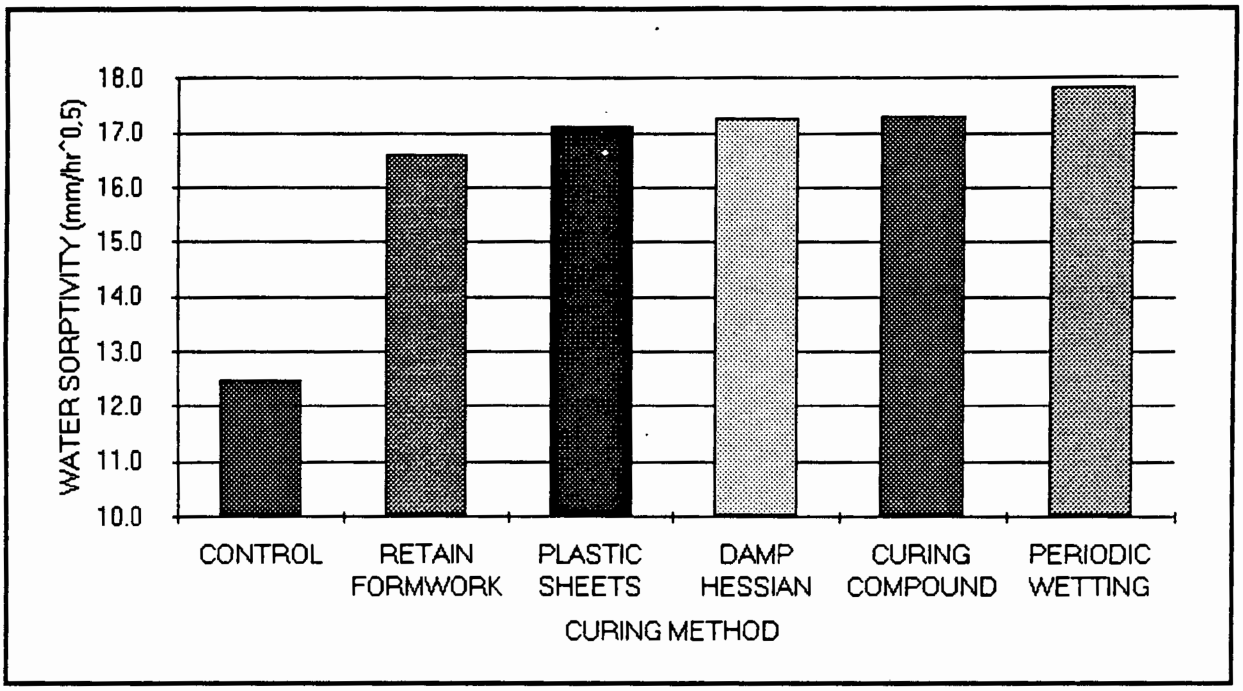


Figure 4.15 Water sorptivity results for comparison of curing methods Set 3

Table 4.3 Average environmental conditions for first seven days after casting (4.5)

Environmental Factors	Average Relative Humidity (%)	Average Temperature (°C)	Average Wind Speed (m/s)
24 hours in formwork	69	16,8	5,0
Day 1 after stripping	77	17,1	6,2
Day 2 after stripping	67	17,4	3,5
Day 3 after stripping	68	16,2	4,1
Day 4 after stripping	61	15,6	5,7
Day 5 after stripping	65	14,4	3,8
Day 6 after stripping	64	15,3	3,9

The actual environmental conditions were not as severe as were desired. In summer, temperature is often above 30°C and relative humidity below 60%. Furthermore, construction sites in the Cape Town area are often situated where they are exposed to the elements. The concrete wall for Site 3 was cast outside the laboratory in a fairly built-up environment. Therefore, higher permeability and sorptivity values may have been obtained if the concrete wall was cast on site and hotter, drier conditions were experienced for the first few days after stripping.

The oxygen permeability index results in Figure 4.14 revealed that the control samples produced the least permeable covercrete. The retained formwork curing method produced the least permeable covercrete of the five curing methods tested, followed by the plastic sheet, damp hessian, periodic wetting and curing compound methods. Based on the coefficient of permeability (k), the retained formwork method was approximately half as effective as the control. The curing compound method was approximately 5 times less effective than the control and approximately 2,5 times less effective than the retained formwork method.

The water sorptivity results in Figure 4.15 show a similar trend to the permeability results. The retained formwork method achieved the lowest sorptivity value of the five curing methods tested, followed by the plastic sheet, damp hessian, curing compound and periodic wetting methods. The retained formwork method was approximately 0,75 times as effective as the control. The periodic wetting method was approximately 1,4 times less effective than the control. The difference between the two durability index test results was the slight improvement of the curing compound in the sorptivity results. This was probably due to the fairly high coefficient of variation of the curing compound sorptivity values.

The following chapter will attempt to determine the effect of environmental conditions on the transport properties of concrete cast on site.

4.7 Conclusions

From the results obtained and the foregoing discussion, it was concluded that:

1. The natural environment exposure tests indicated that permeability decreased as strength grade increased. The decrease became less marked with increasing strength grade. Permeability decreased as the curing relative humidity increased. Permeability decreased with time from 28 to 90 days.

2. The natural environment exposure tests revealed that sorptivity decreased as strength grade increased. The sorptivity decrease became less marked with increasing strength grade. Sorptivity decreased as the curing relative humidity increased.

3. The results of Set 1, especially the sorptivity results, were adversely affected by poor and inconsistent experimental techniques. Thus good experimental techniques are extremely important to ensure meaningful results.

4. The controlled environment tests showed that increasing the curing relative humidity was as effective as decreasing the W/C ratio of the mix to improve durability. Curing at 90% relative humidity for 28 days had a beneficial effect on the durability index values. Curing at 60% relative humidity for 28 days was much less effective.

5. The variability of the oxygen permeability index and water sorptivity test values must be investigated further. It appears that, for the test conditions used in this chapter, the number of test samples should be increased. Four test samples may give more consistent results.

6. A comparison of five curing methods revealed that retained formwork was the most effective curing method, producing the most durable covercrete. Plastic sheets and damp hessian were the second and third most effective curing methods. The curing compound and periodic wetting curing methods were the least effective for the conditions tested.

4.8 References

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CHAPTER 5

SITE WORK

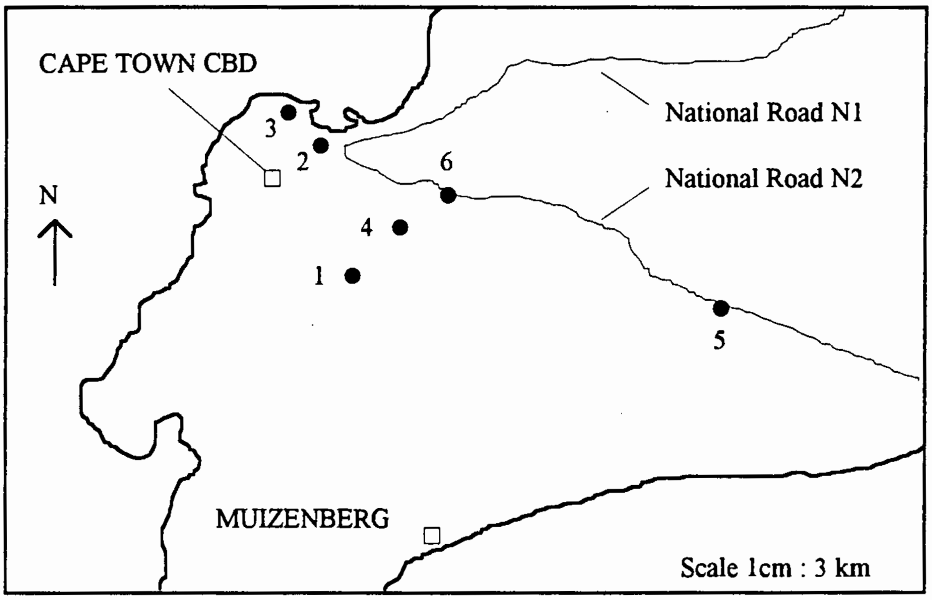
5.1 Introduction

This chapter is primarily concerned with curing practice on construction sites in the Cape Town area. The main objective was to determine the effect of environmental conditions on the transport properties of the covercrete. The oxygen permeability and water sorptivity tests were used to investigate the curing systems used on six construction sites. An average evaporation rate was calculated for each site to determine the effects of environmental conditions.

Discussions were held with the Site Agent and Resident Engineer on each site to determine their opinions on and levels of understanding of curing. The effectiveness of an on-site curing system was assessed by testing the permeability and sorptivity of a coated and an uncoated section of a median barrier unit. In addition, on each site the effects of environmental conditions on the durability index values developed on the north and south faces of concrete were compared. All the results are illustrated graphically and discussed

5.2 Site Procedure

Two different procedures were applied to test the transport properties of concrete cast on site. Figure 5.1 illustrates the position of the sites tested in the Cape Town area. The first procedure involved coring concrete blocks cast on site. This procedure was applied to the Albion Springs, Caltex Garage, Granger Bay and Rondebosch Golf Course sites. The second procedure, involving coring of the actual structure, was applied to the Median Barrier sites on the N2 Freeway.



1. Albion Springs Site - Newlands
2. Caltex Garage Site - Table Bay
3. Granger Bay Site
4. Rondebosch Golf Course Site
5. Median Barrier Site 1 - Khayelitsha
6. Median Barrier Site 2 - Pinelands

Figure 5.1 Map of the Cape Town area showing the sites tested

5.2.1 Site procedure for coring blocks

On each site one 300 x 300 x 450 mm block and ten 100 mm cubes were cast from the site mix. The block was demoulded when the formwork on the structure was removed. The mould was made of wood, although on site steel formwork is used. A steel mould would probably have given more realistic results as the temperature and non-absorbent surface of the steel may influence the rate of moisture loss from the covercrete.

Figure 5.2 indicates the method of coating and coring of the block. The epoxy coating allowed uni-axial drying through two opposite, cured faces. The same curing method as applied to the structure was applied to the north and south faces of the block. This was to compare the effect of the environmental conditions on the durability index values developed on the north and south sides of the structure.

At 28 and 90 days, three 68 mm diameter cores were drilled from each of the north and south faces of the block, as illustrated in Figure 5.2. Each core was drilled to a depth of approximately 50 mm. A high speed, water-cooled diamond saw blade was used to slice off the outer 30 mm of each core. All the samples were immediately transferred to an air-ventilated oven, controlled at a temperature of 50°C, in preparation for the oxygen permeability and water sorptivity tests.

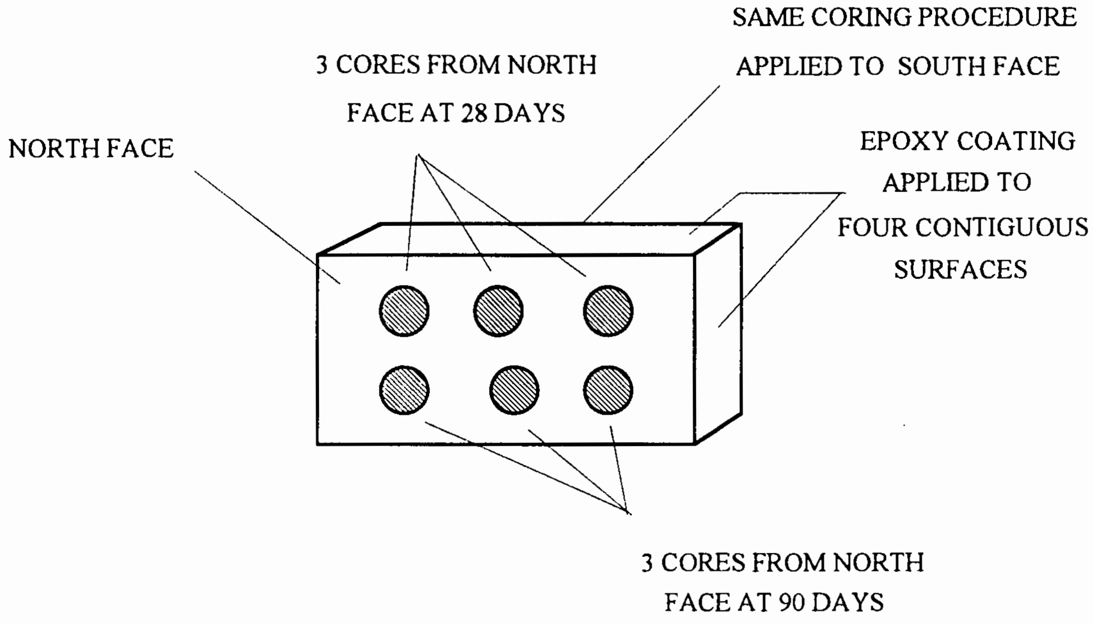


Figure 5.2 Method of coating and coring block to obtain test samples

The ten 100 mm cubes were demoulded from steel moulds after 24 hours and taken back to the laboratory to be immersed in water at a constant temperature of 22 ± 1°C. Three cubes were tested for compressive strength at each of 28 and 90 days. The compressive strength tests were done according to SABS 863 (5.1). The four remaining cubes were used as control samples for the oxygen permeability and water sorptivity tests. A 68 mm diameter core was drilled from each cube perpendicular to one of the side faces. Figure 5.3 indicates the method of coring and slicing the cube in relation to the direction of casting. Two cubes were cored at each of 28 and 90 days. All the samples were immediately transferred to an air-ventilated oven, controlled at a temperature of 50°C, in preparation for the oxygen permeability and water sorptivity tests.

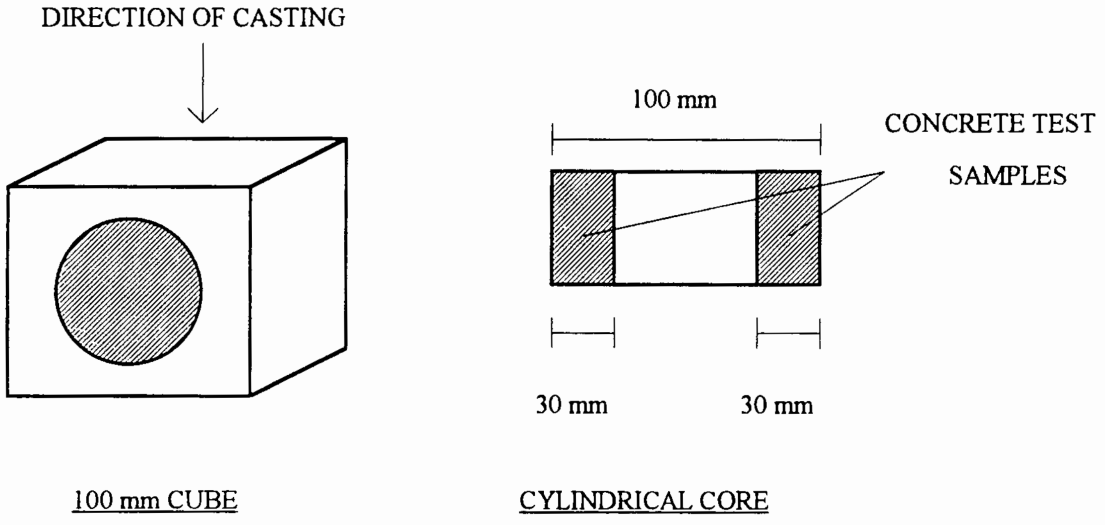


Figure 5.3 Method of coring and slicing cube to obtain test samples

5.2.2 Site procedure for Median Barrier Site 1 and Site 2

The median barrier was tested at two sites. The median barrier units tested on Site 1 were cast on 14 February and 21 April 1994. The median barrier unit tested on Site 2 was cast on 2 August 1994. Figure 5.4 shows the details of one median barrier unit.

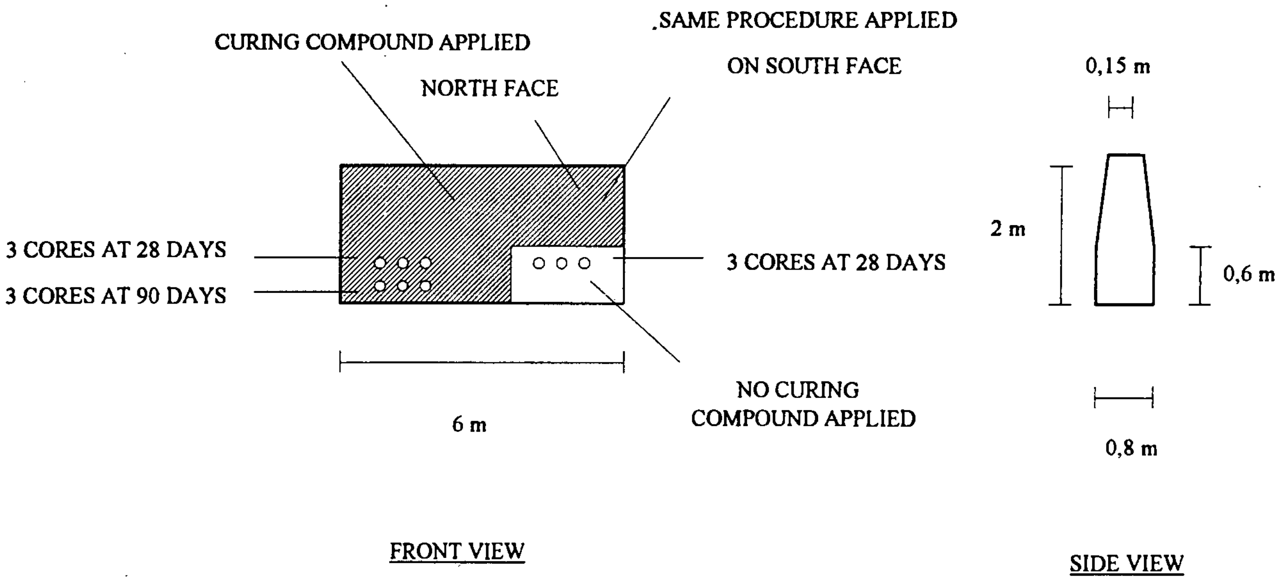


Figure 5.4 Details of median barrier unit, and areas where curing compound applied

a) Median Barrier Site 1

Ten 100 mm cubes were cast from the site mix. After 24 hours the cubes were removed from their moulds and taken back to the laboratory to be immersed in water at a constant temperature of 22 ± 1°C. Three cubes were used to determine the compressive strength of the concrete at each of 28 and 90 days. The four remaining cubes were used as control samples for the oxygen permeability and water sorptivity tests. A 68 mm diameter core was drilled from each cube perpendicular to one of the side faces. The method of coring and slicing of the cubes is shown in Figure 5.3. Two cubes were cored at each of 28 days and 90 days. All the samples were immediately transferred to an air-ventilated oven, controlled at a constant temperature of 50°C, in preparation for the oxygen permeability and water sorptivity tests.

