SENSITIVITY OF STRENGTH AND DURABILITY PROPERTIES OF BLENDED CEMENT CONCRETE TO CHANGES IN WATER/BINDER RATIO AND BINDER CONTENT

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DECLARATION

I, Morné Philip du Preez, hereby declare that this Research Report is my own, unaided work. It is being submitted for the degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

Morné Philip du Preez

February, 2019

ABSTRACT

There are numerous studies that assess the effects of changes in the water/binder (w/b) ratio and binder content on strength and durability properties of concrete. However, limited information is available on the extent to which changes in w/b ratio and binder content affects concrete strength and durability. This study focused on the sensitivity of concrete to changes in these parameters to further the understanding of the material by determining the importance of the parameters on the resultant concrete properties and providing practical guidelines for the mix design process.

Concrete test specimens were made using two w/b ratios (0.45 and 0.65), two binder contents (350 and 450kg/m³) and three binder types PC (plain Portland Cement), 70/30 PC/fly ash (FA) and 50/50 PC/ground-granulated blastfurnace slag (GGBS). One parameter was varied at a time. Compressive strength tests were conducted at 3, 7, 14, 28 and 56 days and durability index tests at 28 and 56 days.

The results indicate that increases in w/b ratio lead to lower compressive strengths and increased permeability, sorptivity and chloride conductivity. Increases in binder content have beneficial effects on compressive strength; however, this trend does not continue indefinitely and is related to the paste content range, aggregate content and grading. Furthermore, binder content increases proved to be detrimental to concrete durability by decreasing the oxygen permeability (OPI) and increasing the water sorptivity (WSI) and chloride conductivity (CCI) indices. In general, for all the binder types investigated, both the strength and durability properties were more sensitive to changes in w/b ratio than binder content.

The compressive strength of FA concretes was the most affected by a change in w/b ratio. The sensitivity hierarchy of compressive strength of PC and GGBS concretes to a change in w/b ratio varied with age. For the three different binder types, sensitivity of compressive strength to changes in w/b ratio generally decreased with age. The extent to which a change in binder content affects compressive strength varies with age and no clear binder type hierarchy is evident. The w/b ratio therefore remains the controlling factor of compressive strength.

For the parameters tested, the OPI of FA concretes exhibited the highest sensitivity to changes in w/b ratio followed by GGBS and PC concretes respectively. Moreover, GGBS concretes were the most sensitive to changes in binder content followed by PC and FA concretes. As with compressive strength, sensitivity of OPI to changes in both w/b ratio and

binder content decreases with age. The sensitivity variance of OPI between changes in w/b ratio and binder content is considered to be minimal, less than 5.0%, and therefore both of these parameters need to be carefully considered in the mix design process when assessing permeability requirements.

The results also indicate that the sensitivity of WSI to changes in w/b ratio follows a similar pattern to compressive strength and decreases in the following order: FA > PC > GGBS. Furthermore, this sensitivity increases with age apart from one FA specimen. The sensitivity trends for binder content variations are not well defined; however, they generally decrease with age. W/b ratios and paste contents therefore need to be kept as low as possible in concrete mixes.

CCI sensitivity to changes in w/b ratio decreases in the following order: PC > FA > GGBS. The sensitivity to changes in binder content generally decreased as follows: GGBS > PC > FA. The extent to which a change in w/b ratio and binder content affects CCI generally decreases with age. These findings reiterated the need to control the paste volume. Adopting the highest replacement levels of GGBS leads to the lowest chloride conductivity. However, these concrete mixes exhibit the highest sensitivity to changes in paste content.

DEDICATION

This research report is dedicated to my Wife.

ACKNOWLEDGEMENTS

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ABBREVIATIONS AND NOTATIONS

CBD	Compacted Bulk Density
CCI	Chloride Conductivity Index
CEM I 52.5R	Rapid hardening Plain Portland Cement, Grade 52.5 R
DI	Durability Index
FA	Fly Ash
GGBS	Ground Granulated Blastfurnace Slag
OPI	Oxygen Permeability Index
PC	Plain Portland cement
RD	Relative Density
SANS	South African National Standard
w/b	Water-to-binder ratio (by mass)
WSI	Water Sorptivity Index

CONCRETE MIX LABELS

PC-350-0.45	Concrete made using 350 kg/m³ of PC binder at a w/b ratio of 0.45
PC-350-0.65	Concrete made using 350 kg/m³ of PC binder at a w/b ratio of 0.65
PC-450-0.45	Concrete made using 450 kg/m³ of PC binder at a w/b ratio of 0.45
PC-450-0.65	Concrete made using 450 kg/m³ of PC binder at a w/b ratio of 0.65
FA-30-350-0.45	Concrete made using 350 kg/m³ of 70/30 PC/FA binder blend at a w/b ratio of 0.45
FA-30-350-0.65	Concrete made using 350 kg/m³ of 70/30 PC/FA binder blend at a w/b ratio of 0.65
FA-30-450-0.45	Concrete made using 450 kg/m³ of 70/30 PC/FA binder blend at a w/b ratio of 0.45
FA-30-450-0.65	Concrete made using 450 kg/m³ of 70/30 PC/FA binder blend at a w/b ratio of 0.65
GB-50-350-0.45	Concrete made using 350 kg/m³ of 50/50 PC/GGBS binder blend at a w/b ratio of 0.45
GB-50-350-0.65	Concrete made using 350 kg/m³ of 50/50 PC/GGBS binder blend at a w/b ratio of 0.65
GB-50-450-0.45	Concrete made using 450 kg/m³ of 50/50 PC/GGBS binder blend at a w/b ratio of 0.45
GB-50-450-0.65	Concrete made using 450 kg/m³ of 50/50 PC/GGBS binder blend at a w/b ratio of 0.45

CHAPTER 1

1 INTRODUCTION

1.1 Background

South Africa like many other developing countries is experiencing continued growth in the construction industry, involving the use of concrete for the development of infrastructure. This growth is depleting natural resources resulting in significant environmental impacts threatening the sustainability of the sector (TRB, 2010). At the same time the generated waste, from the industry, is increasing substantially (Al-Jabri et al., 2009). Given these considerations, there is an increased need to reduce the environmental impact of concrete whilst maintaining its economic and technical aspects.

Blended cement concrete provides significant environmental, economic and technical benefits. Firstly, emissions and energy consumption is reduced by replacing plain Portland cement (PC) with supplementary cementitious materials (SCM's) in blended cement concrete. As SCM's are industrial by-products, lowering the PC demand of concrete by replacement with SCM's therefore lowers the pollution and energy requirements associated with PC production (Van Dam, 2013). Furthermore, by utilising these by-products less waste is directed to landfill sites and natural resources, required for PC production, are conserved. Secondly, the lower production requirements and constituent material costs of blended cement concrete leads to cost savings. Lastly, blended cement concrete provide several technical benefits such as lowering water demand, improvements in workability, durability gains and long term strength improvements (Wang, 2003).

Improving the understanding of the material performance will therefore encourage the use thereof whilst addressing the sustainability challenges facing the concrete construction industry.

1.2 Sensitivity of Concrete to Changes in w/b Ratio and Binder Content

Although there are numerous studies that assess the effects of the change in the water/binder ratio and binder content, of blended cement concrete, on strength and durability properties, limited information is available on the sensitivity of the material to changes in these parameters (Angelucci, 2013).

Sensitivity is the extent to which strength and durability properties of concrete are affected by changes in w/b ratio and binder content. It is measured by conducting sensitivity analyses that quantify the impact of varying the w/b ratio and binder content on the resulting strength and durability properties, and identifying which parameter has a greater influence on the resulting strength and durability properties.

There is thus a need to establish a sensitivity hierarchy of mix design parameters, illustrating their importance on the resultant concrete properties. This will lead to a better understanding of the material performance and provide a firm basis for future trends in codes and specifications for concrete mix design.

1.3 Problem Statement

The steady growth in concrete demand leads to several adverse environmental and economic impacts. Blended cement concrete provides significant environmental, economic and technical gains by reducing emissions, utilising industrial by-products, and enhancing inherent material properties (Van Dam, 2013). Furthering the understanding of the material promotes increased use, innovation and durability.

Blended cement concretes may be optimised by reducing the overall binder content, increasing the SCM replacement percentage and reducing water content. Numerous studies have been conducted on the effect of these parameters on the material but limited information is available on the sensitivity of the material to changes in these the parameters (Angelucci, 2013; Ballim, 1994; Ballim, 2009). The statements outlined below provides context for the matters that need to be addressed in order to improve the understanding of the material and relative importance of the mix design parameters for optimisation purposes.

a) The correlations between compressive strength, water/binder ratio and binder content of concrete is well documented and recorded. Few attempts have been made to understand the sensitivity of compressive strength to changes in these parameters, particularly in relation to blended cement concretes (Angelucci, 2013).
b) The South African Durability Index (DI) tests are used to characterise the quality of the concrete cover. Of these tests, oxygen permeability (SANS 3001-CO3-2, 2015) and chloride conductivity (SANS 3001-CO3-3, 2015) have been formalised for adoption and utilisation in the local construction industry. The water sorptivity test is yet to be formalised; however, it is well documented and recorded (Durability Manual, 2018). The effects of w/b ratio and binder content on these tests are well

documented. However, limited information is available of the sensitivity of these tests to changes in these parameters (Angelucci, 2013).

An understanding of the extent to which a change in w/b ratio and binder content impacts the resulting strength and durability properties of blended cement concretes is therefore required to develop practical guidelines for the concrete mix design process. It is on these grounds that the following aims and objectives are set for this study.

1.4 Aim and Objectives

The aim of this study is to determine the sensitivity of strength and durability properties of blended cement concrete to changes in water/binder ratio and binder content. There is an extensive library of knowledge available on the effects of w/b ratio and binder content on concrete (Angelucci, 2013; Ballim, 1994; Ballim, 2009). This study aims to provide information on the extent to which concrete strength and durability properties are affected by changes in w/b ratio and binder content, illustrating their importance on the resultant concrete properties. In order to achieve this aim, the following objectives were identified:

a) Assessment of the effects and sensitivity of compressive strength of blended cement concrete to changes in the water/binder ratio and binder content.
b) Assessment of the effect and sensitivity of durability of blended cement concrete to changes in the water/binder ratio and binder content considering oxygen permeability, water sorptivity and chloride conductivity.
c) Synthesise the information so as to provide practical implications and recommendations for concrete mix design.