A core drilling machine was used at 28 and 90 days to drill cores from the median barrier. A 68 mm diameter core was drilled perpendicular to the median barrier face to a depth of approximately 50 mm. The top 30 mm of each core was sliced off and used as a test sample. The remaining 20 mm of each core was discarded. Figure 5.5 indicates the method of coring and slicing of the median barrier to obtain the test sample. At 28 days three cores were drilled from a coated and an uncoated section on both the north and south sides of the barrier. At 90 days three cores were drilled from each of the cured north and south faces. The position of the cores drilled at each of 28 and 90 days is shown in Figure 5.4.

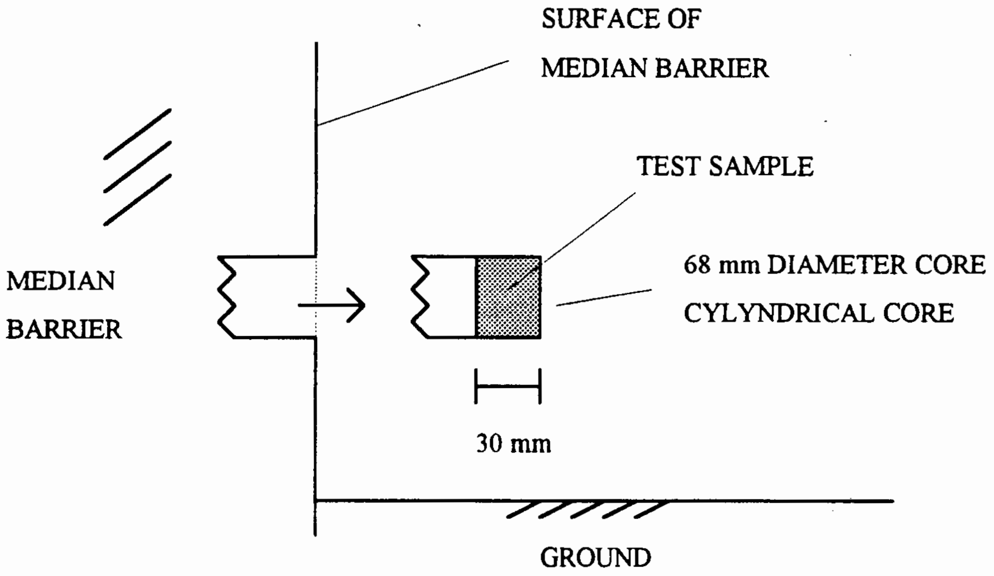


Figure 5.5 Method of coring and slicing median barrier to obtain test sample

b) Median Barrier Site 2

Three cores were drilled from a coated and an uncoated section on the south side of the barrier at 28 days. The north face of the barrier was alongside oncoming traffic at 28 days and no coring was possible. All the samples were immediately transferred to an air-ventilated oven, controlled at a constant temperature of 50°C, in preparation for the oxygen permeability and water sorptivity tests.

5.3 Site Findings

The six sites tested were the Albion Springs, Caltex Garage, Granger Bay, Rondebosch Golf Course and Median Barrier sites. The findings related to each construction site are given below.

5.3.1 Albion Springs Site

An office block was being constructed on the Albion Springs Site. The site is situated on Main Road, Newlands. The construction phase of the project started in March 1993 and was completed by December 1993. The contractors for this project were LTA Cape and the consulting engineers were Liebenberg and Stander. All the concrete for this project was mixed on site. The same curing system was applied to the block as was applied to a 340 x 220 mm rectangular beam on the second floor. The cover to the beam reinforcement was 40 mm. The reinforcement consisted of six Y16 high tensile steel bars, and M12 mild steel stirrups at a 250 mm spacing. The concrete mix design for the beam is listed in Table 5.1.

Table 5.1 The concrete mix design for the beam

Mix Details	All Quantities per m^3
Characteristic 28 day strength	25 MPa
BINDER: OPC	315 kg
SAND: Klipheuwel Sand	767 kg
STONE: Granite (19 mm)	1110 kg
Water content	185 litres
W/C	0,58

The curing system applied to the beam was to retain the side formwork for 18 hours and the soffit formwork for five days. The beam was cast at 15:00 on 9 August 1993. Once the beam was cast, plastic sheets were placed on the top surface of the beam to prevent the concrete drying too early. The side formwork was removed at 09:00 the following morning after having remained on the beam for 18 hours. The average environmental conditions for the first five days after exposure are listed in Table 5.9. The soffit formwork on the beam was removed after five days. Once all the formwork had been removed there was no further curing.

The project specifications stated that all curing should be carried out according to SABS 1200-G:1982 (5.2). SABS 1200-G:1982 maintains that after the formwork has been removed and as soon as it is practicable in the opinion of the engineer, all concrete should be protected from contamination and loss of moisture by one or more of the curing methods given. The curing methods in SABS 1200-G:1982 are listed in Appendix D. The specifications further state that when the ambient temperature is 5°C or higher, the curing period shall be at least five days for concrete made with portland cement.

SABS 0100-Part 2:1992 (5.3), listed in Appendix D, states that when the ambient temperature is 15°C and higher the curing period shall be at least seven days for concrete made with OPC. Note that SABS 1200-G:1982 and SABS 0100-Part 2:1992 use different curing periods and ambient temperatures to specify curing. This was probably due to different committees drawing up the specifications. On the Albion Spring Site none of the curing methods specified in SABS 1200-G:1982 or SABS 0100-Part 2:1992 were used.

The Site Agent was briefly interviewed and made the following comments:

> The Site Agent felt that no curing was necessary in winter as there was enough moisture in the air. The formwork for the beams was normally removed after a period of 18 hours. If the climate was cold the formwork was removed after 24 hours. In summer, however, curing was essential, and thus columns were wrapped in plastic sheets for seven days and floor slabs were flooded with water. Good curing practice

> prevents shrinkage cracking and corrosion of steel. Furthermore, to ensure that curing was performed properly on site it had to be priced in the Bill of Quantities.

There was no Resident Engineer assigned to the project. A Project Manager was however responsible for curing and made the following comments:

> According to the Project Manager the side forms on the beam should have been removed after two days while the soffit formwork should have been removed after seven days. Since winter is a wet period, there is sufficient moisture in the air to cure the structure. Good curing improves durability and prevents shrinkage cracking. Spray-on curing compounds were not used as they hinder the adhesion of the plaster. The Project Manager felt that it was up to the contractor to ensure that curing was correctly applied, else the contractor would be negligent. The project manager did not condemn any of the structural members cured on site.

5.3.2 Caltex Garage Site

A service station, consisting of a ground and first floor, was constructed on the Caltex Garage Site. On this site the curing system applied to a column on the first floor was applied to the block. The column was a 620 x 220 mm rectangular column with 30 mm of cover to the reinforcement. The reinforcement in each column consisted of eight Y16 reinforcement bars and fourteen R8 stirrups at a spacing of 200 mm. The project started in June 1993 and was completed by November 1993. The contractors for this project were Murray & Roberts (Cape) and the consulting civil and structural engineers were Campbell, Bernstein and Irving.

The curing system used on site was to wrap black plastic sheets around the column for four days. The column was cast at 14:00 on 12 August 1993 and the formwork was removed at

06:00 the following morning, 16 hours later. The average environmental conditions for the first five days after exposure are listed in Table 5.9. Once the formwork was removed, the column was immediately wrapped in black plastic sheets for a further four days.

The project specifications stated that all curing should be carried out according to SABS 1200-G:1982. The project specifications had a special clause for curing compounds. This clause specified that under no circumstances would a curing compound be approved for use on concrete surfaces that were to receive any finish. Since all the columns on the second floor were to receive a finish, no curing compound was used. All the concrete for the project was supplied by Ready Mix Materials, and was delivered in concrete ready-mix trucks. The concrete mix design for the column is listed in Table 5.2.

Table 5.2 The concrete mix design for the column

Mix Details	All Quantities per m^3
Characteristic 28 day strength	30,0 MPa
BINDER: OPC	350 kg
SAND: Dune Sand (RMM pit)	672 kg
SAND: Crusher Sand (RMM pit)	233 kg
STONE: Crushed Malmesbury Shale (19 mm)	940 kg
Water content	185 litres
Admixture: Water reducing admixture Fosroc P509	612 ml
W/C	0,53

The curing method used on this site to protect the concrete from contamination and loss of moisture was to cover the concrete with plastic sheeting firmly anchored at the edges. The curing method complies with the recommended curing methods in SABS 1200-G:1982 and SABS 0100 Part 2:1992. However, the curing period of four days does not comply with the curing period in SABS 1200-G:1982 and SABS 0100 Part 2:1992. SABS 1200-G:1982 states that when the ambient temperature is 5°C or higher, the curing period shall be at least five days for concrete made with portland cement. SABS 0100 Part 2:1992 states that the curing period shall be at least 7 days.

The Site Agent was briefly interviewed and made the following comments:

> The Site Agent said that the curing method chosen was one of the methods specified in SABS 1200-G:1982. This method was chosen because it was the most practical. The duration of curing should depend on the climatic conditions. Therefore, curing was applied for longer periods in summer than in winter. The Site Agent felt that good curing prevented surface cracking and aided hydration.

The Resident Engineer was briefly interviewed and made the following comments:

> Spray-on curing compounds were not allowed for this project because the columns would eventually be plastered and the curing compound would hinder adhesion. The same curing methods were specified throughout the year because the Cape Town area has unpredictable weather patterns. The project started in winter with no curing being applied to the first few columns cast. Small hairline cracks appeared in these columns. The cracks disappeared when the columns were wrapped in plastic sheets. Good curing is important to prevent shrinkage cracks and increase strength.

Furthermore, if curing was inadequate then the reinforcement would be prone to aggressive agents that would corrode the steel. The curing practice on civil construction sites was more stringent than on building sites. Daily inspections were the only way to check whether the curing method was being applied properly. Educating contractors is vital to ensuring a good curing practice. The specifications need to be more precise on which method to apply.

5.3.3 Granger Bay Site

The contractors for this project were Concrete Units and the consulting engineers were Watermeyer Prestedge Retief. Concrete Units were casting dolosse that would be placed out to sea to protect the Granger Bay shoreline. The project started in October 1993 and was completed by May 1994. The concrete was mixed on site and poured into moulds. The concrete for each dolos had to reach a minimum strength of 10 MPa after 24 hours. This was to enable a crane to lift each dolos to a nearby storage area. Approximately ten dolosse were cast per day. Each dolos, having a mass of 20 tons, and no reinforcement, remained in the storage area for six weeks before being placed out to sea.

A curing compound was used to cure each dolos. Two tests were performed on this site, namely Test 1 and Test 2. The block for Test 1 was cast at 14:00 on 1 November 1993. The same curing system was applied to the block as was applied to the dolos. The unformed section of the dolos was covered with damp hessian and left overnight. The dolos was stripped at 08:00 the following morning, 18 hours after casting. Approximately 20 minutes later a white spray-on curing compound was applied.

The block for Test 2 was cast at 15:00 on 3 May 1994. The dolos was stripped at 09:00 the following morning, 18 hours after casting. Approximately 15 minutes later a white spray-on curing compound was applied. The average environmental conditions for the first five days after exposure for each block are listed in Table 5.9. The application of the spray-on curing compound to the dolosse was generally consistent although on windy days the application became patchy and uneven. The final finish that was achieved on the formed surfaces was generally good. However, there were isolated areas of blow holes, caused by inadequate vibration. The unformed concrete surfaces had a rough finish.

The curing compound applied was Chemcure, a low viscosity wax emulsion manufactured by Chemrite. The formulation of Chemcure is supposed to ensure that the emulsion breaks down to form a non-penetrating continuous film on contact with a cementitious surface. This film prevents excessive water evaporation, thus permitting more efficient cement hydration. The curing compound changes from a white colour to a clear dry film. The curing compound was only visible on the concrete surface for the first few days after application.

The concrete mix design for Tests 1 and 2 are listed in Table 5.3. Test 1 used an OPC/LASRPC blend that was specified by the consultants. The OPC/LASRPC mix for Test 1 was used for the first month of the project. An LASRPC, used when aggregate may be sensitive to alkali attack, is not normally recommended for reinforced concrete in a marine environment. The consultants initially specified an OPC/LASRPC blend, however, one month after construction they said that an OPC mix would also be suitable. The contractors then used the OPC mix for the rest of the project.

Table 5.3 The concrete mix design for the dolos: Test 1 and Test 2

Mix Details	Quantities for Test 1	Quantities for Test 2
Target 28 day strength	40 MPa	40 MPa
BINDER: OPC	115 kg	175 kg
BINDER: LASRPC	60 kg	0 kg
SAND: Philipi Sand (Dune Sand)	380 kg	380 kg
STONE: Granite 37 mm	550 kg	550 kg
Water content	73 litres	73 litres
W/C	0,42	0,42

The project specifications stated that all curing shall be carried out according to SABS 1200-G:1982. The project specifications also stated that if a curing compound is used, the curing compound manufacturer must supply a certificate confirming compliance with ASTM C309 (5.4). ASTM C309 states that a liquid-membrane-forming compound should restrict the water loss to less than 550 grams per m^2 of surface in 72 hours. The test done on Chemcure found that the average mass loss for Chemcure was 487 grams per m^2. Thus Chemcure complied with the specification. However, the ASTM C309 test is a water retention test and does not appear to be a reliable measure of the effectiveness of curing compounds in practice. The project specifications also stated that the curing of horizontal and vertical surfaces would be paid for per square metre cured.

The Site Agent was briefly interviewed and made the following comments:

> The curing compound was chosen from the recommended techniques because of its ease of application. It was also found that the spray-on curing compound was faster than application by hand. Moreover, as each dolos was lifted in the air by crane the workers did not like to stand underneath the dolos and apply the curing compound by hand. The workers preferred the spray-on curing compound. The Site Agent said that the same curing technique was applied in summer and winter conditions.

> In addition, the Site Agent felt that curing was important to prevent shrinkage cracks in the concrete. If no curing compound was applied, small hairline cracks appeared on the surface of the dolos. Good curing also prevented moisture loss and gave the concrete surface a better finish. The Site Agent believed that curing was carried out adequately in practice. He suggested that the project specifications should have specified the exact amount of curing compound to be applied to each dolos.

The Resident Engineer for the site was briefly interviewed and made the following comments.

> Since the Granger Bay Site is exposed to strong winds throughout the year, curing with plastic sheets was impractical. The Resident Engineer felt that good curing increased the strength of the concrete and prevented shrinkage cracks. The curing method was applied correctly and there were no shrinkage cracks. The Resident Engineer maintained that to keep the curing application consistent the same worker should always apply the curing compound. This would ensure the curing compound was applied correctly and consistently. Regular inspections by the Resident Engineer were still necessary to check that the curing compound had been applied correctly.

5.3.4 Rondebosch Golf Course Site

The project aimed to widen the Vygekraal River from 30 to 60 metres through the Rondebosch Golf Course to where it joins the Black River. The increased run-off generated by the ongoing developments in the catchments of the Black and Vygekraal rivers required the widening of the two river channels. Part of the works involved the construction of a new 60 metre long bridge just downstream of the Black and Vygekraal rivers' confluence. The project started in October 1993 and was finished by May 1994. The contractors for this project were

CIVENG and the client was the Cape Town City Council. The concrete mix design for the abutment on the east bank of the new 60 metre bridge is listed in Table 5.4.

The abutment wall was cast at 11:00 on 7 February 1994. The formwork was stripped 48 hours later. The average environmental conditions for the first five days after exposure are presented in Table 5.9. All the concrete was supplied by Ready Mix Materials. No further curing took place once the formwork was removed. Wet sand was placed on the unformed sections of the abutment wall to prevent the concrete drying early. The finish on the abutment was good, with only a few visible blow holes.

Table 5.4 The concrete mix design for the abutment

Mix Details	All Quantities per m^3
Characteristic 28 day strength	30 MPa
BINDER: LASRPC	317 kg
SAND: Dune Sand	722 kg
STONE: Crushed Malmesbury Shale (19 mm)	1180 kg
Water content	177 litres
Admixture: Water reducing admixture Chem 800	555 ml
W/C	0,56

All curing was performed according to the Cape Town City Council's own specifications. These stated that all concrete, other than thin layers of concrete, should be continuously cured for at least seven days after placement. Curing methods should receive the prior written approval of the Resident Engineer, if different from the following:

(a) ponding water, minimum depth 10 mm.

(b) saturated sand, minimum thickness 50 mm.

(c) continuously sprayed heavy jute sacking or other absorbent material.

(d) continuous sprinkling of entire area (periodical hosing down will not be permitted).

(e) covering the previously saturated surfaces with approved plastic sheets or specifically designed concrete curing paper.

The curing method that was agreed upon by the Resident Engineer and the Site Agent was to throw water on the abutment at hourly intervals. However, the Resident Engineer did not enforce this and after the formwork was removed no further curing took place. Note that the project specifications did not allow for this. The comments below reveal that although the Site Agent and Resident Engineer had a reasonably good understanding of curing, they did very little to ensure proper curing was applied.

The Site Agent and Resident Engineer were briefly interviewed and made the following comments:

> The Site Agent said that proper curing ensures the concrete retains water for a longer period than if the concrete was exposed to the environment. Curing is important for early strength development and the prevention of shrinkage cracks. The formwork was normally retained for five days, unless the formwork was needed elsewhere on site. Should the latter be the case, then another curing method was applied for the remaining period.
>
> The Resident Engineer said that curing involves ensuring that the concrete is kept continually wet to allow the cement to hydrate. He felt that proper curing produced dense, strong concrete that was less likely to crack or spall in the long term. He also

felt that poor curing produced shrinkage cracks due to concrete drying too quickly. Evaporation of moisture from the surface of slabs, especially on windy days, often causes drying shrinkage cracks a few hours after the formwork is removed.

5.3.5 Median Barrier Site

A median barrier was constructed from Pinelands to Khayelitsha on the N2 National Road. Khayelitsha is 20 kilometres from the centre of Cape Town, in the direction of Somerset West. Although under construction, the N2 National Road is at present a dual two-lane freeway. The median barrier was tested at two different sites along the N2. Site 1 was located at Khayelitsha and Site 2 at Pinelands. The contractors for Median Barrier Site 1 were Clifford Harris and the consulting engineers were Hawkins, Hawkins & Osborne. Clifford Harris were also the contractors for Median Barrier Site 2, but the consulting engineers were BKS Incorporated. The concrete on both sites was supplied by Ready Mix Materials. The construction work started in November 1993 and was still in progress in January 1995.

a) Median Barrier Site 1

Two median barrier units were tested on Site 1, namely Test 1 and Test 2. The first median barrier unit (Test 1) was cast at 11:00 on 14 February 1994. The formwork was removed at 11:00 the following morning, 24 hours after casting. The curing compound, Concure WB, was applied six hours later. Concure WB is a low viscosity wax emulsion. When first applied to a fresh cementitious surface the emulsion is supposed to break down to form a continuous, non-penetrating white coating. The coating then dries to a continuous clear film providing a barrier to moisture loss. Thus more efficient cement hydration, improved durability and reduced shrinkage are ensured. The concrete mix design for Median Barrier Site 1 is listed in Table 5.5

Table 5.5 The concrete mix design for Median Barrier Site 1

Mix Details	All Quantities per m^3
Characteristic 28 day strength	30,0 MPa
BINDER: OPC Riebeek West	260 kg
BINDER: Fly Ash	46 kg
SAND: Klipheuwel Sand	883 kg
STONE: Malmesbury Hornfels (13,2 mm)	1020 kg
Water content	167 litres
Admixture: Water reducing admixture Fosroc P509	536 ml
W/C	0,54

The curing specifications for the project were as follows:

> " The curing of concrete with the exception of thin precast products shall be carried out by using an approved curing compound as follows: Where applicable formwork shall be removed as soon as practical according to Clause 6206 and all concrete, except for the surfaces of construction joints, shall be cured by applying a liquid type curing compound. The curing shall be applied to the concrete as soon as is practical after the formwork has been removed. The curing compound shall be an approved non-bituminous pigmented wax liquid compound conforming to the requirements of AASHTO Specification M148, Type 2. The compound shall be applied strictly according to the manufacturer's specification."

> " The pigment shall be one of such a nature that it will become inconspicuous within seven days after application. Samples of the curing compound offered are to be submitted to the Engineer for approval, and no curing compound is to be used until approved by the Engineer. The curing compound shall be applied over the area of concrete required by spraying. Spraying equipment shall be one of the fully atomizing type equipped with a tank agitator that provides for continual agitation of the curing compound during the time of application. The spray must be protected against the wind by means of a hood. "

The second median barrier unit (Test 2) was cast at 10:00 on 21 April 1994. The formwork was removed at 10:00 the following morning, 24 hours later. The curing compound, Chemcure WB, was applied two hours later. The same concrete mix design was used as for Test 1. The average environmental conditions for the first five days after exposure for each test are listed in Table 5.9.

The curing compound, Concure WB, was a liquid membrane-forming curing compound manufactured by Fosroc. The curing compound was tested according to ASTM C309 (5.4). ASTM C309 states that a liquid membrane-forming compound shall restrict the water loss to not more than 550 grams per m^2 of surface in 72 hours. The test done on Concure WB found that the average mass loss for Concure WB was 480 grams per m^2. Thus Concure WB complied with the specification. A few practical problems were noticed on this site. On one section of the barrier the curing compound had not been mixed properly and was very thin. Furthermore, due to the strong winds on site, the curing compound was applied by a roller rather than a spray.

b) Median Barrier Site 2

Only one median barrier unit was tested on Site 2. The median barrier tested was cast at 11:00 on 2 August 1994. The same curing compound for Site 1 was used on Site 2. The formwork was removed at 09:00 the following morning, 22 hours after casting. The curing compound was applied approximately two hours later. The concrete mix design for the Median Barrier Site 2 is listed in Table 5.6. The average environmental conditions for the first five days after exposure are listed in Table 5.9.

Table 5.6 The concrete mix design for Median Barrier Site 2

Mix Details	All Quantities per m^3
Characteristic 28 day strength	40 MPa
BINDER: LASRPC	373 kg
SAND: Klipheuwel Sand	727 kg
STONE: Malmesbury Shale 19 mm	1170 kg
Water content	162 litres
Admixture: Water reducing admixture Fosroc P509	652 ml
W/C	0,43

Hawkins, Hawkins & Osborne and BKS Incorporated were the consulting engineers for Sites 1 and 2 respectively and each firm specified a different mix. The durability implications of the two different mixes are important. Site 1 used an OPC/FA blend as the binder for the concrete. Site 2 used a LASRPC that is a basic portland cement type used when aggregates might be sensitive to alkali attack. For equal strengths an OPC/FA mix gives a lower permeability than a plain OPC mix. However, the higher cement content of the LASRPC mix should produce a more durable concrete with a slower rate of deterioration.

5.4 Discussion of Results

All the individual results of the oxygen permeability, water sorptivity and compressive strength tests are listed in Appendix C; Tables C.1 to C.17. The results in Appendix C show the standard deviations and coefficients of variation for the sites tested. A total of three individual values was excluded from all the durability index values. No individual values were excluded in the calculation of the compressive strength test results.

5.4.1 Curing practice and specifications

The curing methods applied and specified on the sites tested are summarised in Table 5.7. The Granger Bay and Median Barrier sites applied curing compounds and were the only sites to comply with SABS 1200-G:1982 and SABS 0100-Part 2:1992. The Albion Springs and Rondebosch Golf Course sites did not apply any curing after the formwork was removed. The Caltex Garage site only applied four days of curing after the formwork was removed.

Note that although the curing compound applied on the Granger Bay and Median Barrier sites complied with the specifications there is no guarantee that the curing compound was applied correctly. This was evident on Median Barrier Site 1, where the curing compound was not mixed correctly and on the Granger Bay Site, where the application of the curing compound was difficult in windy conditions. Furthermore, the curing system applied on the median barrier sites complied with the specifications but was found to be ineffective after testing the covercrete, as will be shown in section 5.4.6. Thus the investigation of sites revealed that the specifications are not always adhered to, and even where they are, the effectiveness of the curing method is questionable.

Table 5.7 Summary of curing method applied on each site

Construction Site	Curing method applied	Project specifications
Albion Springs	Side formwork removed after 18 hours No further curing	SABS 1200-G:1982 suggests 5 days of curing. SABS 0100-Part 2:1992 suggests 7 days of curing
Caltex Garage	Formwork removed after 16 hours Plastic sheeting for next 4 days	SABS 1200-G:1982 suggests 5 days of curing. SABS 0100-Part 2:1992 suggests 7 days of curing
Granger Bay	Formwork removed after 18 hours Spray-on curing compound Chemcure applied	The curing compound conformed to ASTM C309
Rondebosch Golf Course	Formwork removed after 48 hours No further curing	SABS 1200-G:1982 suggests 5 days of curing. SABS 0100-Part 2:1992 suggests 7 days of curing
Median Barrier Site 1 and Site 2	Formwork removed after 22 - 24 hours Curing compound Concure WB applied by roller	The curing compound conformed to ASTM C309

5.4.2 Compressive strength at 28 and 90 days

The average compressive strength test results for the sites tested at 28 and 90 days are listed in Table 5.8. Each value listed in Table 5.8 represents the average of three individual cube compression tests. The individual results of all the compressive strength tests are presented in Appendix C, Table C17. The compressive strength test results reveal the gain in strength of the site mixes tested. The rates of strength development vary for different cements, and for mixes containing different proportions of the same cement (5.5). The compressive strengths increased with age for all the sites tested.

Table 5.8 Average compressive strength results at 28 and 90 days

Construction Site	Characteristic Strength (MPa)	Binder Type	W/C Ratio	Actual Strength at 28 days (MPa)	Actual Strength at 90 days (MPa)
Albion Springs	25	OPC	0,58	46,6	52,7
Caltex Garage	30	OPC	0,53	49,9	57,7
Granger Bay: Test 1	40*	OPC / LASRPC	0,42	56,6	66,1
Granger Bay: Test 2	40*	OPC	0,42**	40,8	43,7
Rondebosch Golf Course	30	LASRPC	0,56	36,9	46,1
Med. Barrier Site 1: Test 1	30	OPC / Fly Ash	0,54	38,5	57,0
Med. Barrier Site 1: Test 2	30	OPC / Fly Ash	0,54	40,1	54,9
Med. Barrier Site 2	40	LASRPC	0,43	59,7	***

* Target strength

** The W/C ratio given by Site Agent does not agree with actual strength. W/C ratio should be about 0,54 based on actual strength.

*** Result not taken

The concrete on the Granger Bay site was mixed in a batch plant. The cement scale on this site was also reading incorrectly. The results listed in Table 5.8 revealed that for the same W/C ratio the Granger Bay Test 1 28 day strength was 56,6 MPa while Test 2 was 40,8 MPa. The initial 28 day strength of 56 MPa was high compared to the target strength of 40 MPa. However, towards the end of the contract the contractors had reduced the cement content and were achieving 28 day strengths of about 40 MPa. Thus, the 0,42 W/C ratio given for Test 2 was incorrect and should have been about 0,54 based on actual strength. The effects of actual strength on the durability index values for the site and laboratory tests are discussed in more detail in chapter 6.

5.4.3 Average evaporation rate

The average evaporation rate on each site for the first five days of exposure is listed in Table 5.9. The average relative humidity and temperature were calculated from the mean daily relative humidity and temperature readings obtained from the Cape Town Airport weather bureau (5.6). The average evaporation rate was calculated from Figure 2.8 in chapter 2.

The average evaporation rate is intended only as a guide to compare the combined effect of relative humidity and temperature on the durability index values of different sites. Moisture in the gel and capillary pores permeates through the concrete by diffusion. The rate at which moisture is lost from the covercrete is slow in comparison to the rate of evaporation of a free film of water. Wind is expected to affect only the rate of evaporation of a free film of water and not the rate of moisture permeation through the concrete. Consequently, only relative humidity and temperature were used to calculate the average evaporation rate.

The Median Barrier Site 1 Test 1, Granger Bay Test 1 and Rondebosch Golf Course sites experienced the highest average evaporation rates. These three sites were all tested in typical summer climatic conditions. The effect of the average evaporation rate on the durability index values for the site and laboratory tests is discussed in more detail in chapter 6.

Table 5.9 Average evaporation rate for the first five days of exposure (5.6)

Construction Site	Average Relative Humidity (%)	Average Temperature (°C)	Average Evaporation Rate ($g/m^2/h$)
Albion Springs	80	12,7	18,4
Caltex Garage	73	14,9	26,3
Granger Bay: Test 1	63	18,8	50,0
Granger Bay: Test 2	83	15,4	15,8
Rondebosch Golf Course	69	21,0	60,5
Median Barrier Site 1: Test 1	66	16,1	47,3
Median Barrier Site 1: Test 2	75	19,3	40,5
Median Barrier Site 2	78	12,7	21,1

5.4.4 Oxygen permeability index and water sorptivity at 28 and 90 days

The oxygen permeability index and water sorptivity results are the average values calculated from three samples. The 28 and 90 day oxygen permeability index and water sorptivity results for all the sites tested are illustrated graphically in Figures 5.6 and 5.7.

Legend

Abbreviation	Description
AS	Albion Springs Site
CG	Caltex Garage Site
GBT1	Granger Bay Test 1 Site
GBT2	Granger Bay Test 1 Site
RGC	Rondebosch Golf Course Site
MBT1	Median Barrier Site 1 Test 1
MBT2	Median Barrier Site 1 Test 2
MBS2	Median Barrier Site 2

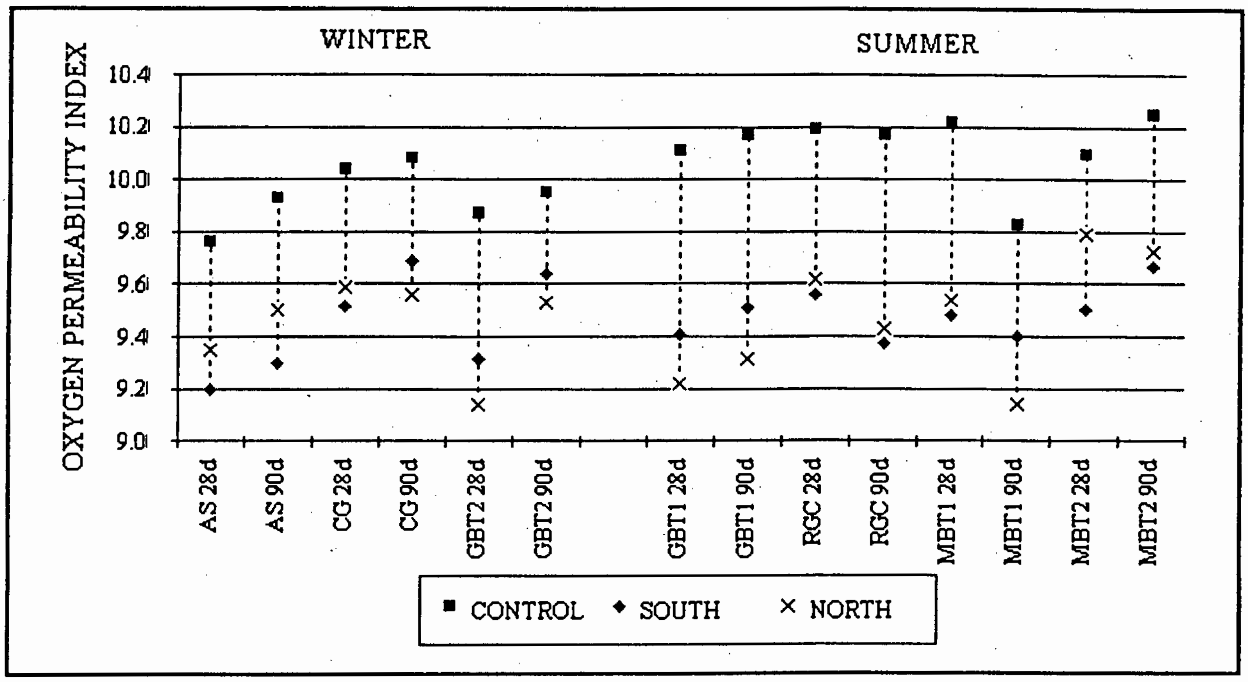


Figure 5.6 Oxygen permeability index results for all sites tested at 28 and 90 days

The permeability and sorptivity of the exposed samples on the summer sites were in some cases higher than the winter sites although this was not always the case. The environmental conditions experienced for the first five days after exposure are listed in Table 5.9. Table 5.9 indicates that higher temperatures and lower relative humidities were experienced by the summer sites. Temperature and relative humidity interact together to influence the hydration reaction and the rate of drying from the concrete surface. Therefore, proper curing is important, especially in summer, to prevent the covercrete drying early. The effect of the environmental conditions on the covercrete will be discussed in more detail in chapter 6.

Figure 5.6 illustrates that age improved the impermeability on the sites tested. The same trend was found for the laboratory Set 1 results. The only exception was Median Barrier Site 1 (90 day) where the impermeability decreased with age. The reason for the counter trend on Median Barrier Site 1 is not known. The permeability index control values for the summer sites were higher than the winter sites with the exception of Median Barrier Site 1 (90 day). This is probably due to the effects of higher temperatures on the early stages of cement hydration in summer.

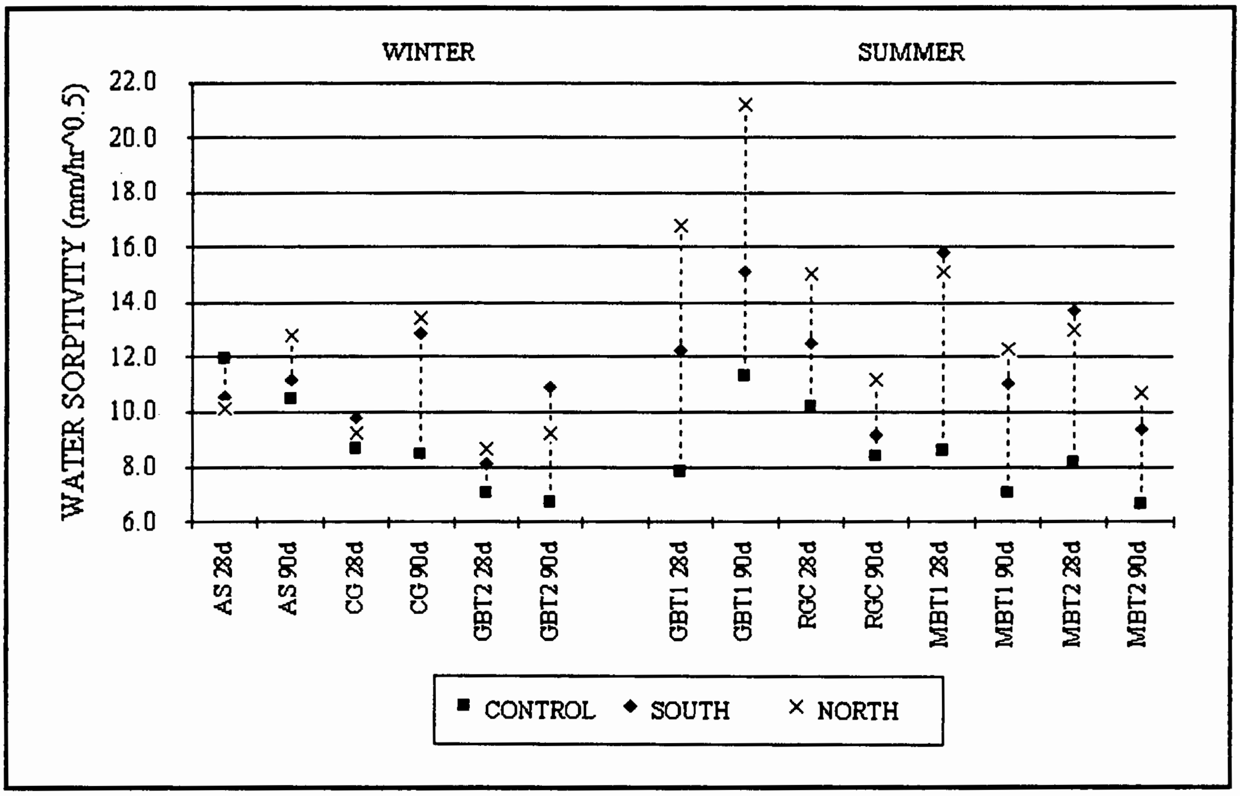


Figure 5.7 Water sorptivity results for all sites tested at 28 and 90 days

The sorptivity results of the Albion Springs, Caltex Garage and Granger Bay sites showed that the sorptivity of the exposed samples increased with age, while the sorptivity of the control samples decreased with age. The same trend was also found for the laboratory Set 1 results. This phenomenon is difficult to explain since the permeability index values for the same samples decreased with age. The sorptivity results may have been affected by surface weathering effects, e.g., carbonation. In addition, sorptivity may also decrease as the covercrete draws water from the interior of the concrete, i.e., self curing takes place. Once self curing has finished, the covercrete dries quickly and hydration ceases, resulting in a porous surface layer. However, these sites may also have suffered from poor and inconsistent experimental techniques.