1.5 Scope and Limitations

The scope of this study was limited to the following aspects:

a) The binders used in this study were limited to plain Portland cement (PC, CEM I 52.5R), a blend of 70/30 PC/fly ash (FA) and 50/50 PC/ground granulated blast furnace slag (GGBS). The PC mixes were used as control points to determine the impact of the SCM's. The SCM types and replacement percentages aligns with the recommended practices of the concrete industry for various applications (Erstwhile Cement and Concrete Institute, 2009).
b) Two binder contents of 350 kg/m^3 and 450 kg/m^3. The selected binder contents comply with SANS requirements and are comparable to existing literature as outlined in Chapter 3.

c) Two w/b ratios of 0.45 and 0.65. The 0.45 w/b ratio was used to investigate the influence of less permeable concrete on the strength and durability properties of concrete whereas the 0.65 w/b ratio was used to supplement existing experimental data and to limit the relative high water contents associated to the set binder contents (refer to Chapter 3).
d) 13.2mm Andesite stone and a blend of 50/50 unwashed granite crusher sand and washed plaster sand was used as coarse and fine aggregate, respectively. Andesite and granite is commonly available and the washed plaster sand improved the grading of the fine aggregate and cohesion of the concrete mixes.
e) Strength testing was limited to standard cube (100mm) crushing tests that were conducted at 5 ages: 3, 7, 14, 28 and 56 days. Curing and testing was conducted up to 56 days to take account of the slow-maturing pozzolanic reactions of FA and latent hydraulic reactions of GGBS.
f) Durability testing was limited to the South African Durability index (DI) tests namely oxygen permeability, water sorptivity and chloride conductivity. Tests were conducted at 2 ages: 28 and 56 days. The 56 day tests were included for reasons outlined in point e above.

1.6 Thesis Outline

This thesis is divided into five chapters as follows:

Chapter 1 gives a general introduction of the study.

Chapter 2 is a literature review of the composition of blended cement concrete and provides an overview of two commonly used supplementary cementitious materials. The effects of water/binder ratio and binder content on strength and durability of concrete is discussed. Factors affecting the durability of concrete, transport mechanisms and the South African Durability Index (DI) tests are outlined. Four case studies are reviewed and discussed.

Chapter 3 gives the experimental details and methodology utilised in this study.

Chapter 4 outlines the experimental results of this study accompanied by the analyses and discussion thereof.

Chapter 5 presents the conclusions based on the findings of this study and provides recommendations for future study.

CHAPTER 2

2 LITERATURE REVIEW

2.1 Introduction

This chapter outlines the composition of blended cement concrete with a comprehensive review on two widely used supplementary cementitious materials, namely fly ash and ground granulated blast furnace slag, and their effect on durability and strength parameters of concrete. An overview is provided on the effect of water/binder ratio and binder content on strength and durability properties of concrete. The factors affecting the durability of concrete, transport mechanisms and the South African Durability Index (DI) tests are also discussed.

2.2 Factors Affecting Durability of Concrete

Durability assessments need to account for the interaction between concrete as a system and its exposure environment. Figure 2.1 lists a number of factors which may influence concrete durability. The factors listed under the concrete system relate to the concrete's ability to resist mechanisms of deterioration, whilst those outlined under the exposure environment influence the degree of aggressiveness that the concrete has to withstand (Ballim et al., 2009).

Durability is related to the resistance of concrete to the ingress of deteriorating substances through various transport mechanisms (Alexander et al., 2001). The quality of the near surface concrete is therefore important to limit the ingress of deteriorating agents that lead to the depassivation and corrosion of the reinforcement (Alexander, 2004). Penetrability primarily influences the passage of the deteriorating agents through the concrete and is defined as the degree to which concrete permits gases, liquids or ionic species to progress through its pore structure. It encompasses four transport mechanisms namely permeation, sorption, diffusion and migration which will be discussed in the subsequent paragraphs.

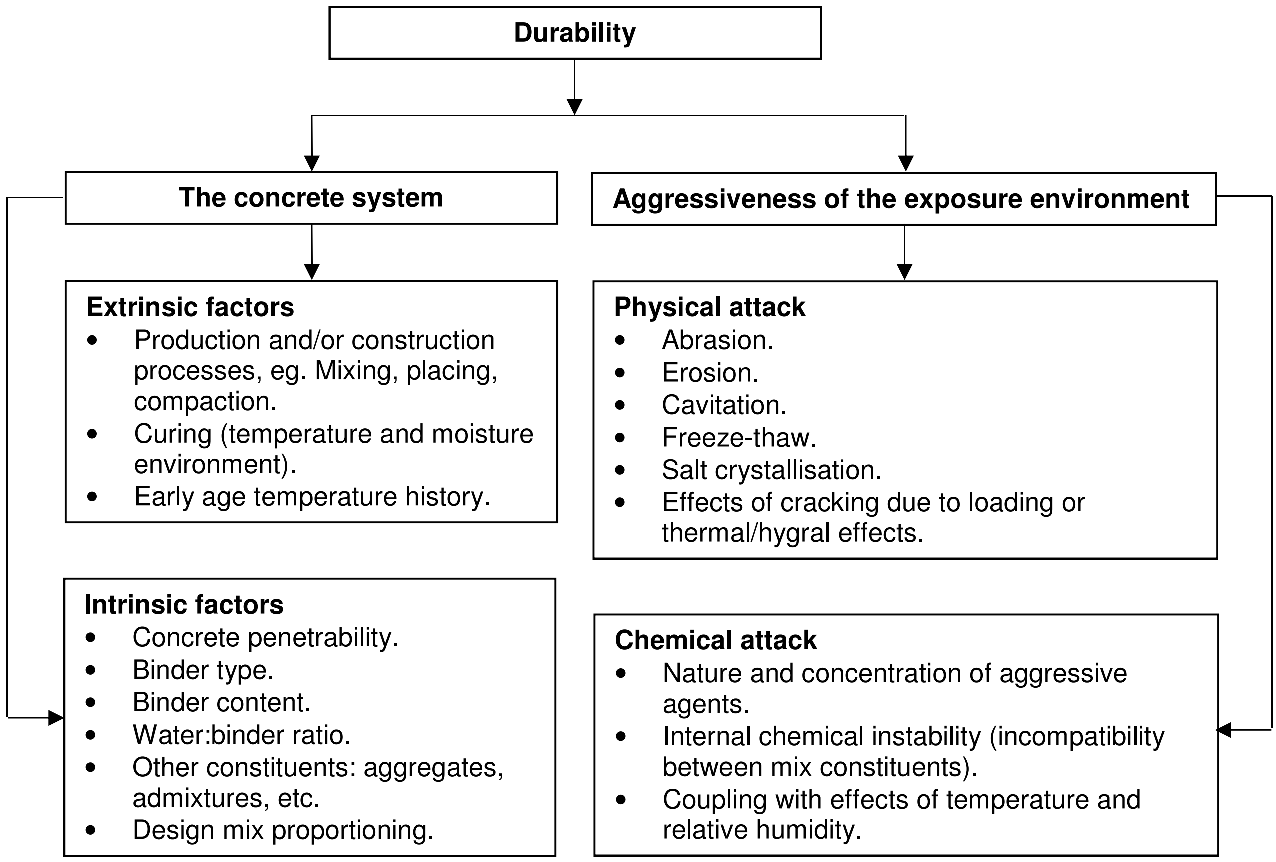


Figure 2.1: Concrete and environment - factors influencing the durability of concrete (Ballim et al., 2009)

2.2.1 Permeation

Permeation describes the process of movement of fluid through the concrete pore structure under the action of a pressure gradient while the pores are saturated (Owens, 2009). Permeability is therefore defined as the ease with which a fluid under pressure can flow through a porous concrete structure (Mehta and Monteiro, 2006).

The mechanism depends on several factors including the concrete microstructure, the moisture condition of the material and the characteristics of the permeating fluid. For a steady-state flow, the rate of transport generally referred as the coefficient of permeability (K), is determined from Darcy's law for laminar flow through a porous medium.

2.2.2 Absorption

Absorption is the process by which fluid moves through the porous concrete structure under capillary suction (Bamforth, 1990). The process occurs in dry or partially saturated conditions where the fluid fills the available pore spaces. The capillary suction is dependent on the pore geometry and the degree of saturation of concrete.

Owens (2009) defines sorptivity as the rate of movement of a wetting front through a porous material under the action of capillary forces. Sorptivity is influenced by hydration of the cover concrete, interconnection of pores, compaction, aggregate orientation, distribution and mix composition.

2.2.3 Diffusion

Diffusion occurs when the concentration of liquid, gas or ions in the external environment is greater that than the concentration of these components within the concrete structure (Bentur, et al., 1997). This concentration gradient allows the components to move through the porous concrete structure. Diffusion is an involved process and depends on the size, porosity and the connectivity of the pores and occurs in partially or fully saturated conditions. Diffusion of chloride ions are of particular concern due to the depassivating effect on embedded steel which leads to corrosion (Bentur, et al., 1997).

The mathematical modelling of the transport mechanism is normally based on Fick's law of diffusion that determines the rate of diffusion of a fluid or liquid into the concrete structure. The concrete structure is assumed to be uniformly permeable (Owens, 2009). Fick's first law shown in equation 2.1 is used to determine the rate of transfer of mass through a unit of section (J). The negative prefix indicates that the flux occurs along a negative concentration gradient. The effective diffusion coefficient, concentration of fluid and distance or penetration depth is determined experimentally.

$$J = -D_{eff}\frac{dC}{dx} \tag{2.1}$$

where:	J	= mass transport rate (g/m²s)
	D_{eff}	= effective diffusion coefficient (m²/s)
	$\frac{dC}{dx}$	= concentration gradient (g/m³/m)
	C	= concentration of fluid (g/m³)
	x	= distance (m)

Generally Fick's second law is employed as it accounts for time variation (refer to equation 2.2). It is based on the validity of several boundary conditions and assumptions including homogenous, inert and constant diffusion properties. These assumptions fail to address that the concrete is heterogeneous, both physical and chemical reactions occur, and that the diffusion properties change with time and with the concentration of the diffusing fluid (Stephen et al., 2010).

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \tag{2.2}$$

where: D = diffusion coefficient (m²/s)

t = time parameter (s)

Using Fick's second law, a time-dependent chloride profile can be predicted when the required parameters are determined. Transport of oxygen is also governed by the diffusion process. Diffusion is considered to be very sensitive to the relative humidity or the degree of saturation of the pores when compared to permeability.

2.2.4 Migration

Migration is the process by which ions in electrolytes move under the action of an electrical field (Ballim et al., 2009). Migration employed by laboratory accelerated test methods, and is described by the Nernst-Planck equation given below in equation 2.3 (Andrade, 1993).

$$-J_j(x) = D_j\frac{\partial C_j(x)}{\partial x} + \frac{z_jF}{RT}D_jC_j\frac{\partial E(x)}{\partial (x)} + C_jV(x) \tag{2.3}$$

where: $J_j(x)$ = unidirectional flux of species j (mol/cm²s)

D_j = diffusion coefficient of species j (cm²/s)

∂C = variation of concentration (mol/cm³)

∂x = variation of distance (cm)

Z_j = electrical charge of species j

F = Faraday's number (coul/eq)

R = gas constant (cal.voltl^{-1}·eq^{-l})

T = absolute temperature (°K)

C_j = bulk concentration of the species j(mol/cm³)

∂E = variation of potential (V)

V = artificial or forced velocity of ion (cm/s)

The model describes the mass flow due to diffusion, migration and convection. The total flux is therefore the sum of diffusion, migration and convection. Migration is considered a prominent mechanism for concrete structures subjected to stray current interference, galvanic corrosion effect, or under cathodic protection in the field.

2.3 Blended Cement Concrete

Concrete is considered to be the most widely used construction material due to its relatively low-cost, widespread availability, versatility and longevity. Unfortunately, this versatility has significant environmental impacts in terms of energy consumption and environmentally harmful gas emissions. These emissions are associated with global climate change which is of growing importance and concern (Van Dam, 2013). Given these considerations, there is an increased need to reduce the environmental impact of concrete whilst maintaining its economic and technical benefits.

To lower the environmental impact of concrete, supplementary cementitious materials (SCM), also referred to as mineral additives, are used in conjunction with plain Portland cement (PC), to make blended cements (Wang, 2003). Depending on the number of SCM's used, blended cement is further defined as either a binary, ternary or quaternary blend where one, two or three SCM's are used respectively (Van Dam, 2013).

Blended cements are increasingly replacing PC in concrete due to the environmental and technical benefits. The substitution of PC with SCM's results in a substantial decrease in emissions associated with cement production as they are generally by-products from other industrial processes or natural materials (NRMCA, 2000). These SCM's also contribute to the technical properties of the concrete by improving workability, durability and long-term strength properties.

2.4 Supplementary Cementitious Materials

SCM are materials that, when blended with PC, contribute to the properties of concrete through hydraulic activity, pozzolanic activity, or both (Kosmatka and Wilson, 2011). Hydraulic activity occurs when SCM reacts directly with water to form cementitious compounds, while pozzolanic activity occurs when SCM chemically reacts with calcium hydroxide, a soluble reaction product of the PC hydration process, in the presence of water to form compounds possessing cementing properties (Neuwald, 2004). Van Dam (2013) reports that calcium silicate hydrate is a preferred hydration product which infers that pozzolanic activity is considered to have a positive effect on the long-term strength and permeability properties of the hardened concrete.

Typical examples of SCM's are fly ash (FA), ground granulated blast-furnace slag (GGBS), condensed silica fume (CSF), limestone and other natural pozzolans. FA and GGBS are the most common SCM's used and will be discussed in the following sections. CSF is typically more expensive than PC and special procedures are warranted when handling, placing and curing mixtures due to the materials inherent extreme fineness, as such it is considered as a property enhancing material and less frequently used (Kruger, 2015). CSF is generally used in concrete to reduce permeability and improve abrasion and chemical resistance particularly for structures exposed to marine and chemical environments.

Limestone is considered to be virtually chemically inert, although there may be some minor reactions. Depending on its fineness, limestone may however act as a fine filler. The effect of limestone on the properties of concrete or mortar depends on the specific limestone and the fineness thereof (Cement and Concrete Institute, 2009). Natural pozzolans represent a family of SCM's produced from natural mineral deposits or biomass. Some of these minerals may be used with only minimal processing whilst others require calcination through heat treatment (NRMCA, 2000). Given limestone's inert nature and the detrimental environmental impacts of utilising natural mineral deposits, the preference is to focus on industrial by-products.

2.5 Fly Ash

Fly ash (FA) is an industrial by-product of coal-fired furnaces at power generation facilities. As the pulverised coal burns, mineral impurities are conveyed in the flue gases, solidifying into spherical glassy particles. These particles are collected from the exhaust gasses by electrostatic precipitators or bag filters (NRMCA, 2000). FA is a variable material and its composition is determined by the source of coal, burning and cooling procedures (Neuwald, 2004). FA generally has a higher particle fineness, approximately 400 m^2/kg Blaine fineness, as compared to PC, around 310 m^2/kg (Motau, 2016 and Mackechnie, 2003). FA is a pozzolan as it forms cementing compounds, calcium silicate hydrate, in water by reacting with calcium hydroxide from the PC hydration process (Arel and Yazici, 2012).

The American Society for Testing and Materials (ASTM) characterises FA by the percentage of compounds present in the material, loss of ignition and several other parameters. The four main constituents are silica dioxide (SiO_2), aluminium oxide (Al_2O_3), iron oxide (Fe_2O_3) and calcium oxide (CaO). The ranges of these constituents are dependent on the selected coal type namely lignite, sub-bituminous, bituminous and anthracite. Lignite, sub-bituminous, bituminous coal types are most commonly used in power generation (Anderson and Brehmer, 2007). Table 2.1 outlines typical FA oxide ranges as compared to PC.

Table 2.1: FA main oxide ranges compared to PC
(Grieve, 2009)

Oxide	FA	PC
	% Composition by mass	
SiO_2	48.0-55.0%	19.0-24.0%
Al_2O_3	28.0-34.0%	4.0-7.0%
CaO	4.0-7.0%	63.0-69.0%
Fe_2O_3	2.0-4.0%	1.0-6.0%

ASTM C618 – 15 (2007) classifies FA on the combined value of the silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3) content. Class F and C designations are given when the combined value exceeds 70 and 50 percent respectively. Class F FA will typically have less calcium oxide than Class C, but no limit is established in the specification. Class F fly ashes are pozzolanic in nature while Class C FA's are both pozzolanic and hydraulic in nature.

The South African National Standard (SANS) providing guidance on the use of FA is SANS 50450-1 (2014). This standard is the identical implementation of EN 450-1:2012 and characterises FA by classification. Class N and Class S designations are given to selected but unclassified and classified FA's respectively. Class S FA is either air-classified (sub 45 micron particle size) or twice-classified (sub 8 micron particle size).

Given South Africa's significant coal reserves, power generation is dominated by coal-fired power stations. The annual production of coal ash is approximately 35 million tons with FA and bottom ash accounting for 29 and 6 million tons respectively. Coal ash production is estimated to reach 42 million tons by 2020. FA sales were recorded at 2.5 million tons per annum in 2014 showing the significant available reserves of the SCM's. The production of blended cement is the predominant application of FA in the South African building and construction industry (Kruger, 2015).

Generally, FA has been used in blended cements at levels ranging from 15% to 25% by mass although levels of up to 30% to 50% have been used in large structures to control temperature rise. Thomas (2007) indicated that high FA dosages, of 40% to 60%, produce concrete with good mechanical properties and durability. There are however draw backs to using high dosage levels and the optimum dosage is case-dependant. Similarly, Crouch et al. (2007) reported improved 28 day compressive strength and permeability results for high volume fly ash concretes at 50% PC replacement. Madhavi et al. (2014) supported the findings of Thomas (2007) and Crouch et al. (2007) and noted extended setting times and low early age strength for FA replacements values of 50 to 60% as compared to general replacement figures of 15 to 25%.

2.5.1 Effect of FA on Strength

Due to the pozzolanic reaction in FA concretes, early age strength development, up to 14 days, is generally lower than those displayed by concretes made with PC, with strength maturing significantly in the long term. Bertolini et al. (2013) reports marked reductions in the early age compressive strength of concrete with the proportional replacement of common cement with FA. As the level of replacement increases the early-age strength decreases as less calcium hydroxide, from the PC hydration process, is available for the hydraulic reaction (Van Dam, 2013). However, long-term strength development is improved when FA is used but the time taken to achieve the same strength as for common cement increases with increased replacement percentages.

Figure 2.2 illustrates the effect of FA on the compressive strength development of concrete, up to 28 days. The control mix is only composed of PC binder whereas the FA mixes contain blends of PC and FA binders. The replacement percentage, shown as a number after the FA designation, indicates the mass of PC replaced by an equal mass of FA in the mixes. Up to 7 days, compressive strength generally decreases with increasing FA replacement. At 28 days, this effect is less notable and some FA mixes exceed the control mix (Mohamed and Najm, 2017).