Some of the sorptivity results were inhibited by poor and inconsistent experimental techniques in the sample preparation that were due to inexperience in the earlier phases of the project. The saturated weights of the Albion Springs, Caltex Garage and Granger Bay site samples were obtained by saturating the samples in water for 24 hours. However, the samples for the Rondebosch Golf Course and Median Barrier sites were initially saturated in water for 24 hours and then vacuum saturated for a further two hours.

Two samples were used to calculate the average sorptivity control values on the Albion Springs, Caltex Garage and Granger Bay sites. At the time the tests were performed the problem of the variability of sorptivity measurements was not fully appreciated. As a result only two samples were allowed for the control samples, as shown in Appendix C. However, as soon as this problem of variability was recognised, three control samples were used for the remaining sites.

The effect of curing compounds may also have influenced the sorptivity results on the Granger Bay and Median Barrier sites. The surfaces of the test samples were brushed with a wire brush to remove the curing compound. However, this may not have been sufficient to remove all the compound. The top 3 mm of each concrete sample should be sliced off to ensure that the curing compound does not influence the permeability or sorptivity values.

Except for Granger Bay Test 1 (90 day), the sorptivity of the control samples decreased with age as they were completely submerged in water so that no drying of the surface layer was possible. The reason for the increase in sorptivity with age for the Granger Bay Test 1 (90 day) control value is not known. The control and exposed samples of the Rondebosch Golf Course and Median Barrier sites decreased with age. The results appear more realistic because the permeability values for the same sites decreased with age. Furthermore, the Rondebosch Golf

Course and Median barrier sites were the last sites tested and experimental techniques had improved.

The exposed sorptivity samples varied with age. This may have been due to poor and inconsistent experimental techniques. However, the variation is unusual and warrants further investigation. Further analysis of the permeability and sorptivity results will concentrate primarily on the 28 day durability index results in chapter 6. The correlation between the average evaporation rate, actual strength and durability index values will be analysed.

5.4.5 North-south orientation

The oxygen permeability and water sorptivity results for the sites tested are presented in Figures 5.8 and 5.9. The 28 day permeability values on the south face were lower than on the north face on two of the seven sites tested. However, by 90 days the permeability on the south face was lower on five of the seven sites tested. The same trend was observed for the sorptivity tests. The 28 day sorptivity values on the south face were lower than on the north face on three of the seven sites tested. However, by 90 days the sorptivity on the south face was lower on six of the seven sites tested.

Figures 5.8 and 5.9 revealed that the permeability and sorptivity of the south face tended to improve with age, while the north face may not have improved with age. This implies that any surface layer deterioration from weathering on a structure, will occur more readily on the north face than the south face. The north face is directly exposed to the sun that dries the surface layer and slows down the rate of hydration. Since the south face is more shaded, it will have a higher rate of hydration than the north face. This important point, suggests that concrete directly exposed to the sun should get additional protection to ensure adequate durability. The additional protection may cover various approaches, such as curing methods and coatings.

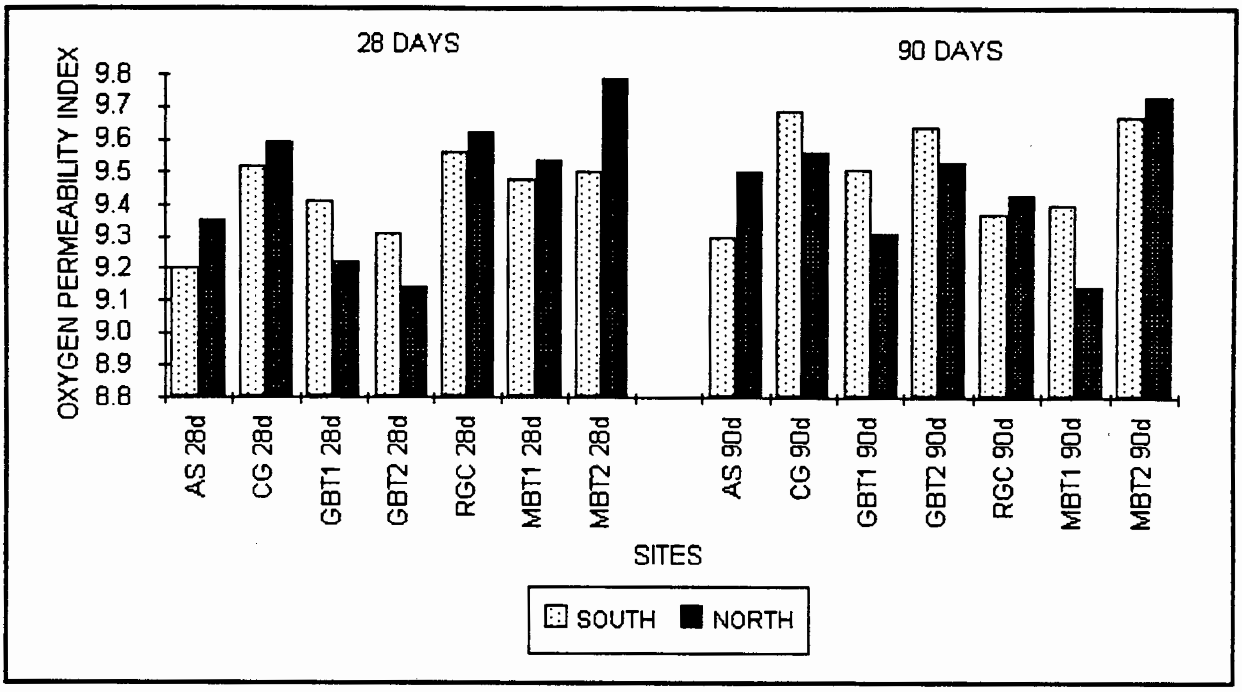


Figure 5.8 Oxygen permeability index results for north-south orientation

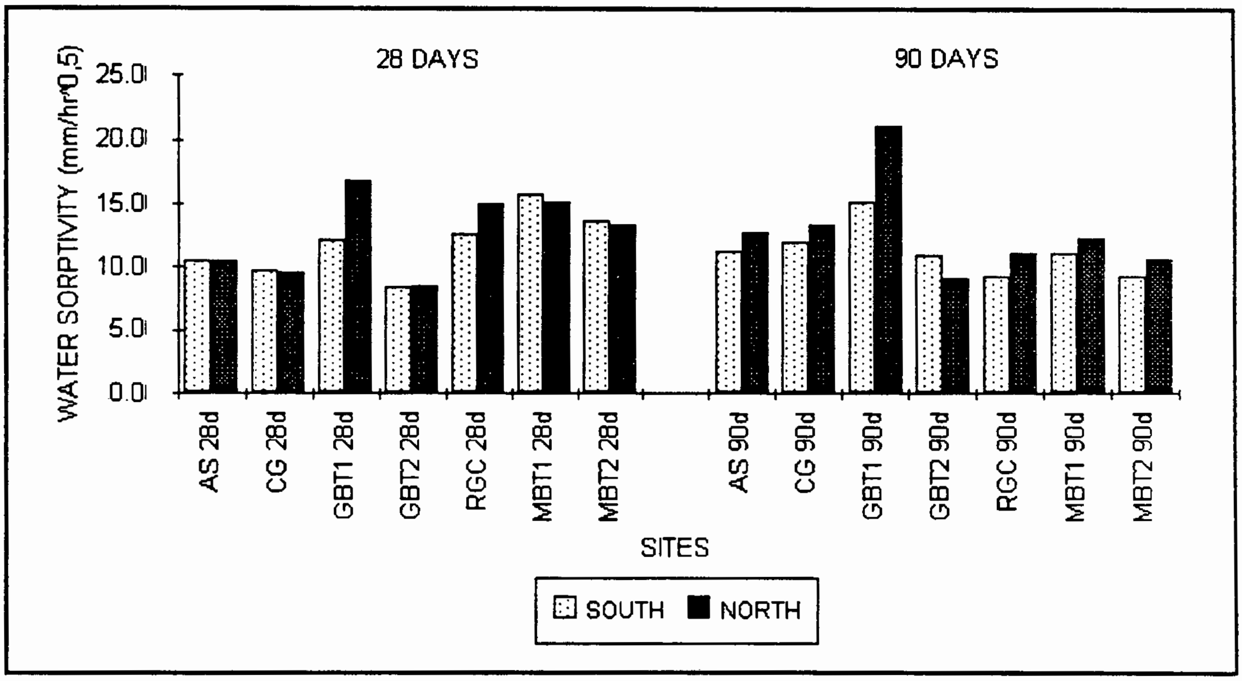


Figure 5.9 Water sorptivity results for north-south orientation

The 28 day permeability index and sorptivity results for winter and summer are shown in Figures 5.10 and 5.11. The permeability results indicated that there was little difference between the winter and summer results for the north-south orientation. However, sorptivity was less affected by the north-south orientation in winter than in summer. The north and south values were similar in winter while in summer there were large differences between the two. Permeability is affected by direct sun in winter and summer, while sorptivity is affected only in summer. Permeability is thus more sensitive to the north-south orientation than sorptivity. These results show the importance of proper curing and of protecting the concrete from direct sun, especially in summer.

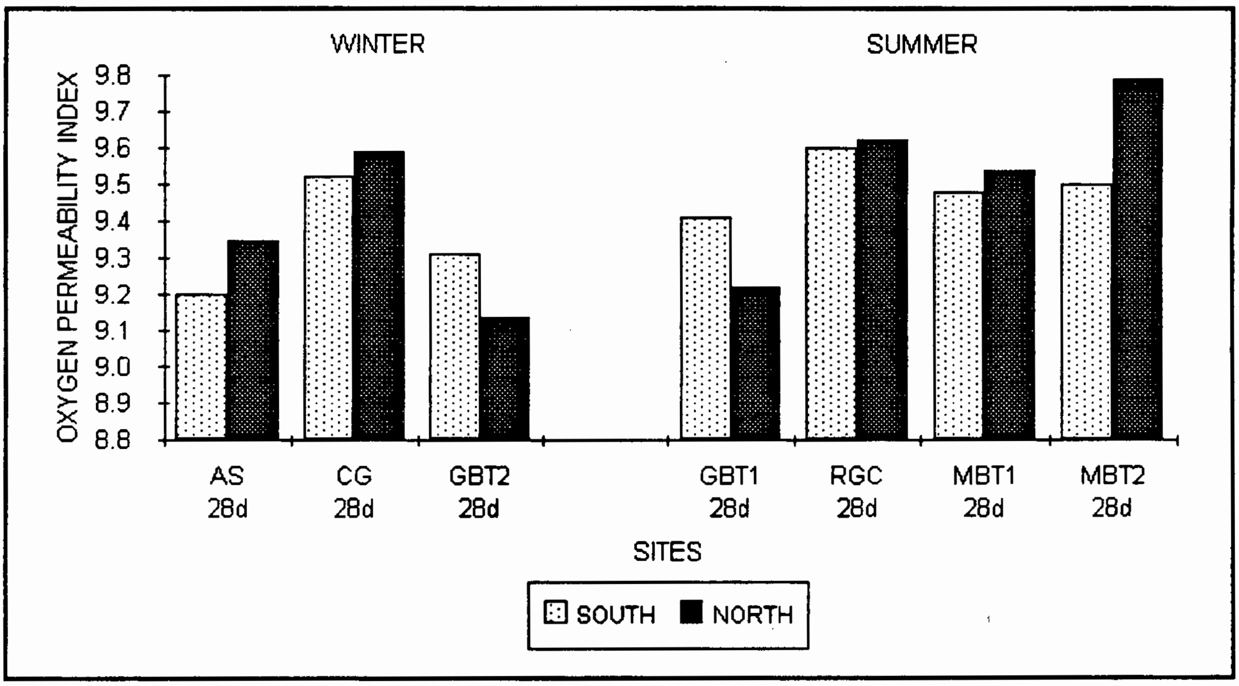


Figure 5.10 Oxygen permeability index results for winter and summer (28 days)

The differences between the north and south values are large on the Granger Bay Test 1 site where it is significant that the north face is poorer. The differences between the north and south values are much smaller on the Median Barrier sites. This was probably due to the drying effect of sun on the north face balanced by the drying effect of south-easterly winds on the south face. The 90 day permeability and sorptivity results are sometimes poorer than the 28 day results. The same trend was found in the laboratory Set 1 tests and was discussed in section 5.4.4.

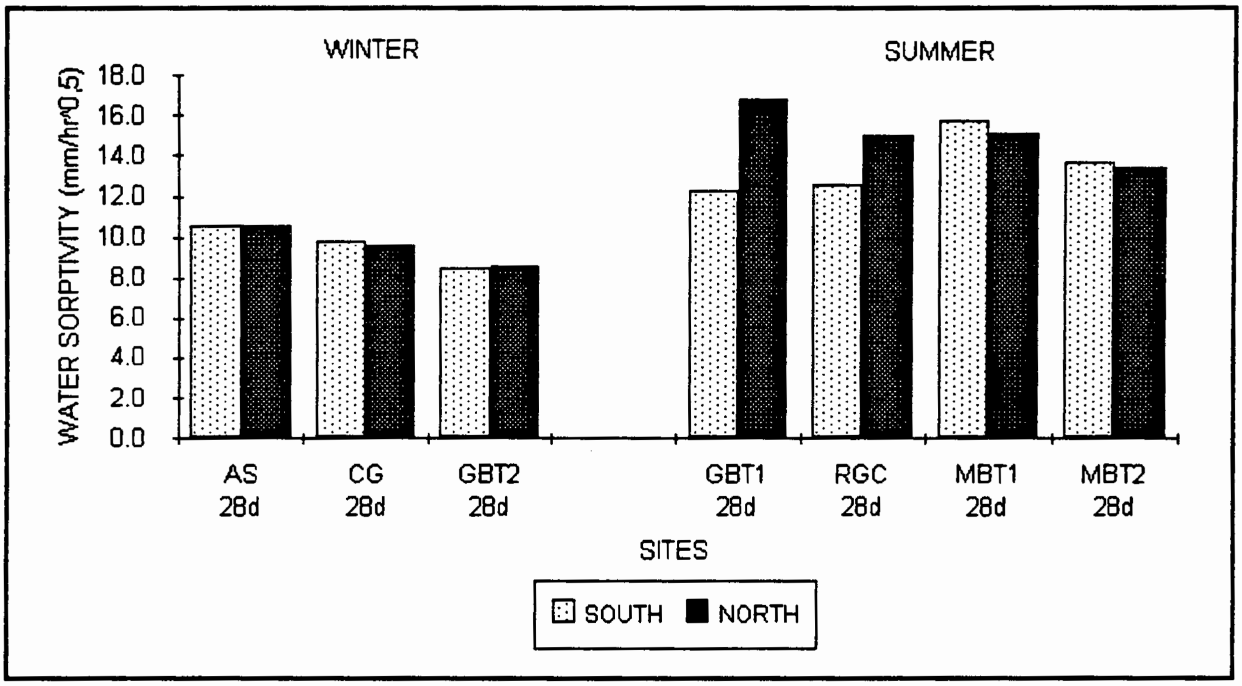


Figure 5.11 Water sorptivity results for winter and summer (28 days)

5.4.6 The effectiveness of the median barrier curing system

The effectiveness of the curing system applied at Median Barrier Sites 1 and 2 was assessed by testing the permeability and sorptivity of a coated and an uncoated section of the median barrier unit. The oxygen permeability and water sorptivity results are illustrated graphically in Figures 5.12 and 5.13.

Median Barrier Site 1 Test 1 and Test 2 were cast at the beginning of February and the end of April respectively. Median Barrier Site 2 was cast at the beginning of August. The results for Median Barrier Site 1 Test 1 showed that the coated section performed only slightly better than the uncoated section. The results for Median Barrier Site 1 Test 2 revealed that the uncoated section performed better than the coated section. The uncoated section had a lower sorptivity value although the permeability values were similar.

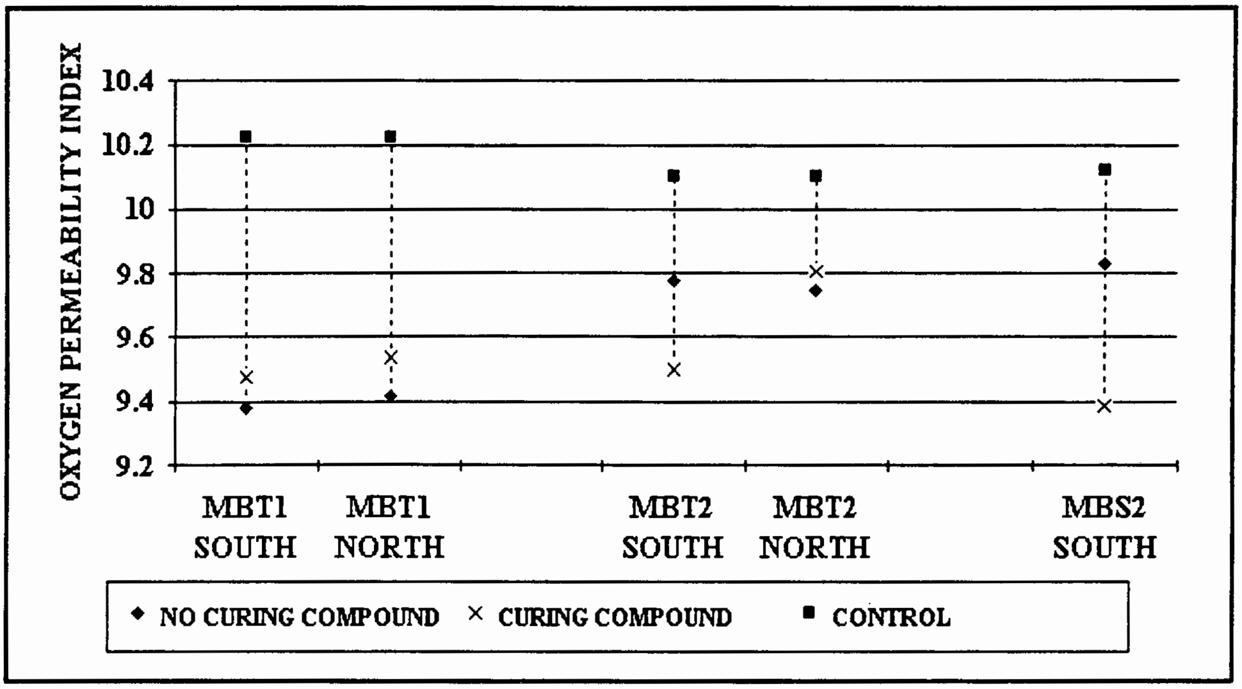


Figure 5.12 Oxygen permeability index results for the median barrier (28 days)

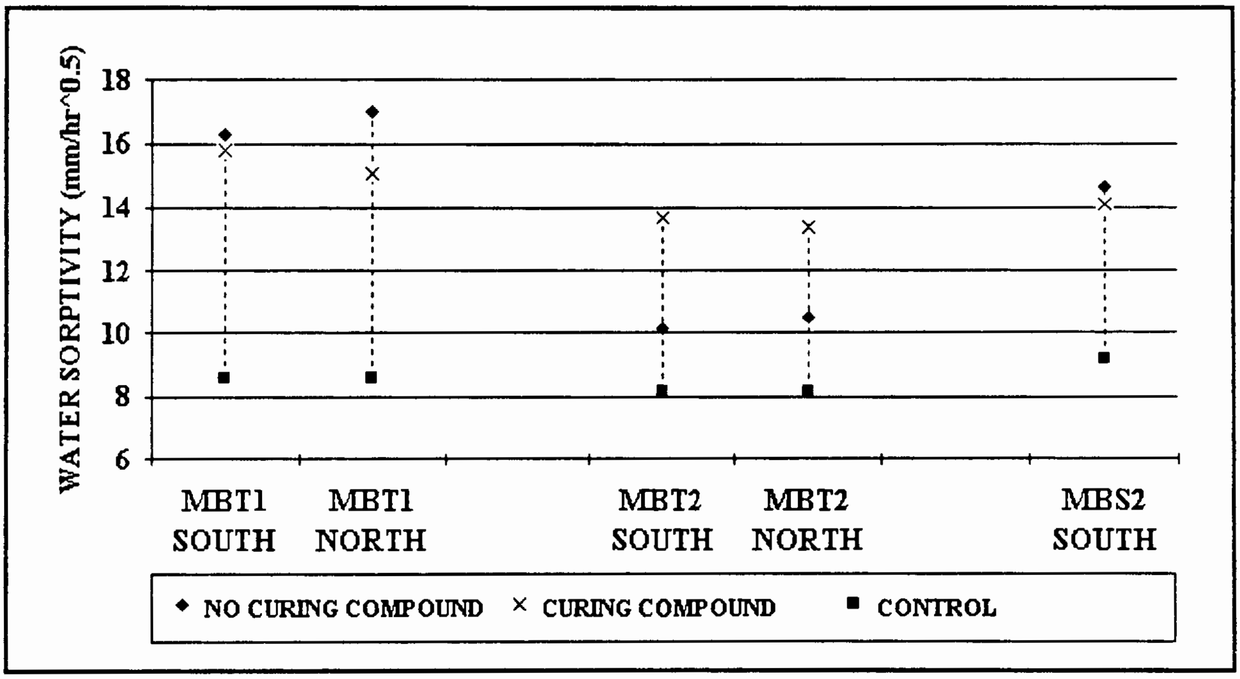


Figure 5.13 Water sorptivity results for the median barrier (28 days)

The results for Median Barrier Site 2 showed that the uncoated section performed better than the coated section. The uncoated section produced a lower permeability index value although the sorptivity values were similar. Thus concrete treated with curing compound performed only slightly better than uncoated concrete in February. The compound proved ineffective in both April and August. Table 5.9 showed that Median Barrier Test 1 had the highest average evaporation rate, followed by Median Barrier Test 2 and Site 2. Thus it seems that the lower average evaporation rate for Median Barrier Test 2 and Median Barrier Site 2 may have helped to cure the uncoated sections of the concrete.

The poor performance of the curing compound may also be due its late application. After the formwork had been stripped, the curing compound was applied approximately six hours later at Median Barrier Site 1 Test 1 and two hours later at Median Barrier Site 1 Test 2 and Site 2. Other possible reasons for the poor performance of the curing compound may be that the curing compound was diluted, incorrectly mixed, or simply ineffective.

The following chapter will discuss the effects of average evaporation rate and actual strength on the durability index values for the laboratory and site results.

5.5 Conclusions

From the results obtained and the foregoing discussion, it was concluded that:

1. Generally, the sites tested showed that curing on site was not performed according to the project or national specifications. The only sites that complied with the project and national specifications used curing compounds. The remaining sites applied either no curing method after the formwork was removed or the curing method was not applied for the specified time.

2. Some of the results of the exposed sorptivity samples increased with age while others decreased with age. This is unusual and should be investigated further. The control sorptivity sample results decreased with age. The exposed and control permeability samples decreased with age.

3. The north-south orientation revealed that the durability of the south face would improve with age while the north face might not. This implies that if there is to be any deterioration on a structure with age, it would most likely occur on the north face.

4. Permeability is affected by the north-south orientation in winter and summer, while sorptivity is only affected in summer. Permeability thus appears to be more sensitive to the north-south orientation than sorptivity.

5. The results of some of the sorptivity and permeability tests were spoiled by poor and inconsistent experimental techniques. Therefore, good experimental techniques are extremely important to ensure meaningful results.

6. The curing system tested on the median barrier was ineffective in winter and summer environmental conditions. This may be due to either the late or incorrect application of the curing compound, or an ineffective curing compound. The effectiveness of curing compounds as a curing method needs to be reviewed critically.

7. The variability of the oxygen permeability index and water sorptivity results of concrete must be investigated further. It appears that, for the test conditions used in this chapter, the number of test samples should be increased. Four test samples may give more consistent results.

5.6. References

5.1 South African Bureau of Standards, Compressive Strength of Concrete, SABS 863, Nov. 1986.

5.2 South African Bureau of Standards, Standard Specification for Civil Engineering Construction, SABS 1200-G:1982.

5.3 South African Bureau of Standards, Materials and Execution of Work, SABS 0100-Part 2:1992.

5.4 American Society for Testing Materials, Standard Test Method for Water Retention by Concrete Curing Materials, ASTM C309-1989.

5.5* Woods, H. Rational development of cement specifications, Journal Portland Cement, Association Research and Development Laboratories, vol. 1, no. 1, Jan. 1959, pp. 4-11.

5.6 Cape Town Airport Weather Bureau, Surface temperature, humidity and wind readings, Station DF Malan, Jul. 1993 to Dec. 1994.

* Copies of these works were not obtained. Details presented in this project report were those cited in other references. These references are documented with the work that is presented.

CHAPTER 6

SITE AND LABORATORY RESULTS

6.1 Introduction

This chapter discusses in more detail some of the laboratory and site results presented in chapters 4 and 5. Consideration is given to the relationship between the measured durability index values and the parameters of actual strength and average evaporation rate. The nature and implications of the observed trends in the relationships are discussed. All the analyses and comparisons in this chapter refer to the 28 day oxygen permeability index and water sorptivity results, i.e., the "true" index results[1].

The durability tests performed may include oxygen permeability, water sorptivity and chloride diffusion tests. Durability index tests may serve as a means to control concrete quality during construction. The surface layer of concrete can be specified with durability index limits, and payment made on the achievement of such values. Should the desired durability limits not be achieved, other measures such as a suitable coating or sealant can be applied to ensure cover quality. A correlation is still needed between the durability index values at 28 days and the accelerated or long-term durability performance of concrete. Durability limits can be set in the specifications once these correlations are established.

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[1] The true index results refer to durability index tests performed at 28 days after casting and this is standard used at the University of Cape Town and the University of the Witwatersrand.

6.2 Effect of Strength on the Durability Index Values

6.2.1 Oxygen permeability

The oxygen permeability index against 28 day actual strength results are presented in Figure 6.1. These are the results of the laboratory Set 2 and site tests. The laboratory results shown are the control and 60% relative humidity samples for Set 2. The best fit lines, through the site control and site exposed values, are presented in Figure 6.1. The dotted lines connect the 20, 40 and 60 MPa strength results for Set 2.

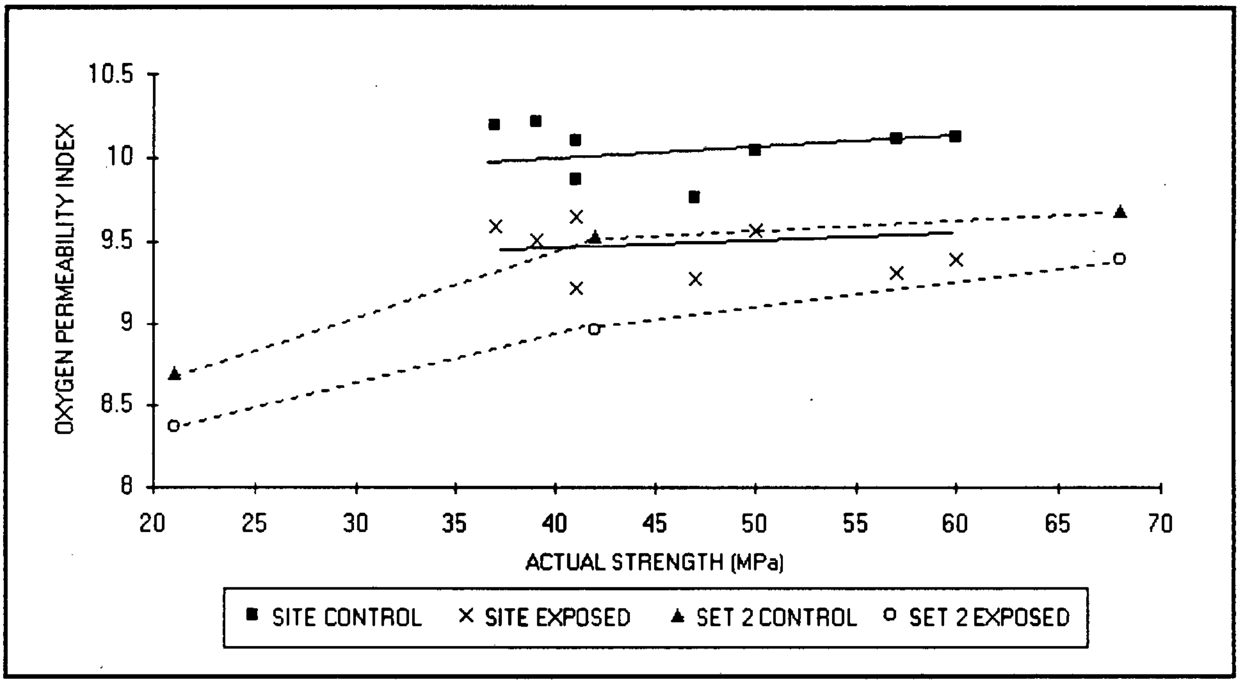

Figure 6.1 Oxygen permeability index versus actual strength: Site and Set 2 (28 day values)

The best fit lines depicted in Figure 6.1 indicate possible limits for future specifications. The procedure involves testing concrete on site at 28 days to obtain a permeability index value. If this value falls within the specified limits, then the permeability of the concrete is sufficient to ensure a durable cover. However, should it fall outside the limits, then the covercrete is too permeable to provide sufficient protection to the underlying steel. Many more tests must be conducted to establish acceptable permeability index limits.

Figure 6.1 gives typical permeability index values that may be expected on site. The exposed laboratory samples were the most permeable, while the site control samples proved the least permeable. The site control and site exposed values revealed the oxygen permeability index values to be virtually independent of strength. This was due to the high strength of the site concrete, i.e., above 40 MPa. Strength thus appears to be a poor predictor of the surface transport properties, particularly for site concrete.

The Set 2 control and exposed samples reveal that increasing the strength, from 20 to 40 MPa, has a large effect on reducing the surface permeability of concrete. However, the effect was less marked above 40 MPa, particularly for the control samples. The site permeability index values were higher than the laboratory values because the actual strength of concrete was plotted, and not the W/C ratio. For example, the Rondebosch Golf Course site obtained a 36,9 MPa strength at 28 days while for the same W/C ratio Set 2 achieved 42,2 MPa.

The oxygen permeability index plotted against actual strength test results for the laboratory Sets 2 and 3 are presented in Figure 6.2. Sets 2 and 3 produced similar permeability index values when compared to the site values. Set 3 shows the oxygen permeability index values of three curing methods. The results of this Set clearly illustrate the large difference in permeability index values between the retained formwork and the curing compound methods. This difference, similar to that between the Set 2 60% and 90% relative humidity results, depicts the large improvement in permeability that can be achieved by choosing an effective curing method.

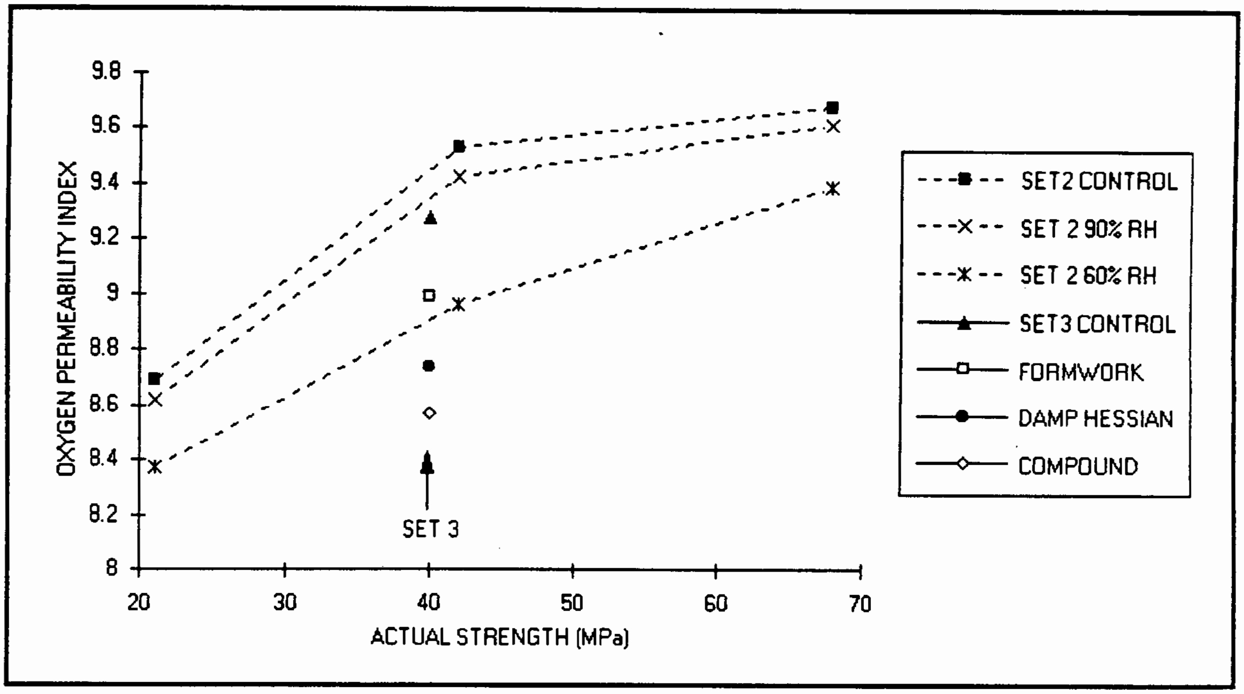

Figure 6.2 Oxygen permeability index versus actual strength: Set 2 and Set 3 (28 day values)

6.2.2 Water sorptivity

The water sorptivity plotted against 28 day actual strength test results are presented in Figure 6.3. These are the results of the laboratory Set 2 and site tests; the former being the control and 60% relative humidity samples. The best fit lines through the site control and site exposed values presented in Figure 6.3 indicate possible limits for these values in future specifications. The dotted lines connect the 20, 40 and 60 MPa strength results for Set 2.

The test procedure involves testing concrete on site at 28 days to obtain a water sorptivity value. If this value falls within the specified limits, then the sorptivity of the concrete is sufficient to ensure a durable cover. However, if the value falls outside the specified limits, then the sorptivity of the covercrete is too high and will not provide sufficient protection to the underlying steel. Many more tests must be conducted to establish acceptable sorptivity limits.

Figure 6.3 gives typical sorptivity values to be expected on site. The exposed laboratory samples had the highest sorptivity values, while the site controls had the lowest. The site control and site exposed results showed that the water sorptivity values were virtually independent of strength. This was due to the high strength of the site concrete, i.e., above 40 MPa. Strength is thus a poor indicator of the surface transport properties, particularly for site concrete.

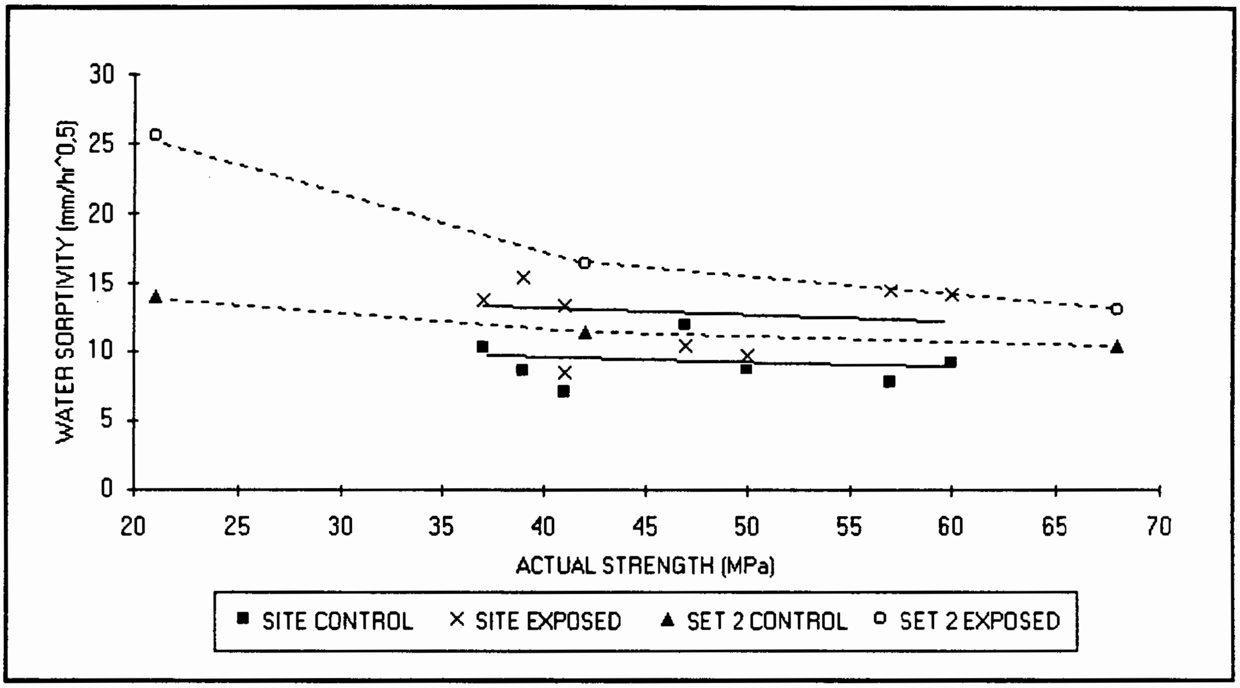

Figure 6.3 Water sorptivity versus actual strength: Site and Set 2 (28 days values)

The Set 2 control and exposed values reveal that an increasing strength, from 20 to 40 MPa, has a large effect on decreasing concrete sorptivity. However, the effect was less marked above 40 MPa, particularly for the control samples. The sorptivity values of the site exposed samples were higher than the sorptivity values of the laboratory controls, as with the permeability results. In addition, the site sorptivity values were lower than the laboratory sorptivity values because the actual strength of concrete was plotted, and not the W/C ratio.