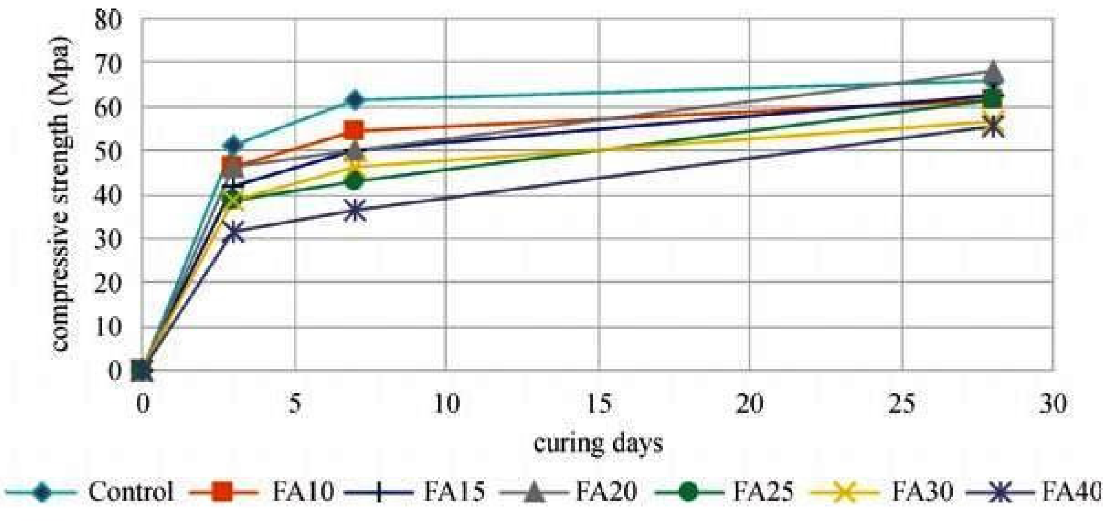


Figure 2.2: Effect of fly ash on compressive strength development of concrete (Mohamed and Najm, 2017)

2.5.2 Effect of FA on Durability

FA refines the microstructure of the hydrated cement paste by transforming larger pores into finer ones which has a marked impact on the resulting concrete permeability (Ballim, 1994). This is due to the slow-maturing pozzolanic reaction of FA that densifies the concrete matrix by reacting with water and hydroxides, released by the hydration of PC, and filling the pores of the concrete matrix. Due to this refinement process, the interconnectivity of pores in the concrete matrix is disrupted, the permeability reduced and the concrete's resistance to the transport of deteriorating substances improved (Du Preez, 2002).

Thomas and Matthews (1992) noted that concretes containing FA are of lower permeability than equal-grade PC concretes, the differences increasing with FA content. This is applicable to a binder content range between 250-350 kg/m^3 and replacement percentages up to 50%. Mukadam (2014) showed that the OPI of the mixes containing FA are consistently higher than for the other binder combinations as shown in Figure 2.3 due to the pore refining and filler effects of the SCM. Decreases in water sorptivity were also observed as depicted in Figure 2.4. Furthermore, FA decreased the chloride conductivity of specimens as compared to PC mixes (Figure 2.5); however, the beneficial impact of GGBS was the most notable as discussed under section 2.6.2.

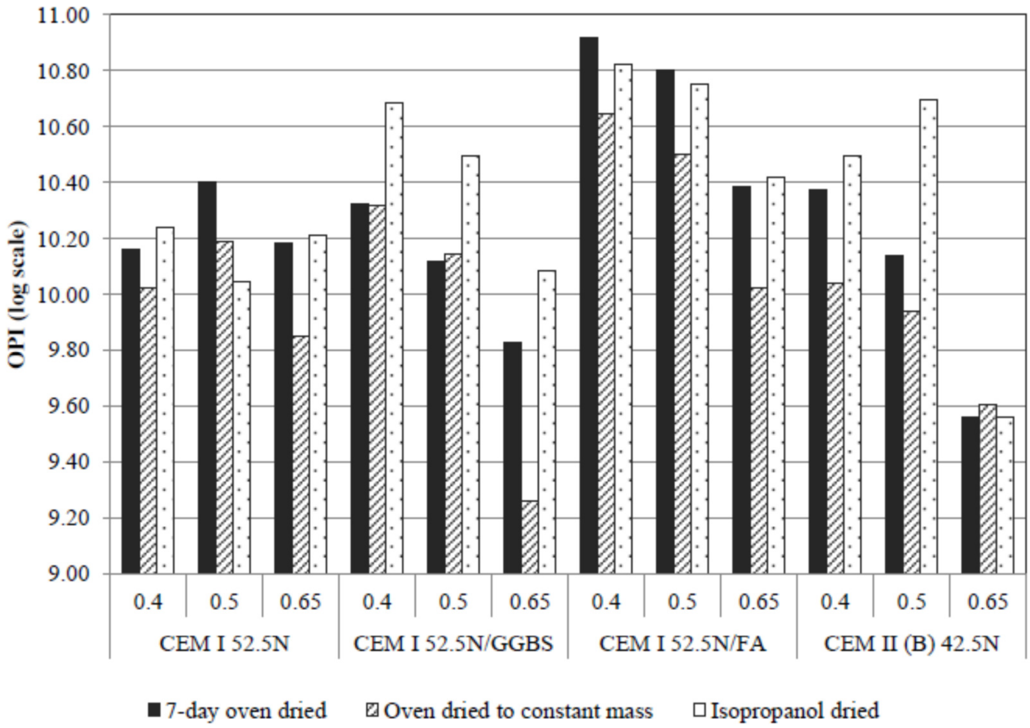


Figure 2.3: OPI results for various binder combinations
(Mukadam, 2014)

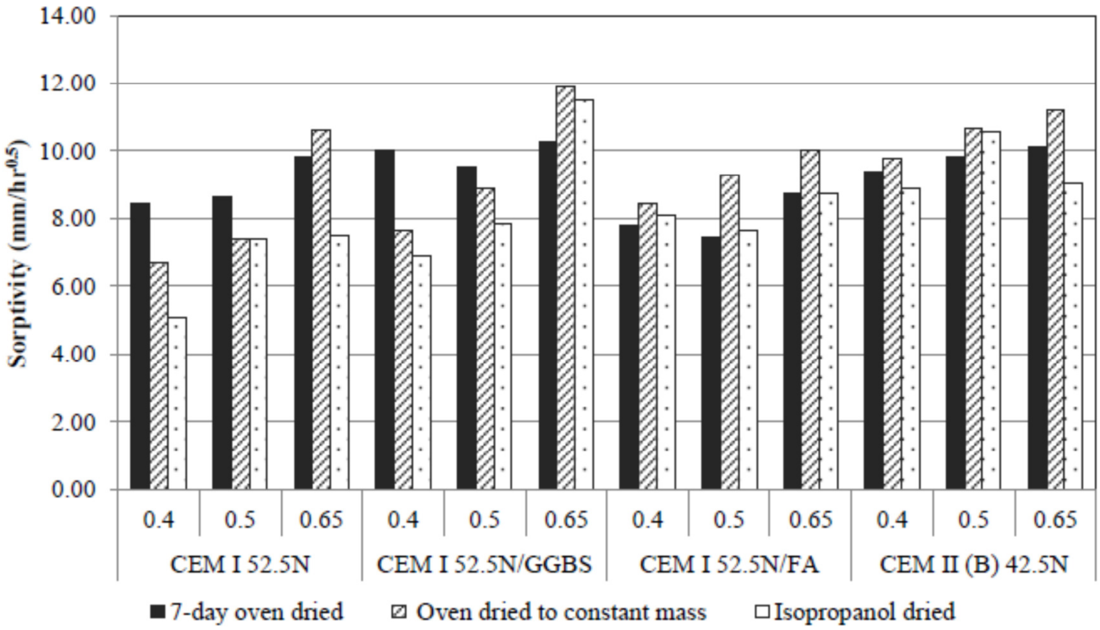


Figure 2.4: WSI results for various binder combinations
(Mukadam, 2014)

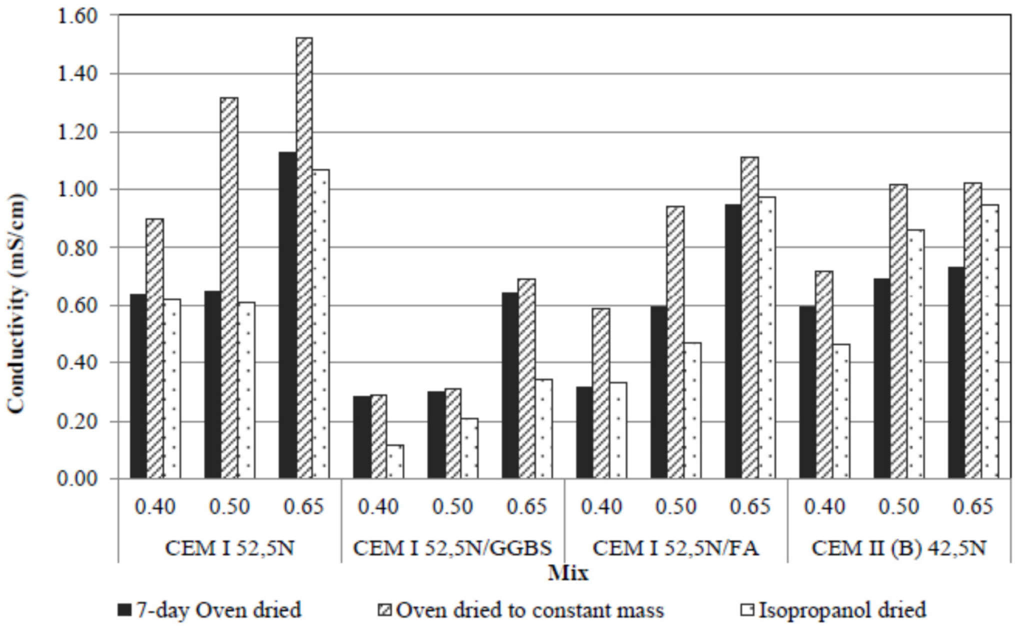


Figure 2.5: Chloride conductivity results for various binder combinations
(Mukadam, 2014)

2.6 Ground Granulated Blast Furnace Slag

Slag is an industrial by-product of blast furnaces when iron ore is reduced to pig iron. During this process the remaining molten material (slag) is directed into a granulator where the material is water-quenched, to form glassy granules, dried and then ground into a fineness similar to PC producing GGBS (Van Dam, 2013). Alternate types of slag, such as air-cooled and pulverised, are produced by varying the particular process. GGBS is a latent hydraulic binder requiring an alkali activator to react with and in water to form cementing compounds (Grieve, 2009).

The composition of slag varies considerably depending on the composition of the raw materials in the iron production process. The main constituents are calcium oxide (CaO), silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) and magnesium oxide (MgO). The typical ranges of these constituents are outlined in Table 2.2 and compared to typical ranges in PC.

Table 2.2: Chemical composition of GGBS and PC
(Grieve, 2009)

Oxide	GGBS	PC
	% Composition by mass	
SiO_2	34.0-40.0%	19.0-24.0%
CaO	32.0-37.0%	63.0-69.0%
Al_2O_3	11.0-16.0%	4.0-7.0%
MgO	10.0-13.0%	0.5-3.6%

The reactivity of GGBS relates to the activity index of the material which is dependent on its glass content, chemical composition (increased CaO and Al_2O_3 leads to higher reactivity), fineness and activation effect of different PC clinkers. However, this mainly depends upon the fineness of the material (Divsholi et al., 2014). GGBS generally has a higher particle fineness, >360 m^2/kg Blaine fineness, as compared to PC, around 310 m^2/kg (Afrisam, 2013 and Mackechnie, 2003).

In accordance with ASTM C989, GGBS has three strength grades which are determined by their respective mortar strength when they are mixed with an equal mass of PC. The three grades, 80, 100, and 120, are classified according to their slag activity index. This index is calculated by dividing the average compressive strength of the slag cement cubes by the average compressive strength of the reference cement and expressing this value as a percentage. Grades 100 and 120 are the most commonly used. The standard prescribes the mixture proportions for each type of cube, a size requirement of residue left on a 45 micron sleeve and a limit on the air content in the slag mortar. Restrictions are also imposed on the sulphur and sulphate contents (Cervantes and Roesler, 2007).

The South African standard governing GGBS is SANS 55167-1 (2011). This standard is the identical implementation of EN 15167-1:2006. The standard prescribes that the slag chemical composition should consist of at least two-thirds by mass of the sum of the calcium oxide (CaO), magnesium oxide (MgO) and silicon dioxide (SiO_2). The remainder shall be aluminium oxide (Al_2O_3), together with small amounts of other compounds such as iron oxide (FeO), manganese oxide (MnO), potassium oxide (K_2O), sulphur (S) and titanium dioxide (TiO_2).

GGBS is an attractive SCM as the typical dosage is significantly higher than that of FA (Van Dam, 2013). GGBS can be used as a direct replacement for PC. Generally replacement rates for GGBS vary from 30% up to 85, with 50% being used in most applications. Higher replacement rates up to 85% are used in special applications like aggressive environments and to reduce the heat of hydration in mass concrete (Siddique and Khan, 2011).

2.6.1 Effect of GGBS on Strength

GGBS contributes to concrete strength by its steady hydration process which refines the pore structure over time. Lower early age strengths, as comparted to PC concretes, are generally reported but this improves over time (Angelucci, 2013).

For replacement rates up to 50%, Divsholi et al. (2014) reported slight increases in the 28-day compressive strength and similar values at 3 days as compared to PC. In the first 7 days the compressive strength is generally slightly lower than PC. In the 7 to 14 day range, the compressive strength is about equal to the strength of concrete without SCM. Refer to Figure 2.6. The ultimate gain in strength is noticed after the 28 day mark especially when 120 grade GGBS is used (Elliot, 2007).

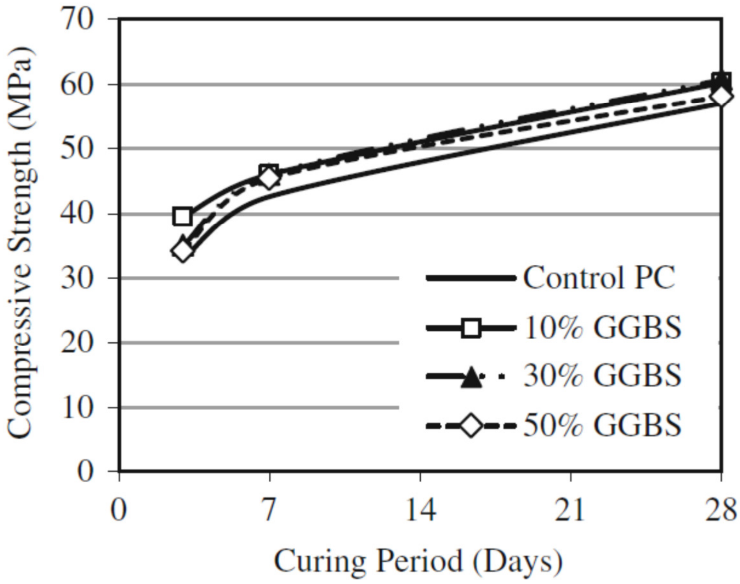


Figure 2.6: Effect of GGBS replacement on compressive strength
Divsholi et al. (2014)

2.6.2 Effect of GGBS on Durability

The benefit of GGBS in concrete lies in its chloride binding capabilities which leads to lower chloride diffusion coefficients that either PC only or FA extended mixes (Ballim, 1994). Kumar et al. (1986) concluded that the average pore size of PC concrete was larger than that of GGBS concrete due to the latent hydraulic reaction of GGBS that densifies the concrete matrix and reduces the pore size. This in turn decreases the penetration and diffusion of chloride ions.

Figure 2.5 indicates the beneficial role of GGBS with lower conductivity values than FA and PC binder combinations. Mukadam (2014) showed that the OPI of the mixes containing GGBS were higher than the PC mixes, at a w/b ratio of 0.40. As the w/b ratio increased, GGBS has a detrimental effect on OPI as shown in Figure 2.3. Increases in water sorptivity were also observed for GGBS mixes as depicted in Figure 2.4.

2.7 Water/Binder Ratio

2.7.1 Effect of w/b Ratio on Strength

W/b ratio is regarded as the determining factor for both strength and penetrability of the hydrated cement paste and refers to the ratio of the total water to the total binder utilised (Grieve, 2009). The microstructure of the hydrated cements paste and the associated mechanical properties depend largely on this ratio.

For a low w/b ratio (0.25) paste the hydrated cement paste obtains a dense microstructure due to comparatively small spacing between the binder particles. Hydration occurs rapidly via diffusion of water molecules inside the unhydrated cement particles to from an "inner product" (Malhotra, 1994). However, for a high w/b (0.65) paste the hydration products of the cement particles need to extend further to interact with one another. As a result, "outer product" forms through dissolution and precipitation which is weaker that the "inner product" structure (Malhotra, 1994). Therefore concretes with low w/b ratios have enhanced strength due to a high densification of the hydrated cement paste microstructure.

This theory is supported by Yang et al. (2010) whose results note a decrease in the compressive strength of concrete with an increase in the w/b ratio. Figure 2.7, complied by (Mukadam, 2014), further supports this point and shows a decrease in compressive strength for all binders as the w/b ratio is increased.

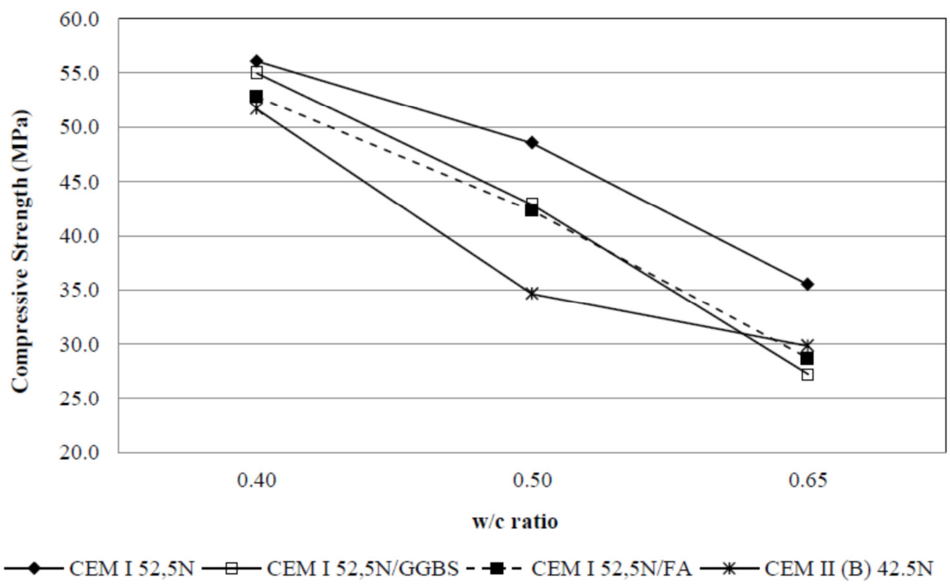


Figure 2.7: 28-day compressive strength results
(Mukadam, 2014)

2.7.2 Effect of w/b Ratio on Durability

The permeability of the concrete system is most affected by the capillary pores and the degree of interconnectivity. At low w/b ratios hydration products rapidly occupy the voids between cement particles. However, at higher w/b ratios hydrations products need to extend over larger distances to occupy these voids resulting in a higher capillary pores fraction Angelucci, 2013). Permeability therefore increases considerably with an increase in w/b ratio due to the associated increase in porosity and interconnectivity of pores (Ballim, 1994). At low w/b ratios, the paste microstructure is denser and permeability is reduced whereas at high w/b ratios the excess water present in the matrix evaporates with time leaving larger, interconnected capillary pores resulting in a higher permeability (Malhotra, 1994). This is clearly shown in Figure 2.8.

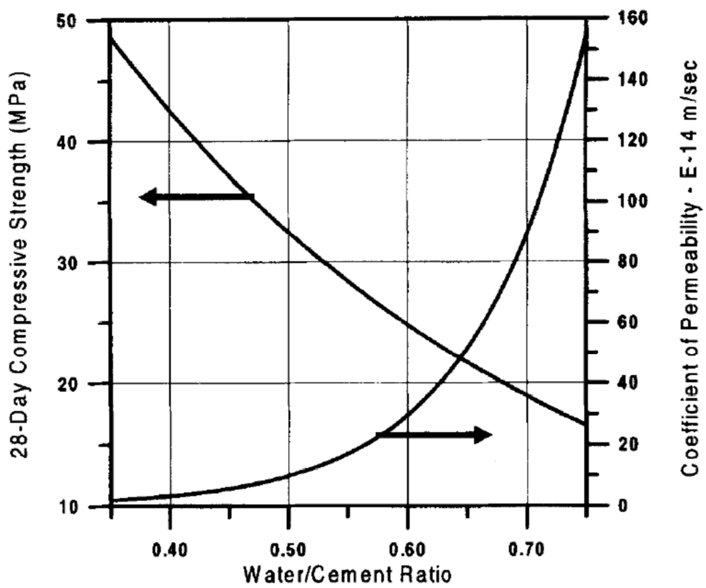


Figure 2.8: Effect of w/b ratio on 28-day compressive strength and permeability of PC concretes
(Hover, 1998)

Metha and Monteiro (2006) further concluded that the development of the interfacial transition zone is more enhanced at higher w/b ratios due to the formation of larger portlandic crystals, which account for the weakest and most porous phase of the concrete system. The permeability of concrete will be low provided a low enough w/b ratio is used, irrespective of how much water there is in the mix. According to Ballim (1994), this may only be the case for mixes that are well proportioned. In cases where the water content is increased while keeping the w/b ratio constant then the bleeding phenomenon will lead to excessive voids around the aggregates which increases the transport properties. This places emphasis on the importance of proper mix proportioning to ensure durable concrete is produced.