The water sorptivity against actual strength test results for laboratory Sets 2 and 3 are presented in Figure 6.4. These produced similar sorptivity values when compared to the site values. The water sorptivity values of three curing methods are shown from Set 3. The results of Set 3 clearly illustrate the large difference in sorptivity values between the retained formwork and periodiic wetting methods. This difference shows the improvement in sorptivity that can be achieved by choosing an effective curing method.

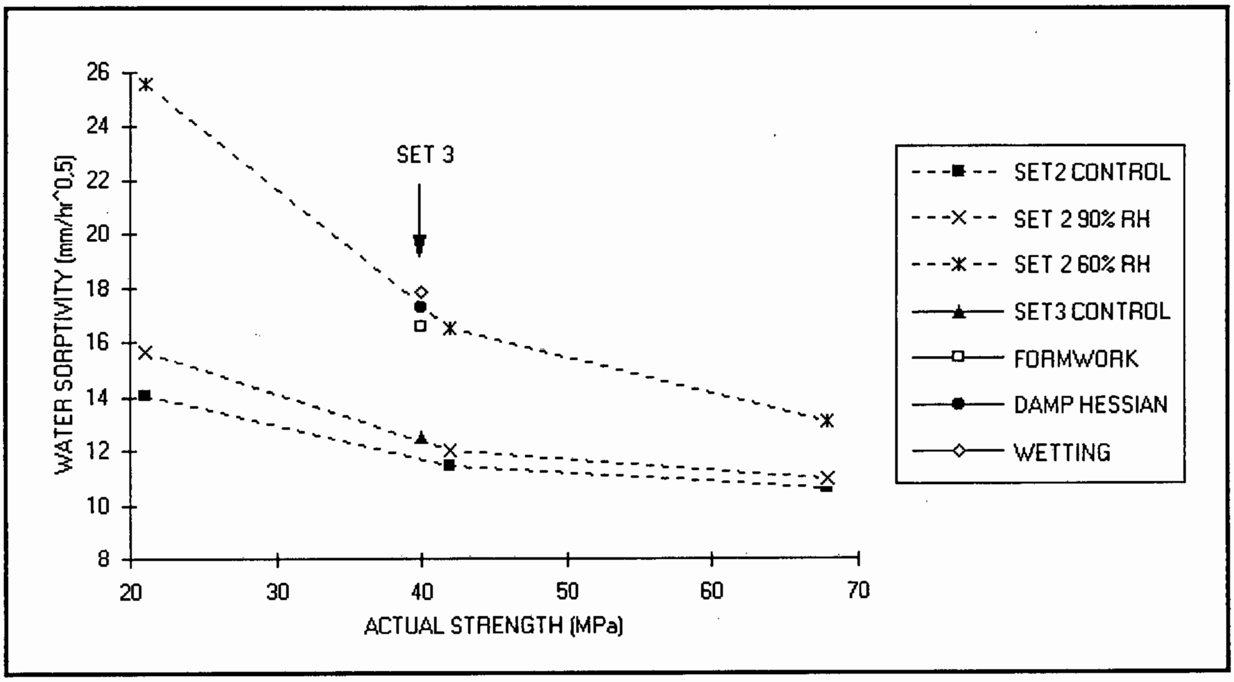

Figure 6.4 Water sorptivity versus actual strength: Set 2 and Set 3 (28 days values)

6.3 Effect of Average Evaporation Rate on Durability Index Values

The average evaporation rate was calculated from Figure 2.8 in chapter 2. The environmental conditions for the first five days after stripping were used to calculate the average evaporation rate.

6.3.1 Oxygen permeability

Figure 6.5 presents the oxygen permeability percentage increase versus the average evaporation rate results. These are the results of laboratory Set 2, Set 3 and site tests. The oxygen permeability percentage increase is the difference between the exposed and control permeability values, expressed as a percentage. Darcy values were used to calculate the oxygen permeability percentage increase. The laboratory Set 2 results illustrated are the 40 and 60 MPa samples exposed to 60% and 90% relative humidity for 28 days. The laboratory Set 3 results illustrated are the retained formwork and curing compound methods.

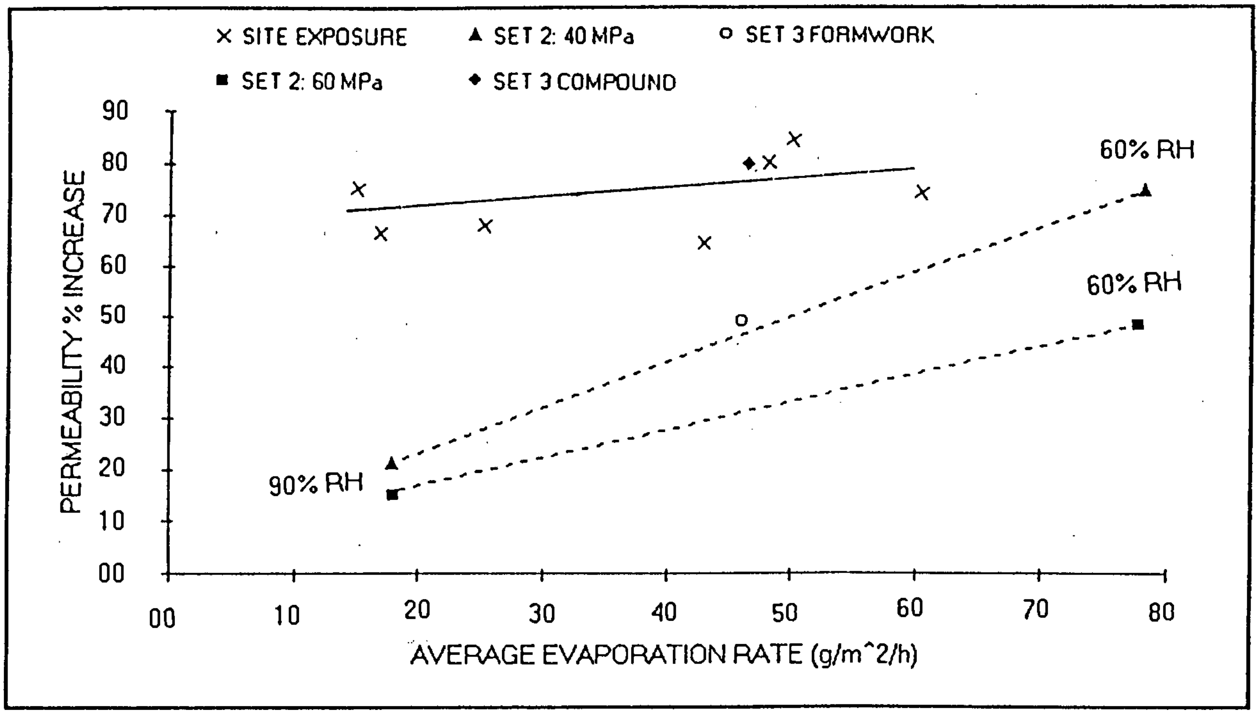

Figure 6.5 Permeability percentage increase versus average evaporation rate (28 day values)

Figure 6.5 presents the best fit line for the site results from chapter 5. These results show the relationship between the average evaporation rate and the permeability percentage increase values. The variation of the site values may be due to the different curing methods and strength mixes used on each site. The line indicates that permeability percentage increased along with average evaporation rate.

The dotted lines in Figure 6.5 illustrate the laboratory Set 2 results. The lines connect the 60% to the 90% relative humidity values for the 40 and 60 MPa strength concretes. The results revealed that the permeability percentage increased as the average evaporation rate increased. The slope of the 40 MPa line is steeper than the 60 MPa line, showing that high strength concretes are less affected by the average evaporation rate than low strength concretes.

The individual values of two curing methods from Set 3, the curing compound and the retained formwork method are plotted. Each method was exposed to the same environmental conditions. The curing compound method performed poorly as reflected in the high permeability percentage increase value. The retained formwork curing method performed better than the curing compound method as indicated by the low permeability percentage increase value. Set 2 thus shows the effect of strength on the permeability percentage increase values, while Set 3 shows the large difference in permeability percentage increase values that can be achieved by using different curing methods.

The site tests achieved much higher permeability percentage increase values than the laboratory tests. Note that Set 2 was exposed to a controlled environment for 28 days while the site tests were exposed to the natural environment. The more severe environmental conditions on site thus resulted in higher permeability percentage increase values. The curing compound tested in Set 3 and exposed to the natural environment achieved a similar permeability percentage increase value to the site values. The retained formwork method achieved a low permeability percentage increase value. However, as the curing survey revealed, this method is seldom used on construction sites in the Cape Town area.

6.3.2 Water sorptivity

Figure 6.6 presents the sorptivity percentage increase versus the average evaporation rate results. These are the results of laboratory Set 2, Set 3 and site tests. The sorptivity percentage increase is the difference between the exposed and control sorptivity values, expressed as a percentage. The laboratory Set 2 results illustrated are the 40 and 60 MPa samples exposed to 60% and 90% relative humidity for 28 days. The laboratory Set 3 results shown are the retained formwork and curing compound methods.

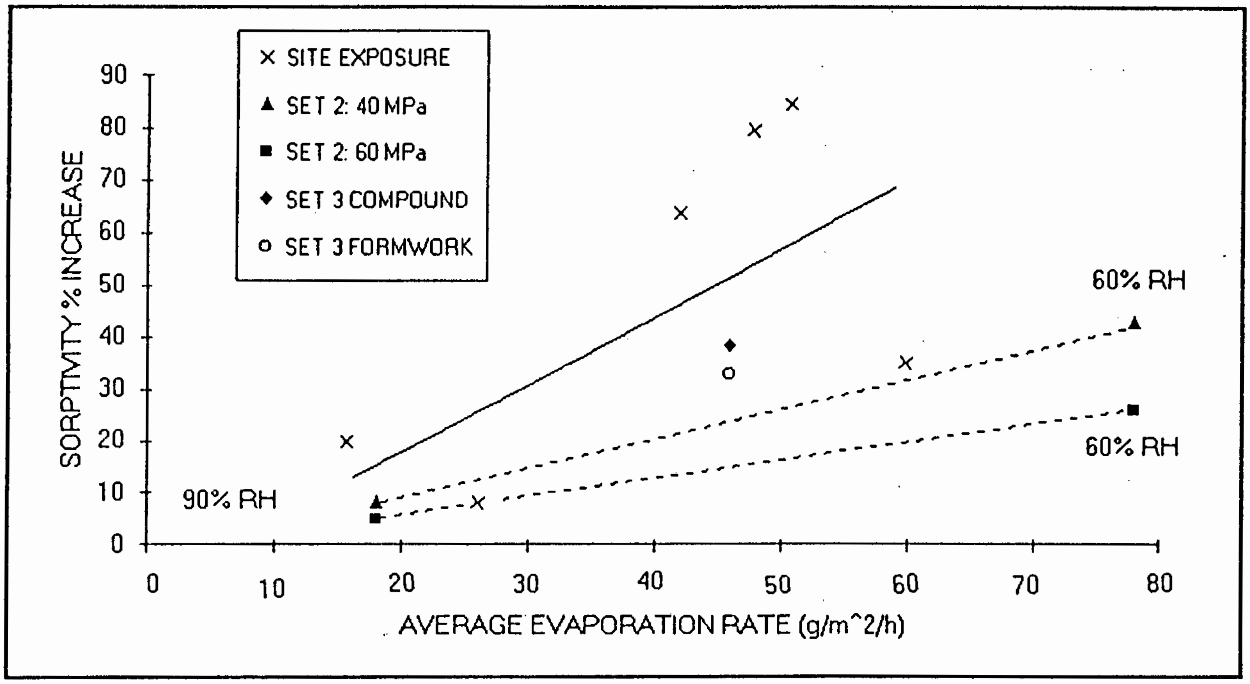

Figure 6.6 Sorptivity percentage increase versus average evaporation rate (28 day values)

Figure 6.6 presents the best fit line for the site results from chapter 5. These results show the relationship between the average evaporation rate and the sorptivity percentage increase values. The site sorptivity values in Figure 6.6 appear to be more variable than the site permeability values in Figure 6.5. This was probably due to the poor and inconsistent experimental techniques of some of the site sorptivity tests, as discussed in chapter 5. The line indicated that the sorptivity percentage increased with increasing average evaporation rate.

The dotted lines in Figure 6.6 illustrate the laboratory Set 2 results. The lines connect the 60% to the 90% relative humidity values for the 40 and 60 MPa strength concretes. The results revealed that sorptivity percentage increased as the average evaporation rate increased. The slope of the 40 MPa line is steeper than the slope of the 60 MPa line, indicating that high strength concretes are less affected by the average evaporation rate than low strength concretes.

The individual values of two curing methods from Set 3, the curing compound and the retained formwork method, are plotted in Figure 6.6. Each method was exposed to the same environmental conditions. The sorptivity percentage difference between the two methods was not as large, relative to Set 2, as the permeability percentage difference. Set 2 thus shows the effect of strength on the sorptivity percentage increase values, while Set 3 reveals the effect of using different curing methods.

A comparison of the site and laboratory results indicated that the site results obtained much higher sorptivity percentage increase values than the laboratory tests. Note that Set 2 was exposed to a controlled environment for 28 days while the site tests and Set 3 were exposed to the natural environment. The more severe environmental conditions on site thus resulted in higher sorptivity percentage increase values.

6.4 Conclusions

From the results obtained and the foregoing discussion, it was concluded that:

1. The permeability and sorptivity of the site results remained constant as the actual strength increased. This was due to the high strength of the site concrete, i.e., above 40 MPa.

2. The Set 2 permeability and sorptivity results revealed that an increase in strength, from 20 to 40 MPa, has a large effect on decreasing the surface permeability and sorptivity of concrete. However, the effect was less marked above 40 MPa, particularly for the control samples.

3. The type of curing method chosen was found to have a significant effect on permeability index values, whilst the effect on the sorptivity values was much smaller.

4. The permeability and sorptivity percentage increased as the average evaporation rate increased. It can therefore be concluded that permeability and sorptivity are affected by temperature and relative humidity.

5. High strength concretes are less affected by the average evaporation rate than low strength concretes.

The following chapter will present the more important findings and conclusions of this project.

CHAPTER 7

CONCLUSIONS

The following conclusions are drawn from the previous results and discussion:

- The survey showed that contractors and consultants have a good understanding of the benefits of proper curing and the adverse effects of poor or non-existent curing. This is a positive aspect, since it means that the construction industry can now take steps to move towards performance-based curing specifications. The curing benefits identified in the survey correlated well with the benefits found in the literature.

- Contractors and consultants were of the opinion that curing was more beneficial to developing the durability properties than the strength properties of concrete. Contractors were of the opinion that the quality of concrete achieved on construction projects was generally adequate while consultants thought the quality achieved was good.

- The curing specifications in SABS 1200-G:1982 and SABS 0100-Part 2:1992 need to be reviewed and updated. The curing specifications could be enforced by making curing a measurable pay item in the Bill of Quantities or by retaining part of the concrete price.

- Curing compounds are the most commonly applied curing method to columns and beams. Furthermore, curing methods are predominantly chosen for their practical ease of application rather than their proven efficiency of curing. The effectiveness of curing compounds as a curing method needs to be reviewed critically.

- The current curing practice could be greatly improved by educating all site personnel and this could start from the site management down. Furthermore, a dedicated person or team must be given the responsibility for curing.

- The only new suggestion for a site-based test was a dye that reacts differently depending on the degree of hydration. More research work is needed to find an acceptable site-based test to determine the effectiveness of curing methods used on site.

- The natural environment exposure tests indicated that permeability decreased as strength grade increased. The decrease became less marked with increasing strength grade. Permeability decreased as the curing relative humidity increased. Permeability decreased with time from 28 to 90 days.

- The natural environment exposure tests revealed that sorptivity decreased as strength grade increased. The sorptivity decrease became less marked with increasing strength grade. Sorptivity decreased as the curing relative humidity increased.

- The controlled environment tests showed that increasing the curing relative humidity was as effective as decreasing the W/C ratio of the mix to improve durability. Curing at 90% relative humidity for 28 days had a beneficial effect on the durability index values. Curing at 60% relative humidity for 28 days was much less effective.

- The variability of the oxygen permeability index and water sorptivity test values must be investigated further. It appears that, for the test conditions used in this project, the number of test samples should be increased. Four test samples may give more consistent results.

- A comparison of five curing methods revealed that retained formwork was the most effective curing method, producing the most durable covercrete. Plastic sheets and damp hessian were the second and third most effective curing methods. The curing compound and periodic wetting curing methods were the least effective for the conditions tested.

- Generally, the sites tested showed that curing on site was not performed according to the project or national specifications. The only sites that complied with the project and national specifications used curing compounds. The remaining sites applied either no curing method after the formwork was removed or the curing method was not applied for the specified time.

- Some of the exposed sorptivity samples increased with age while others decreased with age. This is unusual and should be investigated further. The control sorptivity samples decreased with age. The exposed and control permeability samples decreased with age.

- The north-south orientation revealed that the durability of the south face would improve with age while the north face might not. This implies that if there is to be any deterioration on a structure with age, it would most likely occur on the north face.

- Permeability is affected by the north-south orientation in winter and summer, while sorptivity is only affected in summer. Permeability thus appears to be more sensitive to the north-south orientation than sorptivity.

- The results of some of the sorptivity and permeability tests were spoiled by poor and inconsistent experimental techniques. Therefore, good experimental techniques are extremely important to ensure meaningful results.