2.8 Binder Content

2.8.1 Effect of Binder Content on Strength

Various prescriptive specifications and requirements focus on binder contents; however, it directly impacts the w/b ratio and should not be considered in isolation. Previous studies have led to contradictory findings on the effect of this parameter on compressive strength.

Wasserman et al. (2009) recorded that strength is independent of binder content for a given w/b ratio as shown in Figure 2.9. This is consistent with the prevailing concept that strength is a function mainly of w/b ratio. Different results were however obtained in other studies.

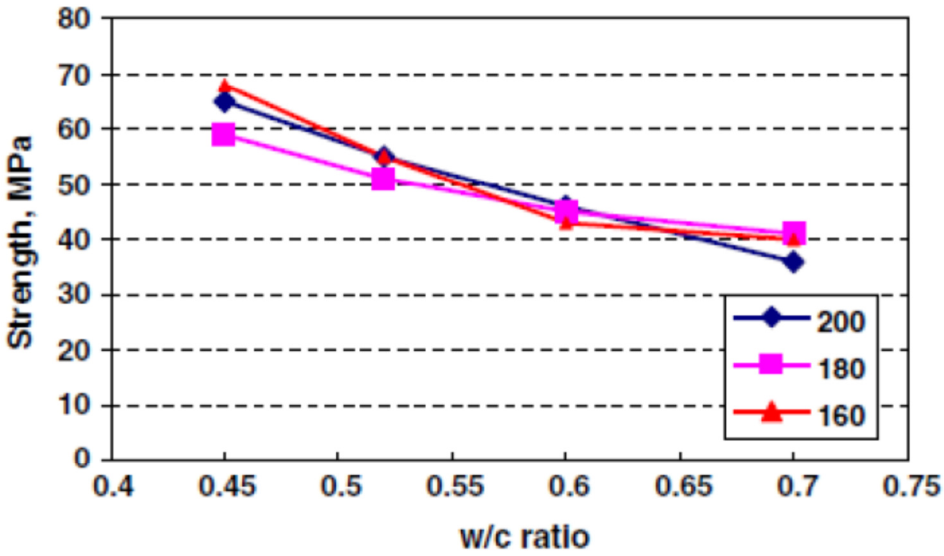


Figure 2.9: Effect of binder content (160, 180 and 200 kg/m³) on 28-day compressive strength

Wasserman et al. (2009)

Bertolini et al. (2013) reported in their experiments that for a given w/b ratio, an increase in the compressive strength is noted as the cement content increases. However, the report is limited to w/b ratios in the range of 0.42 to 0.61, binder contents of 300 to 400kg/m³ and FA contents of 0-30%. Furthermore, Yigiter et al. (2007) found that for low w/b ratios, increases in binder content had positive impacts on strength; however, further binder content increases had the opposite effect although less pronounced. For high w/b ratios, similar trends were observed but the effect was less evident. This is shown in Figure 2.10 and may be explained as follows (Angelucci, 2013):

a) At low w/b ratios and binder contents, insufficient paste volume is available to bind the aggregates which results in discontinuities (pores and voids) in the concrete.
b) If the binder content is increased for a constant w/b ratio, more paste is available to bind the aggregates which lead to strength improvements.
c) Continued increases in the binder content for a constant w/b ratio results in further increases in the paste volume which leads to higher inherent proportion of pore spaces with negative effects on strength.

d) Comparable points can be made when considering high w/b ratios although the overall impact of increasing binder contents will be less pronounced. This is due to the high past volumes from onset regardless of low binder contents.

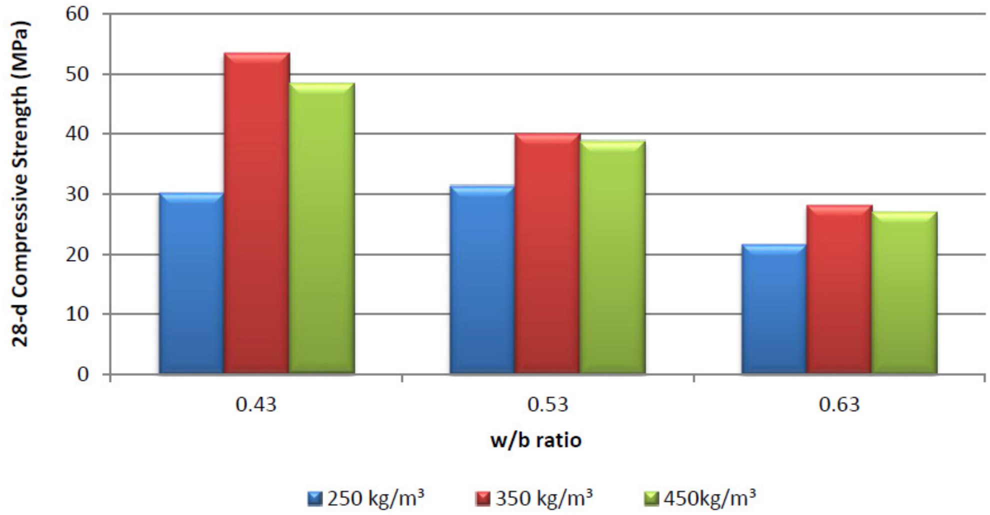


Figure 2.10: Compressive strength vs binder content for PC concretes (Yigiter et al., 2007)

Angelucci et al. (2017) found that compressive strength generally decreases with increasing binder content, although differences were relatively low and averaged less than 5 MPa for binder reductions of 65 to 100 kg/m³ (Figure 2.11). This was attributed to easier crack propagation through concrete containing more paste.

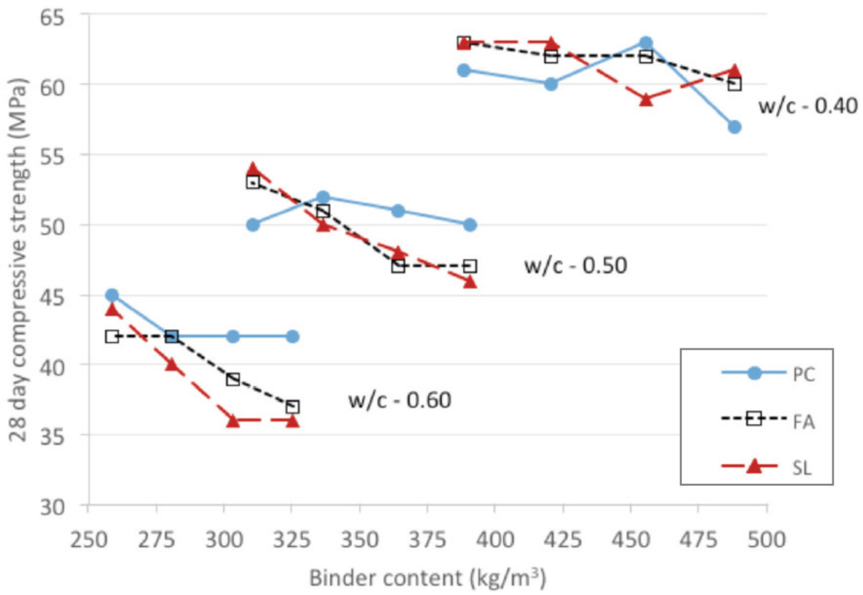


Figure 2.11: Binder content vs compressive strength at 28 days (Angelucci et al., 2017)

2.8.2 Effect of Binder Content on Durability

Prescriptive approaches are generally followed in design standards that provide minimum binder content and associated compressive strength requirements for given exposure conditions. These approaches have been shown to be too conservative and in some instances detrimental to concrete durability (Wasserman, 2009). Increasing the binder content at a constant w/b ratio increases the paste volume which is the most significant contributor to porosity and permeability of the concrete system (Kolias et al., 2005). This has a detrimental impact on durability and is more prevalent in high w/b ratios.

Permeability was found to increase consistently with increasing binder content apart from FA concrete. This is due to the fact that the pozzolanic reaction of FA refines the microstructure of the hydrated cement paste by transforming larger pores into finer ones, increasing the matrix density (Thomas and Matthews, 1992). GGBS concrete tended to have higher permeability as compared to FA and PC concretes (Angelucci et al., 2017). These findings are presented in Figure 2.12.