- The curing system tested on the median barrier was ineffective in winter and summer environmental conditions. This may be due to either the late or incorrect application of the curing compound, or an ineffective curing compound. The effectiveness of curing compounds as a curing method needs to be reviewed critically.

- The permeability and sorptivity of the site results remained constant as the actual strength increased. This was due to the high strength of the site concrete, i.e., above 40 MPa.

- The controlled environment permeability and sorptivity tests revealed that an increase in strength, from 20 to 40 MPa, has a large effect on decreasing the surface permeability and sorptivity of concrete. However, the effect was less marked above 40 MPa, particularly for the control samples.

- The type of curing method chosen was found to have a significant effect on permeability index values, whilst its effect on the sorptivity values was much smaller.

- The percentage increase in permeability and sorptivity increased as the average evaporation rate increased. It can therefore be concluded that permeability and sorptivity are affected by temperature and relative humidity.

- High strength concretes are less affected by the average evaporation rate than low strength concretes.

APPENDIX A

CONCRETE CURING SURVEY

Accompanying Letter

Department of Civil Engineering
University of Cape Town
Private Bag Rondebosch 7700
Telephone: (021) 650-2584
January 1994

Dear Sir

Special Programme on Concrete Durability

We are conducting a survey among contractors and consultants in the Civil Engineering and Building industries. The purpose of this research is to find out the opinion of yourself and other experts on the present situation concerning concrete curing. Your answers will hopefully enable us to identify how to achieve more durable concrete construction in the South-Western Cape.

Your answers are very important to the accuracy of our research. It will take only a short time to answer the simple questions on the enclosed questionnaire and return it in the stamped reply envelope. Of course all answers will be treated as confidential and will only be used anonymously in combination with those of other Civil Engineering consultants and contractors in the South-Western Cape.

Please return the completed questionnaire as soon as you can, but not later than 21 February 1994. Thank you for your help.

Yours sincerely

Andre Krook	Prof. M.G. Alexander
M.Sc(Eng) Student	Supervisor

Format of the Questionnaire

1. In which sector have you mainly worked in the last five years? (Tick relevant box)

	Building Construction
	Civil Construction
	Consulting

If other please give details :

2. What do you understand by the phrase : "concrete curing"?

3. How important do you think curing is for developing the strength and durability properties of concrete? (Tick the relevant box)

	Not very important	Somewhat important	Very important	Extremely important
Strength				
Durability				

4(a). What type of curing method would you apply or specify for the following structural members? (Complete the table)

Season	Type of structural member	Type of curing method applied	Period of curing (days)	Period of retention of formwork (days)
Summer	Columns			
	Beams			
	Slabs			
Winter	Columns			
	Beams			
	Slabs			

4(b). Why would you choose this type of curing method for the following structural members? (Tick the relevant box)

Structural Member	Practical e.g. ease of application	Cost	Proven efficiency of curing	Other
Columns				
Beams				
Slabs				

If other please give details : ______________________________

5. What do you think are the benefits of good curing?

____

____

____

____

6. In your opinion and experience, what quality (strength & durability) of concrete is usually achieved on construction sites for the following structural members? (Tick relevant box)

Structural Member	Poor quality	Adequate quality	Good quality	Very good quality
Column				
Beam				
Slab				

7. What are the adverse effects you have noticed that may be caused by poor or non-existent curing?

____

____

____

____

____

8. Can you make any suggestions for a site-based test to determine the effectiveness of curing methods used on construction projects?

9. What is your opinion of the usefulness and practicality of the current curing specifications in SABS 1200-G:1982 and SABS 0100-Part 2:1992?

CONSULTING ENGINEERS

10. How would you ensure that concrete curing on site complies with the Specification?

CONTRACTING ENGINEERS

11. How would you like to see that concrete curing on site is correctly achieved according to the Specification?

Please include any further comments or suggestions on an additional piece of paper. Thank you for completing this questionnaire.

Response Letter

Department of Civil Engineering
University of Cape Town
Private Bag Rondebosch 7700
Telephone: (021) 650-2584
May 1994

Dear Sirs

Concrete Curing Survey: Response to Questionnaire

This questionnaire was posted in January 1994 to 230 members of the Concrete Society of Southern Africa, with a return of 23%. We appreciate your response in returning your questionnaire. A brief summary of the information collected in the survey is presented below.

Contractors and consultants both felt that curing was more beneficial to developing the durability properties than the strength properties of concrete. Furthermore, 75% of the consultants thought that durability was extremely important, whereas for contractors this figure was only 39%. The most commonly applied or specified curing method for columns and beams was curing compounds. For slabs, ponding was the most popular curing technique. The methods chosen for columns, beams and slabs were applied for their practical ease of application. Cost and proven efficiency of curing were of low priority when choosing a curing method.

The adverse effects of bad curing were considered to result in shrinkage cracks (38% of respondents), low strengths (18%), dusting (11%), low abrasion resistance (10%), high permeability (11%), brittleness, spalling and corrosion. One contractor mentioned that the adverse effects of poor curing are not normally noticed in the short term and in construction one seldom has the opportunity to observe the long term effects of good or bad curing.

Surprisingly, contractors felt that the quality of concrete achieved on construction projects was adequate while consultants thought the quality was good. One contractor said that poor sand and stone in the SW Cape can only produce low quality concrete. Furthermore, there was a difference in quality achieved on individual construction sites and between civil and building sites. It was felt that civil sites produced a higher quality of concrete because of more stringent curing measures.

The results showed that a range of opinion exists among contractors and consultants on the current curing specifications. Curing is important it should be enforced and standardised with no alternatives. The codes should not be specific so the contractor can choose the method that suits him best. Furthermore, some contractors said that they would like to see more information on curing in dry strong winds in summer. One consultant mentioned that the specifications set out what is required but do not adequately emphasize the importance of curing.

Presently, consultants felt that the only way to ensure that curing complied with the specifications was through regular inspections or full time supervision. Both contractors and consultants suggested that they would like to see curing become a priced item in the Bill of Quantities. The rate could be set at a fixed percentage of the concrete rate for various members. Another suggestion was to retain 15% of the concrete price if curing was not adequately carried out. Hence the need to develop and stipulate a site-based test to measure the effectiveness of curing.

There were few suggestions for such a site based test. The suggestions included a modified abrasion resistance test, curing cubes in a similar fashion to the structure and then testing these cubes for strength and permeability properties, and coring samples from extra pieces of beam or slab cast on-site and later broken off. Comment was also made that the current curing practice could be greatly improved by educating all site personnel. Furthermore, a dedicated person or team must be given the responsibility for curing.

We would like to thank those that took the effort to answer and return the questionnaire. Your answers have been most useful. We intend to take many of the ideas forward in further discussion with the specifying authorities.

Yours Sincerely

Andre Krook
M.Sc(Eng) Student

Prof. M.G. Alexander
Supervisor

APPENDIX B

LABORATORY TEST RESULTS

Legend

Abbreviation	Description
Control	Sample submerged in water continuously
80%RH	Sample exposed to 80% relative humidity for six days and then exposed to the natural environmnet
50%RH	Sample exposed to 50% relative humidity for six days and then exposed to the natural environment
90%RH	Sample exposed to 90% relative humidty for 28 days
60%RH	Sample exposed to 60 % relative humidity for 28 days
*	Sample either broken or damaged
#	Individual result excluded
Compound	Curing compound
Plastic	Plastic sheets
Wetting	Periodic wetting
Hessian	Damp hessian
Formwork	Formwork retained

Table B1 Set 1 oxygen permeability index results 20 MPa

Sample	Test age (days)	Individual Index Value	Average Index Value	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	9,49			
Control 2	28	9,50	9,50		
80% RH 1	28	8,85			
80% RH 2	28	8,78			
80% RH 3	28	8,99	8,87	0,11	1,2
50% RH 1	28	8,76			
50% RH 2	28	8,84			
50% RH 3	28	8,64	8,75	0,10	1,1
Control 1	90	9,45			
Control 2	90	*	9,45		
80% RH 1	90	8,87			
80% RH 2	90	8,89			
80% RH 3	90	8,99	8,91	0,06	0,7
50% RH 1	90	8,68			
50% RH 2	90	8,87			
50% RH 3	90	8,89	8,81	0,12	1,3

Table B2 Set 1 water sorptivity results 20 MPa

Sample	Test age (days)	Individual Value (mm/hr^0,5)	Average Value (mm/hr^0,5)	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	13,00			
Control 2	28	11,39	12,19		
80% RH 1	28	13,98			
80% RH 2	28	14,24			
80% RH 3	28	15,55	14,59	0,84	5,8
50% RH 1	28	16,37			
50% RH 2	28	*			
50% RH 3	28	18,28	17,33		
Control 1	90	10,38			
Control 2	90	11,00	10,69		
80% RH 1	90	15,46			
80% RH 2	90	16,48			
80% RH 3	90	16,96	16,30	0,77	4,7
50% RH 1	90	# 24,94			
50% RH 2	90	20,88			
50% RH 3	90	19,69	20,29		

Table B3 Set 1 oxygen permeability index results 40 MPa

Sample	Test age (days)	Individual Index Value	Average Index Value	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	*			
Control 2	28	9,75	9,75		
80% RH 1	28	9,59			
80% RH 2	28	9,58			
80% RH 3	28	9,78	9,65	0,11	1,2
50% RH 1	28	9,55			
50% RH 2	28	9,41			
50% RH 3	28	9,42	9,46	0,08	0,8
Control 1	90	10,06			
Control 2	90	9,85	9,96		
80% RH 1	90	9,70			
80% RH 2	90	9,77			
80% RH 3	90	9,63	9,70	0,07	0,7
50% RH 1	90	9,56			
50% RH 2	90	9,60			
50% RH 3	90	9,79	9,65	0,13	1,3

Table B4 Set 1 water sorptivity results 40 MPa

Sample	Test age (days)	Individual Value (mm/hr^0,5)	Average Value (mm/hr^0,5)	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	*			
Control 2	28	9,75	9,75		
80% RH 1	28	9,65			
80% RH 2	28	10,57			
80% RH 3	28	9,73	9,99	0,51	5,1
50% RH 1	28	10,14			
50% RH 2	28	11,23			
50% RH 3	28	10,40	10,59	0,57	5,4
Control 1	90	9,91			
Control 2	90	7,45	8,68		
80% RH 1	90	12,12			
80% RH 2	90	12,55			
80% RH 3	90	10,81	11,83	0,90	7,6
50% RH 1	90	15,59			
50% RH 2	90	13,12			
50% RH 3	90	14,05	14,26	1,25	8,7

Table B5 Set 1 oxygen permeability index results 60 MPa

Sample	Test age (days)	Individual Index Value	Average Index Value	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	9,76			
Control 2	28	9,78	9,77		
80% RH 1	28	9,74			
80% RH 2	28	9,66			
80% RH 3	28	9,84	9,74	0,09	0,9
50% RH 1	28	9,58			
50% RH 2	28	9,88			
50% RH 3	28	9,64	9,70	0,16	1,6
Control 1	90	9,75			
Control 2	90	9,84	9,79		
80% RH 1	90	10,01			
80% RH 2	90	10,09			
80% RH 3	90	9,95	10,02	0,07	0,7
50% RH 1	90	10,10			
50% RH 2	90	9,91			
50% RH 3	90	9,94	9,98	0,10	1,0

Table B6 Set 1 water sorptivity results 60 MPa

Sample	Test age (days)	Individual Value (mm/hr^0,5)	Average Value (mm/hr^0,5)	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	9,67			
Control 2	28	9,19	9,43		
80% RH 1	28	10,07			
80% RH 2	28	12,30			
80% RH 3	28	9,50	10,62	1,48	14,0
50% RH 1	28	9,40			
50% RH 2	28	8,37			
50% RH 3	28	10,80	9,53	1,22	12,8
Control 1	90	7,77			
Control 2	90	8,54	8,15		
80% RH 1	90	9,43			
80% RH 2	90	8,94			
80% RH 3	90	9,22	9,20	0,25	2,7
50% RH 1	90	10,94			
50% RH 2	90	13,35			
50% RH 3	90	13,87	12,72	1,56	12,3

Table B7 Set 1 compressive strength test results

Sample	Test age (days)	Individual Value (MPa)	Average Value (MPa)	Standard Deviation (σ)	Coefficient Variation (%)
20 MPa 1	28	20,5			
20 MPa 2	28	20,6			
20 MPa 3	28	19,0	20,0	0,9	4,5
20 MPa 4	90	20,8			
20 MPa 5	90	21,7			
20 MPa 6	90	25,2	22,6	2,3	10,3
40 MPa 1	28	44,0			
40 MPa 2	28	44,8			
40 MPa 3	28	43,2	44,0	0,8	1,8
40 MPa 4	90	44,4			
40 MPa 5	90	49,1			
40 MPa 6	90	46,0	46,5	2,4	5,1
60 MPa 1	28	58,9			
60 MPa 2	28	64,2			
60 MPa 3	28	62,0	61,7	2,7	4,3
60 MPa 4	90	65,0			
60 MPa 5	90	64,2			
60 MPa 6	90	69,1	66,1	2,6	4,0

Table B8 Set 2 oxygen permeability index results 20 MPa

Sample	Test age (days)	Individual Index Value	Average Index Value	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	8,64			
Control 2	28	8,77			
Control 3	28	8,64	8,69	0,09	1,0
90 % RH 1	28	8,55			
90 % RH 2	28	8,67			
90 % RH 3	28	8,64	8,62	0,06	0,7
60 % RH 1	28	8,43			
60 % RH 2	28	8,30			
60 % RH 3	28	8,38	8,37	0,07	0,8

Table B9 Set 2 water sorptivity results 20 MPa

Sample	Test age (days)	Individual Value (mm/hr^0,5)	Average Value (mm/hr^0,5)	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	14,98			
Control 2	28	13,74			
Control 3	28	13,42	14,04	0,23	1,7
90 % RH 1	28	15,88			
90 % RH 2	28	15,38			
90 % RH 3	28	*	15,63		
60 % RH 1	28	26,34			
60 % RH 2	28	25,65			
60 % RH 3	28	24,66	25,55	0,84	3,3

Table B10 Set 2 oxygen permeability index results 40 MPa

Sample	Test age (days)	Individual Index Value	Average Index Value	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	9,46			
Control 2	28	9,60			
Control 3	28	9,54	9,53	0,04	0,4
90 % RH 1	28	9,51			
90 % RH 2	28	9,35			
90 % RH 3	28	9,42	9,43	0,08	0,9
60 % RH 1	28	9,02			
60 % RH 2	28	8,83			
60 % RH 3	28	9,04	8,96	0,12	1,3

Table B11 Set 2 water sorptivity results 40 MPa

Sample	Test age (days)	Individual Value (mm/hr^0,5)	Average Value (mm/hr^0,5)	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	12,48			
Control 2	28	10,64			
Control 3	28	11,22	11,45	0,41	3,6
90 % RH 1	28	12,58			
90 % RH 2	28	11,85			
90 % RH 3	28	11,52	11,98	0,54	4,5
60 % RH 1	28	15,92			
60 % RH 2	28	16,93			
60 % RH 3	28	16,19	16,35	0,52	3,2

Table B12 Set 2 oxygen permeability index results 60 MPa

Sample	Test age (days)	Individual Index Value	Average Index Value	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	9,91			
Control 2	28	9,61			
Control 3	28	9,53	9,68	0,06	0,6
90 % RH 1	28	9,68			
90 % RH 2	28	9,65			
90 % RH 3	28	9,52	9,62	0,09	0,9
60 % RH 1	28	9,44			
60 % RH 2	28	9,31			
60 % RH 3	28	9,41	9,39	0,07	0,7

Table B13 Set 2 water sorptivity results 60 MPa

Sample	Test age (days)	Individual Value (mm/hr^0,5)	Average Value (mm/hr^0,5)	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	10,29			
Control 2	28	10,30			
Control 3	28	10,50	10,36	0,14	1,3
90 % RH 1	28	11,67			
90 % RH 2	28	10,89			
90 % RH 3	28	10,39	10,98	0,65	5,9
60 % RH 1	28	12,34			
60 % RH 2	28	# 17,09			
60 % RH 3	28	13,75	13,05		

Table B14 Set 2 compressive strength test results

Sample	Test age (days)	Individual Value (MPa)	Average Value (MPa)	Standard Deviation (σ)	Coefficient Variation (%)
20 MPa 1	28	21,4			
20 MPa 2	28	20,4			
20 MPa 3	28	20,8	20,9	0,5	2,4
40 MPa 1	28	41,4			
40 MPa 2	28	41,8			
40 MPa 3	28	43,4	42,2	1,1	2,5
60 MPa 1	28	71,8			
60 MPa 2	28	68,1			
60 MPa 3	28	65,6	68,5	3,1	4,6

Table B15 Set 3 oxygen permeability index results.