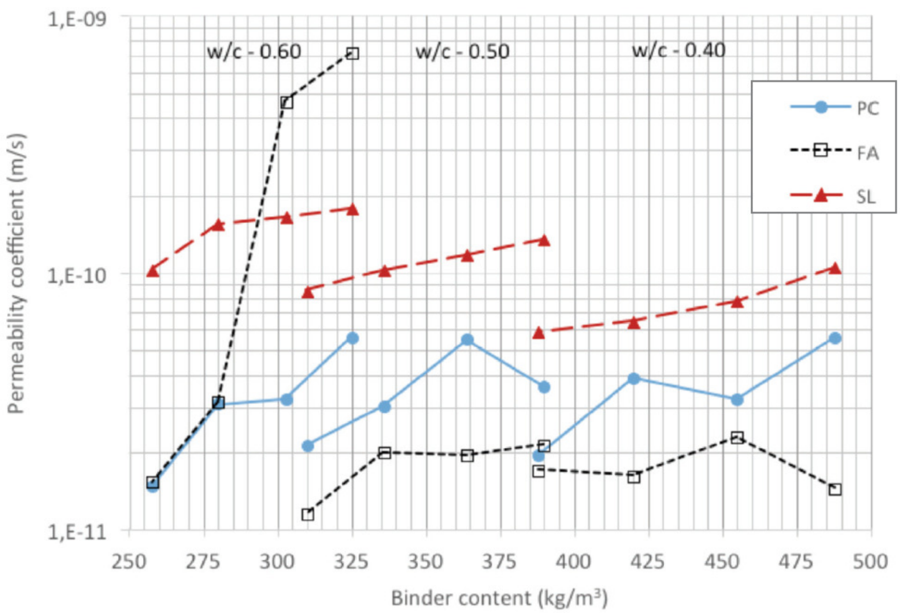


Figure 2.12: Permeability coefficient versus binder content at 28 days (Angelucci et al., 2017)

Angelucci et al. (2017) further noted decreases in absorption of concrete with lower w/b ratios but this tended to rise as the binder contents increased for concretes with the same w/b ratios. Figure 2.13 outlines these relationships between sorptivity and binder content.

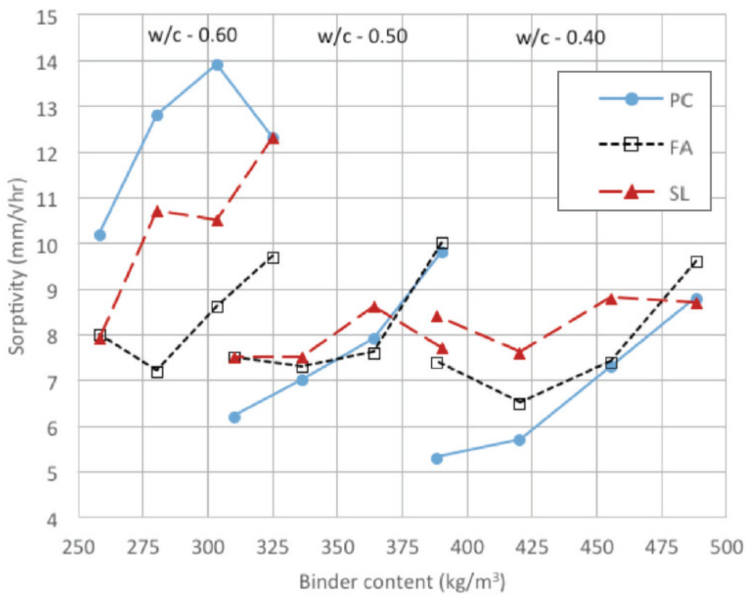


Figure 2.13: Sorptivity versus binder content at 28 days
(Angelucci et al., 2017)

PC concrete had the highest CCI value and was the most affected by changes in w/b ratio and binder content. FA concrete had an intermediate CCI value and showed sensitivity to changes in binder content at higher w/b ratios. GGBS concrete had the lowest CCI value and sensitivity to changes in binder content (Angelucci et al., 2017). Refer to Figure 2.14 as reference.

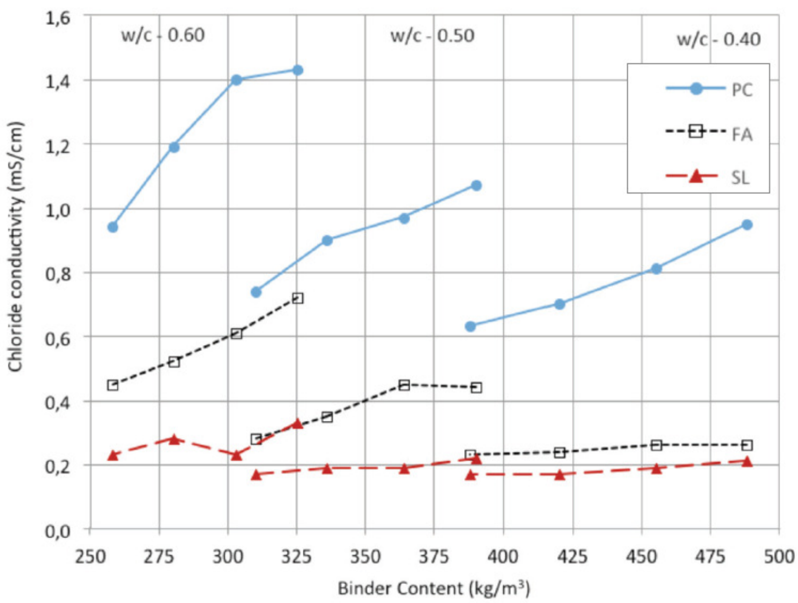


Figure 2.14: Chloride conductivity versus binder content at 28 days
(Angelucci et al., 2017)

2.9 Prescriptive vs Performance-Based Specifications

Prescriptive approaches outline requirements for material compositions and proportions, procedures and test methods. Such approaches are 'recipe-type' specifications and generally include requirements for, amongst others, minimum compressive strength, maximum w/b ratio, minimum SCM content and cover depth. No direct requirements are imposed on concrete performance and these requirements have limited effectiveness and often stifle innovation (Bickley *et al.*, 2006). Material and construction variability is therefore not taken into account and it is difficult to ensure that the specified requirements are achieved (Day, 2005).

The South African durability standard comprises of exposure classes, cover depth, crack width, cement content and w/b ratios and allows for alternative approaches if they can be shown to be valid or useful. Although the standard accounts for some advances in concrete technology it still lags behind many aspects related to durability (Kessy *et al.*, 2015). Comparable international standards, including European, Canadian, Australian and American, are also predominantly prescriptive in nature and fail to meet the needs of modern code formulations or the demands of modern concrete construction (Alexander *et al.,* 2010).

For concrete durability, the emphasis must be placed on concrete cover quality and thickness whilst recognising the contribution of modern binder systems. The impact of w/b ratio and binder content on the resulting durability properties is therefore of importance (Angelucci, 2013). Minimum binder contents impose a lower limit for concrete mixes but upper limits are not explicitly specified and adherence to specifications of maximum w/b ratios and minimum binder contents often results in higher binder contents than required (Wasserman *et al.*, 2009).

Performance-based specifications aim to address these shortcomings by taking into account exposure conditions and measured material characteristics, in particular transport related properties for durability (Alexander *et al.*, 2010). The main objective of performance based specifications is therefore to enable the design and specification of concrete mixes taking account of local material availability, functional demand, type of application and exposure environment (Angelucci, 2013). This leads to project cost optimisations and efficient solutions addressing the concrete durability performance requirements. Performance based methodologies therefore provide a holistic approach that take account of the relationships between the mix design parameters, constituent materials and desired concrete properties. In South Africa, the Durability Index (DI) approach is increasingly being implemented and the impact of mix design parameters on the resulting durability properties need to be further investigated and understood.

2.10 Durability Index Tests

Durability of reinforced concrete structures is a prevalent problem worldwide. To address this problem, three durability index tests (DI) have been developed in South Africa that measure the resistance of concrete to the transport of deteriorating substances (Alexander et al., 2001). The tests are based upon the philosophy that durability will only be notably improved when it is possible to measure parameters that control durability performance. The DI tests therefore provide a performance based approach to improve the durability of reinforced concrete construction. Each test relates to a transport process in concrete and the suite is comprised of the Oxygen Permeability Index (gaseous diffusion), Water Sorptivity Index (water absorption) and Chloride Conductivity Index (ionic diffusion). Table 2.3 lists the tests and applicable South African standards or methods.

Table 2.3: Durability index tests

Durability Index Test	*Standard/Method*
Oxygen permeability	SANS 3001-CO3-2 (2015)
Water sorptivity	Durability Manual (2018)
Chloride conductivity	SANS 3001-CO3-3 (2015)

The durability indices obtained from these tests methods are related to service life prediction models (Beushausen & Alexander, 2008). For example, OPI is used as a predictive tool for estimating carbonation depths in structures, while the CCI is used for chloride ingress estimations. These prediction models are based on empirical correlations between index values and rates of ingress of aggressive agents. Further correlations are aimed at fundamental modelling founded on hydration and microstructure development joined with transport models and accounting for environmental influences (Griesel and Alexander, 2003). Index value requirements and specifications may be implemented in construction specifications to provide the required concrete quality for the required service life and environment. Suggested ranges for durability classification are outlined in Table 2.4. The durability classes, listed in the Table, are relative to the desired durability and only for indicative purposes.

Table 2.4: Ranges for durability classification
(Alexander et al., 2001)

Durability Class	Oxygen Permeability (OPI, log scale)	*Water Sorptivity* (WSI, mm/√hr)	Chloride Conductivity (CCI, mS/cm)
Excellent	>10.0	<6.0	<0.75
Good	9.5-10.0	6.0-10.0	0.75-1.50
Poor	9.0-9.5	10.0-15.0	1.50-2.50
Very Poor	<9.0	>15.0	>2.50

The testing procedures are well documented; some have been adopted and captured as South African National Standards (SANS) as outlined in Table 2.7.1; hence only an overview is provided below.

2.10.1 Oxygen Permeability Test

This test method involves measuring the pressure decay of oxygen passed through concrete disc specimens placed in a falling head permeameter (Beushausen & Alexander, 2008). The coefficient of permeability (k) is determined from the Darcy equation, governing the rate of pressure decay of a falling head permeameter (Balim, 1993). Figure 2.15 shows the apparatus arrangement.