Sample	Test age (days)	Individual Index Value	Average Index Value	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	9,55			
Control 2	28	9,17			
Control 3	28	9,13	9,28	0,03	0,3
Formwork 1	28	8,88			
Formwork 2	28	9,08			
Formwork 3	28	9,02	8,99	0,10	1,2
Plastic 1	28	8,81			
Plastic 2	28	8,98			
Plastic 3	28	9,06	8,95	0,12	1,4
Hessian 1	28	8,78			
Hessian 2	28	8,74			
Hessian 3	28	8,71	8,74	0,02	0,3
Wetting 1	28	8,56			
Wetting 2	28	8,66			
Wetting 3	28	8,76	8,66	0,10	1,2
Compound 1	28	8,49			
Compound 2	28	8,62			
Compound 3	28	8,61	8,57	0,07	0,9

Table B16 Set 3 water sorptivity results

Sample	Test age (days)	Individual Value (mm/hr^0,5)	Average Value (mm/hr^0,5)	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	13,34			
Control 2	28	11,18			
Control 3	28	12,94	12,49	1,24	10,0
Formwork 1	28	16,71			
Formwork 2	28	16,34			
Formwork 3	28	16,72	16,59	0,22	1,3
Plastic 1	28	17,87			
Plastic 2	28	16,91			
Plastic 3	28	16,58	17,12	0,67	3,9
Hessian 1	28	18,37			
Hessian 2	28	16,91			
Hessian 3	28	16,54	17,27	0,97	5,6
Wetting 1	28	18,18			
Wetting 2	28	17,81			
Wetting 3	28	17,52	17,84	0,21	1,1
Compound 1	28	17,74			
Compound 2	28	18,66			
Compound 3	28	15,53	17,31	1,61	9,3

Table B17 Set 3 compressive strength test results

Sample	Test age (days)	Individual Value (MPa)	Average Value (MPa)	Standard Deviation (σ)	Coefficient Variation (%)
40 MPa 1	28	41,5			
40 MPa 2	28	39,1			
40 MPa 3	28	40,1	40,2	1,2	3,0

APPENDIX C

SITE TEST RESULTS

Legend

Abbreviation	Description
Control	Sample submerged in water continuously
South	Sample from south face
North	Sample from north face
Curing Compound South	Sample from south face and curing compound applied
No Curing South	Sample from south face and no curing compound applied
*	Sample either broken or damaged
#	Individual result excluded

Table C1 Oxygen permeability index results for the Albion Springs Site

Sample	Test age (days)	Individual Index Value	Average Index Value	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	9,68			
Control 2	28	9,84	9,76		
South 1	28	9,35			
South 2	28	9,07			
South 3	28	9,16	9,20	0,14	1,6
North 1	28	9,37			
North 2	28	9,45			
North 3	28	9,23	9,35	0,11	1,2
Control 1	90	10,07			
Control 2	90	9.80	9,93		
South 1	90	9,30			
South 2	90	9,26			
South 3	90	9,34	9,30	0,04	0,4
North 1	90	9,44			
North 2	90	9,51			
North 3	90	9,55	9,50	0,06	0,6

Table C2 Water sorptivity results for the Albion Springs Site

Sample	Test age (days)	Individual Value (mm/hr^0,5)	Average Value (mm/hr^0,5)	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	10,80			
Control 2	28	13,18	11,99		
South 1	28	10,49			
South 2	28	11,16			
South 3	28	10,08	10,58	0,55	5,2
North 1	28	11,55			
North 2	28	10,14			
North 3	28	9,97	10,55	0,87	8.2
Control 1	90	9,45			
Control 2	90	11,54	10,50		
South 1	90	11,27			
South 2	90	11,29			
South 3	90	11,01	11,19	0,16	1.4
North 1	90	12,62			
North 2	90	13,02			
North 3	90	10.55	12.06	1,32	11,0

Table C3 Oxygen permeability index results for the Caltex Garage Site

Sample	Test age (days)	Individual Index Values	Average Index Values	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	10,06			
Control 2	28	10,02	10,04		
South 1	28	9,50			
South 2	28	9,57			
South 3	28	9,51	9,52	0,04	0,4
North 1	28	9,56			
North 2	28	9,75			
North 3	28	9,44	9,59	0,16	1,6
Control 1	90	*			
Control 2	90	10,08	10,08		
South 1	90	9,72			
South 2	90	9,60			
South 3	90	9,74	9,69	0,08	0,8
North 1	90	9,63			
North 2	90	9,63			
North 3	90	9,41	9,56	0,13	1,4

Table C4 Water sorptivity results for the Caltex Garage Site

Sample	Test age (days)	Individual Value (mm/hr^0,5)	Average Value (mm/hr^0,5)	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	8,68			
Control 2	28	*	8,68		
South 1	28	10,71			
South 2	28	9,67			
South 3	28	8,92	9,76	0,90	9,2
North 1	28	10,59			
North 2	28	9,44			
North 3	28	8,60	9,55	1,00	10,5
Control 1	90	8,63			
Control 2	90	8,35	8,49		
South 1	90	12,16			
South 2	90	9,65			
South 3	90	14,02	11,94	2,19	18,3
North 1	90	12,95			
North 2	90	13,31			
North 3	90	14,01	13,42	0,54	4,0

Table C5 Oxygen permeability index results for the Granger Bay Site Test 1

Sample	Test age (days)	Individual Index Value	Average Index Value	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	10,15			
Control 2	28	10,08	10,11		
South 1	28	9,33			
South 2	28	9,39			
South 3	28	9,49	9,41	0,08	0,9
North 1	28	9,28			
North 2	28	9,21			
North 3	28	9,15	9,22	0,07	0,7
Control 1	90	10,21			
Control 2	90	10,13	10,17		
South 1	90	*			
South 2	90	9,54			
South 3	90	9,48	9,51		
North 1	90	9,40			
North 2	90	9,32			
North 3	90	9,22	9,31	0,09	1,0

Table C6 Water sorptivity results for the Granger Bay Site Test 1

Sample	Test age (days)	Individual Value (mm/hr^0,5)	Average Value (mm/hr^0,5)	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	8,20			
Control 2	28	7,48	7,84		
South 1	28	12,33			
South 2	28	12,36			
South 3	28	12,00	12,23	0,20	1,6
North 1	28	17,40			
North 2	28	16,16			
North 3	28	16,76	16,77	0,62	3,7
Control 1	90	11,97			
Control 2	90	10,70	11,34		
South 1	90	10,55			
South 2	90	15,73			
South 3	90	12,59	12,96	2,61	20,1
North 1	90	20,88			
North 2	90	22,66			
North 3	90	19,95	21,17	1,38	6,5

Table C7 Oxygen permeability index results for the Granger Bay Site Test 2

Sample	Test age (days)	Individual Index Value	Average Index Value	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	9,88			
Control 2	28	9,86	9,87		
South 1	28	9,38			
South 2	28	9,30			
South 3	28	9,24	9,31	0,07	0,7
North 1	28	9,15			
North 2	28	9,13			
North 3	28	9,12	9,14	0,01	0,2
Control 1	90	9,92			
Control 2	90	10,32			
Control 3	90	9,98	10,07	0,24	2,4
South 1	90	9,82			
South 2	90	9,61			
South 3	90	9,48	9,64	0,17	1,8
North 1	90	9,57			
North 2	90	9,46			
North 3	90	9,55	9,53	0,06	0,6

Table C8 Water sorptivity results for the Granger Bay Site Test 2

Sample	Test age (days)	Individual Value (mm/hr^0,5)	Average Value (mm/hr^0,5)	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	7,25			
Control 2	28	6,83	7,04		
South 1	28	8,16			
South 2	28	9,27			
South 3	28	7,84	8,42	0,75	8,9
North 1	28	8,93			
North 2	28	8,37			
North 3	28	8,47	8,59	0,30	3,5
Control 1	90	6,77			
Control 2	90	6,27			
Control 3	90	7,14	6,73	0,62	9,2
South 1	90	9,13			
South 2	90	11,11			
South 3	90	10,71	10,32	1,05	10,1
North 1	90	9,68			
North 2	90	9,08			
North 3	90	8,94	9,23	0,39	4,2

Table C9 Oxygen permeability index results for the Rondebosch Golf Course Site

Sample	Test age (days)	Individual Index Value	Average Index Value	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	10,18			
Control 2	28	10,20	10,19		
South 1	28	9,71			
South 2	28	9,47			
South 3	28	9,62	9,60	0,12	1,2
North 1	28	9,66			
North 2	28	9,61			
North 3	28	9,59	9,62	0,04	0,4
Control 1	90	10,20			
Control 2	90	10,15	10.17		
South 1	90	9,42			
South 2	90	9,44			
South 3	90	9,39	9,42	0,02	0,2
North 1	90	9,45			
North 2	90	9,41			
North 3	90	9,44	9,43	0,02	0,2

Table C10 Water sorptivity results for the Rondebosch Golf Course Site

Sample	Test age (days)	Individual Value (mm/hr^0,5)	Average Value (mm/hr^0,5)	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	9,55			
Control 2	28	10,89	10,22		
South 1	28	11,69			
South 2	28	12,76			
South 3	28	13,19	12,55	0,77	6,1
North 1	28	14,82			
North 2	28	14,13			
North 3	28	16,12	15,02	1,01	6,7
Control 1	90	8,50			
Control 2	90	8,31	8,41		
South 1	90	8,41			
South 2	90	7,97			
South 3	90	9,15	9,32	0,60	7.0
North 1	90	10,85			
North 2	90	13,38			
North 3	90	*	11,12		

Table C11. Oxygen permeability index results for the Median Barrier Site 1 Test 1

Sample	Test age (days)	Individual Index Value	Average Index Value	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	10,30			
Control 2	28	10,27			
Control 3	28	10,17			
Control 4	28	10,15	10,22	0,08	0,7
Curing Compound South 1	28	9,46			
Curing Compound South 2	28	9,53			
Curing Compound South 3	28	9,46	9,48	0,04	0,4
Curing Compound North 1	28	9,66			
Curing Compound North 2	28	9,51			
Curing Compound North 3	28	9,45	9,54	0,11	1,1
No Curing South 1	28	9,40			
No Curing South 2	28	9,35			
No Curing South 3	28	9,39	9,38	0,03	0,3
No Curing North 1	28	9,43			
No Curing North 2	28	9,34			
No Curing North 3	28	9,50	9,42	0,08	0,9
Control 1	90	9,76			
Control 2	90	9,86			
Control 3	90	9,87	9,83	0,06	0,6
Curing Compound South 1	90	9,37			
Curing Compound South 2	90	9,54			
Curing Compound South 3	90	9,31	9,40	0,12	1,3
Curing Compound North 1	90	9,11			
Curing Compound North 2	90	9,65			
Curing Compound North 3	90	9,17	9,31	0,30	3,2

Table C12 Water sorptivity results for the Median Barrier Site 1 Test 1

Sample	Test age (days)	Individual Value (mm/hr^0,5)	Average Value (mm/hr^0,5)	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	8,78			
Control 2	28	9,44			
Control 3	28	8,04			
Control 4	28	8,15	8,60	0,65	7,5
Curing Compound South 1	28	15,49			
Curing Compound South 2	28	15,77			
Curing Compound South 3	28	16,11	15,79	0,31	1,9
Curing Compound North 1	28	14,17			
Curing Compound North 2	28	15,63			
Curing Compound North 3	28	15,50	15,10	0,81	5,3
No Curing South 1	28	15,55			
No Curing South 2	28	16,84			
No Curing South 3	28	15,82	16,07	0,68	4,2
No Curing North 1	28	16,55			
No Curing North 2	28	17,46			
No Curing North 3	28	*	17,01		
Control 1	90	7,09			
Control 2	90	6,88			
Control 3	90	7,27	7,08	0,20	2,8
Curing Compound South 1	90	10,31			
Curing Compound South 2	90	10,68			
Curing Compound South 3	90	12,25	11,08	1,03	9,3
Curing Compound North 1	90	13,45			
Curing Compound North 2	90	11,38			
Curing Compound North 3	90	12,11	12,31	1,05	8,6

Table C13 Oxygen permeability index results for the Median Barrier Site 1 Test 2

Sample	Test age (days)	Individual Index Value	Average Index Value	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	10,14			
Control 2	28	10,07			
Control 3	28	10,09	10,10	0,03	0,3
Curing Compound South 1	28	9,51			
Curing Compound South 2	28	9,55			
Curing Compound South 3	28	9,42	9,50	0,07	0,7
Curing Compound North 1	28	9,88			
Curing Compound North 2	28	9,78			
Curing Compound North 3	28	9,69	9,79	0,09	1,0
No Curing South 1	28	9,83			
No Curing South 2	28	9,76			
No Curing South 3	28	9,76	9,78	0,04	0,4
No Curing North 1	28	9,63			
No Curing North 2	28	9,73			
No Curing North 3	28	9,88	9,75	0,12	1,3
Control 1	90	10,25			
Control 2	90	10,31			
Control 3	90	10,18	10,25	0,07	0,7
Curing Compound South 1	90	9,85			
Curing Compound South 2	90	9,54			
Curing Compound South 3	90	9,63	9,67	0,16	1,6
Curing Compound North 1	90	9,54			
Curing Compound North 2	90	9,74			
Curing Compound North 3	90	9,73	9,67	0,11	1,2

Table C14 Water sorptivity results for the Median Barrier Site 1 Test 2

Sample	Test age (days)	Individual Value (mm/hr^0,5)	Average Value (mm/hr^0,5)	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	8,56			
Control 2	28	8,20			
Control 3	28	7,74	8,16	0,41	5,0
Curing Compound South 1	28	13,96			
Curing Compound South 2	28	11,99			
Curing Compound South 3	28	15,09	13,68	1,57	11,5
Curing Compound North 1	28	13,78			
Curing Compound North 2	28	14,07			
Curing Compound North 3	28	12,33	13,39	0,93	6,9
No Curing South 1	28	9,82			
No Curing South 2	28	10,14			
No Curing South 3	28	10,56	10,17	0,37	3,6
No Curing North 1	28	# 13,00			
No Curing North 2	28	10,38			
No Curing North 3	28	10,60	10,49		
Control 1	90	6,29			
Control 2	90	7,11			
Control 3	90	6,55	6,65	0,42	6,3
Curing Compound South 1	90	9,26			
Curing Compound South 2	90	9,47			
Curing Compound South 3	90	# 7,54	9,37		
Curing Compound North 1	90	10,22			
Curing Compound North 2	90	11,88			
Curing Compound North 3	90	10,06	10,72	1,01	9,4

Table C15 Oxygen permeability index results for the Median Barrier Site 2

Sample	Test age (days)	Individual Index Value	Average Index Value	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	10,03			
Control 2	28	10,20			
Control 3	28	10,11	10,12	0,09	0,9
Curing Compound 1	28	9,34			
Curing Compound 2	28	9,46			
Curing Compound 3	28	9,38	9,39	0,06	0,6
No Curing 1	28	9,94			
No Curing 2	28	9,67			
No Curing 3	28	9,88	9,83	0,14	1,5

Table C16 Water sorptivity results for the Median Barrier Site 2

Sample	Test age (days)	Individual Value (mm/hr^0,5)	Average Value (mm/hr^0,5)	Standard Deviation (σ)	Coefficient Variation (%)
Control 1	28	9,42			
Control 2	28	9,80			
Control 3	28	8,35	9,19	0,75	8,2
Curing Compound 1	28	15,72			
Curing Compound 2	28	13,36			
Curing Compound 3	28	14,22	14,44	1,19	8,3
No Curing 1	28	# 10,48			
No Curing 2	28	14,00			
No Curing 3	28	15,26	14,63		

Table C17 Compressive strength test results for all sites

Site	Test age (days)	Characteristic Strength (MPa)	Individual Value (MPa)	Average Value (MPa)	Standard Deviation (σ)	Coefficient Variation (%)
Albion Springs	28	25	44,0			
	28		49,4			
	28		46,5	46,6	2,7	5,8
Albion Springs	90		51,4			
	90		53,0			
	90		53,6	52,7	1,1	2,2
Caltex Garage	28	30	50,6			
	28		48,1			
	28		51,0	49,9	1,6	3,1
Caltex Garage	90		56,6			
	90		58,8			
	90		57,6	57,7	1,1	1,9
Granger Bay Block 1	28	40	59,5			
	28		52,2			
	28		58,1	56,6	3,9	6,8
Granger Bay Block 1	90		64,2			
	90		67,7			
	90		66,5	66,1	1,8	2,7
Granger Bay Block 2	28	40	41,7			
	28		39,8			
	28		40,8	40,8	1,0	2,3
Granger Bay Block 2	90		42,6			
	90		43,8			
	90		44,7	43,7	1,1	2,4
Rondebosch Golf Course	28	30	37,5			
	28		36,1			
	28		37,0	36,9	0,7	1,9
Rondebosch Golf Course	90		47,6			
	90		45,5			
	90		45,3	46,1	1,3	2,8
Median Barrier Site 1 Test 1	28	30	39,1			
	28		38,4			
	28		38,1	38,5	0,5	1.3
Median Barrier Site 1 Test 1	90		58,9			
	90		55,9			
	90		56,2	57,0	1,7	2.9
Median Barrier Site 1 Test 2	28	30	41,7			
	28		40,1			
	28		40,2	40,7	0.9	2,2
Median Barrier Site 1 Test 2	90		53,3			
	90		54,5			
	90		57.0	54.9	1,9	3,4
Median Barrier Site 2	28	40	58,7			
	28		59,6			
	28		60,9	59,7	1,1	1,9

APPENDIX D

CURING SPECIFICATIONS

SABS 1200-G:1982: Concrete (Structural)

"Clause 5.5.8 Curing and protection

After formwork has been removed (see 5.2.5) and as soon as it is practicable in the opinion of the engineer, all concrete shall, subject to the provisions of 5.5.9.1, be protected from contamination and loss of moisture by one or more of the following methods:

a) ponding the exposed surfaces by means of water;

b) covering the concrete with sand, or mats made of a moisture retaining material, and keeping the covering continuously wet;

c) continuously spraying the exposed surface with water;

d) covering the concrete with waterproof or plastics sheeting firmly anchored at the edges;

e) the use of an approved curing compound applied in accordance with the manufacturers instructions.

Whatever method of curing is adopted, its application shall not cause staining, contamination, or marring of the surface of the concrete. Water used shall comply with the requirements of 3.3. When the ambient temperature is 5°C or higher, the curing period shall be at least 5 days for concrete made with portland cement, at least 2 days for concrete made with rapid-hardening portland cement, and at least 7 days for concrete made with portland blastfurnace cement. When the ambient temperature is below 5°C, the curing periods shall be extended by 72, 36, and 72 hours respectively."

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Part 2: Materials and execution of work

"Protection and curing of concrete

Clause 10.8.1.2

In the case of concrete surfaces not in contact with forms, one of the following procedures shall be adopted as soon as practicable after completion of placement and compaction, subject to the provisions of 10.8.2 and 10.8.3.

a) Ponding or continuous sprinkling of the exposed surfaces with water;
b) covering the concrete with sand, or with mats made of a moisture-retaining material, and keeping the covering continuously wet;
c) the continuous application of steam (not exceeding 60 °C) or mist spray;
d) covering the concrete with waterproof or plastics sheeting firmly anchored at the edges;
e) the use of an approved curing compound, applied in accordance with the manufacturer's recommendations.

NOTE - Some curing compounds inhibit bond finishes, such as toppings, plasters or paints, applied to the hardened concrete. The compound used should therefore be suitable for the intended finish."

"Clause 10.8.1.3

Moisture loss from surfaces placed against wooden forms shall be minimised by keeping the forms wet until they are removed. After form removal, the concrete shall be cured by one of the methods given in (a) to (e) above, for the duration of the time prescribed below.

Whichever method of curing is adopted, its application shall not cause staining, contamination or marring of the surface of the concrete and the water used shall be in accordance with 4.2. When the ambient temperature is 15°C and higher the curing period shall be at least 7 days for concrete made with ordinary portland cement or portland cement 15 slag or portland cement 15 fly ash, and at least 10 days for concrete made with portland blastfurnace cement, and with blends of portland cement and more than 15% of ground granulated blastfurnace slag or fly ash.

When the ambient temperature is below 5°C, the curing periods shall be doubled. When the ambient temperature is between 5°C and 15°C, the curing period shall be determined by interpolation between the above times."