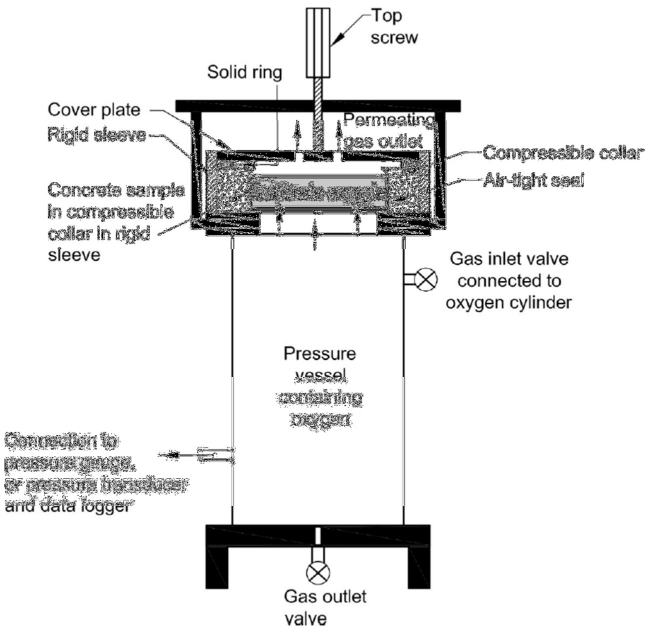


Figure 2.15: Oxygen Permeability Index test cell arrangement
(SANS 3001-CO3-2, 2015)

Concrete disc specimens of 70 ± 2mm diameter and 30 ± 2mm thickness are preconditioned by oven drying at 50 ± 2°C for not less than 7 days and not more than 8 days. After drying, the specimens are removed from the oven and placed in a desiccator to cool to 23 ± 2°C for a minimum of 2 hours and a maximum of 4 hours. The specimens are then weighed and the thickness and diameter measured. Afterwards the specimens are placed in compressible rubber collars and inserted into a falling head permeameters. The collars ensure that all oxygen losses occur through the specimen. The apparatus is charged with oxygen, at an initial pressure of 100 ± 5kPa, and allowed to decay to 50kPa or up to a period of 6 hours, whichever occurs first. During this period, the pressure drop is recorded at 15 minute intervals. The oxygen permeability coefficient is determined from the following equation:

$$k = \frac{\omega V g d}{R A \theta t} \ln \frac{P_0}{P} \tag{2.4}$$

where:	k	= coefficient of permeability (m/s)
	ω	= molecular mass of permeating gas (0.032 kg/mol)
	V	= volume if the pressure cylinder (m^3)
	g	= acceleration due to gravity (9.81 m/s^2)
	d	= specimen thickness (m)
	R	= universal gas constant (8.313 Nm/Kmol)
	A	= cross-sectional area of specimen (m^2)
	θ	= absolute temperature (K)
	t	= time (sec)
	P_0, P	= pressure at start of test and at time t respectively (kPa)

In order to simplify the above coefficient, the “oxygen permeability index” is defined as the negative log of the k value as follows:

$$OPI = -\log_{10} k \tag{2.5}$$

OPI values for concrete typically range from 8.50 to 10.50 with higher values being representative of less permeable concrete (Ballim et.al, 2009). Figure 2.16 displays typical results of OPI tests for widely used South African concretes. The test outlines the gas permeation properties of concrete and an estimation of its resistance to the transport of gaseous substances into concrete.

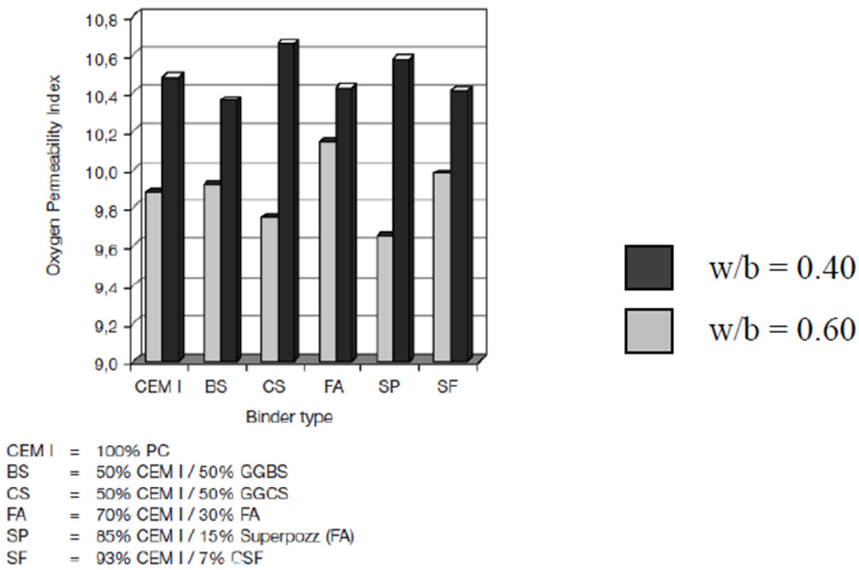


Figure 2.16: Typical OPI results for South African concretes at 28 days (Ballim et.al, 2009)

2.10.2 Water Sorptivity Test

The water sorptivity test is based on measuring the unidirectional ingress of water into a preconditioned concrete disk specimen (Beushausen & Alexander, 2008). Sorptivity is defined as the rate of movement of a wetting front through a porous material under the action of capillary forces. This is largely influenced by the pore geometry including the orientation and connectivity (Du Preez, 2002).

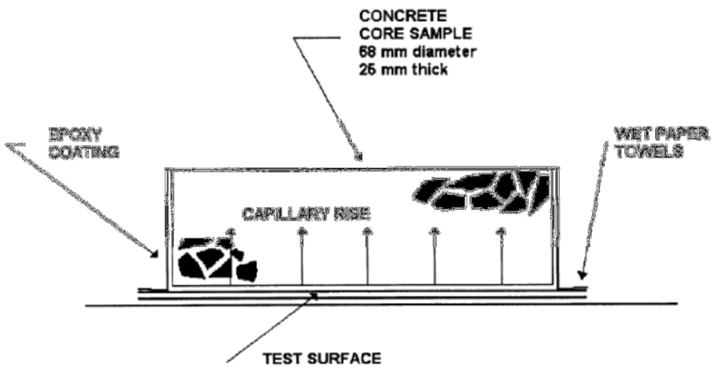


Figure 2.17: Schematic of water sorptivity test (Alexander et al., 2006)

Specimens are prepared (70 ± 2mm dimeter and 30 ± 2mm thickness) and pre-conditioned by oven drying (at 50°C for 7 days) and sealing on the circumferential surfaces, to ensure unidirectional movement. Thereafter, the test surfaces of the specimens are exposed to a saturated calcium hydroxide solution and the specimens are weighed at 3, 5, 7, 9, 12, 16, 20 and 25 minute intervals to determine the mass of absorbed solution (Figure 2.17). Prior to saturation, the specimens are vacuum saturated as shown in Figure 2.18.

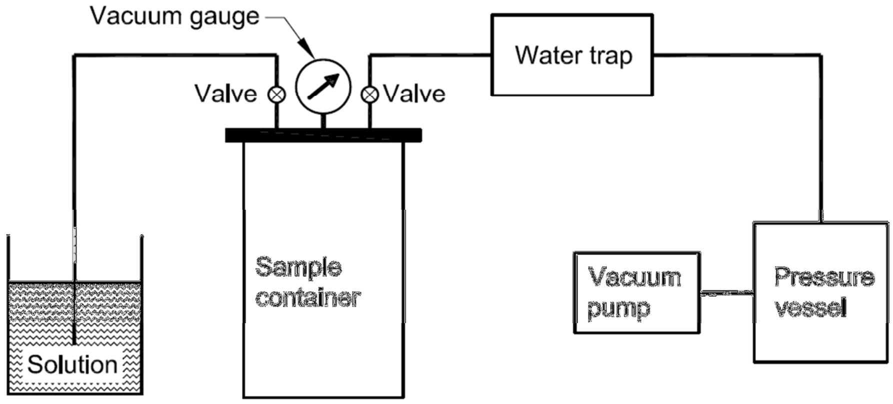


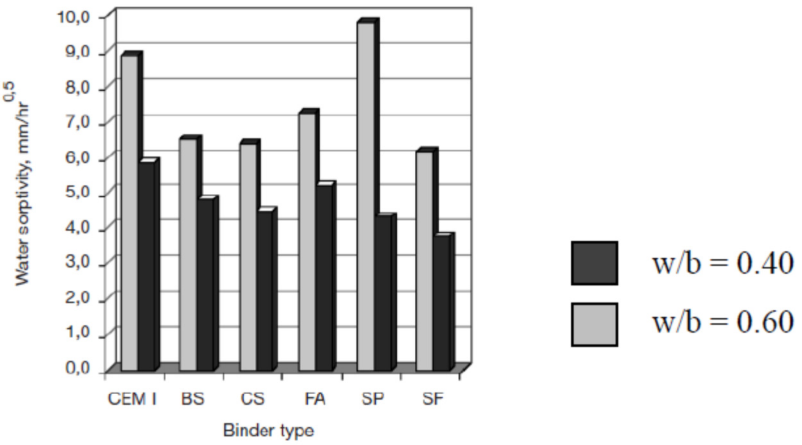
Figure 2.18: Schematic of vacuum saturation tank
(Alexander, 2017)

The sorptivity, S, is calculated from the slope of the straight line of mass of saturated calcium hydroxide solution absorbed versus the square root of time as follows:

$$S = \frac{Fd}{M_{sv} - M_{s0}} \qquad (2.6)$$

where: F = slope of line of best fit (g/√hr)
d = average thickness of specimen (mm)
M_{sv} = mass of vacuum saturated surface dry specimen (g)
M_{s0} = mass of oven-dried concrete (g)

Lower water sorptivity values indicate higher quality of concrete cover. Typical water sorptivity values range from 3.5mm/√h to 9.5mm/√h for various blended cements at 28 days of age (Ballim et al., 2009), these ranges are outlined in Figure 2.19.



CEM I = 100% PC
BS = 50% CEM I / 50% GGBS
CS = 50% CEM I / 50% GGCS
FA = 70% CEM I / 30% FA
SP = 85% CEM I / 15% Superpozz (FA)
SF = 93% CEM I / 7% CSF

Figure 2.19: Typical WSI results for South African concretes
(Ballim et al., 2009)

2.10.3 Chloride Conductivity Test

Diffusion is the process by which ions and molecules travels through a porous material under the action of a concentration gradient. This transport mechanism is of particular importance to chlorides which pose long term durability concerns by depassivating the reinforcement and thus inducing corrosion. The chloride conductivity test measures this phenomenon in concrete specimens.

The test involves pre-conditioning of the specimens by oven drying, followed by vacuum saturation and soaking in 5M NaCl solution. The test measures the ionic flux (current, i) across the saturated specimens due to an applied potential difference (10V) as shown in Figure 2.20.

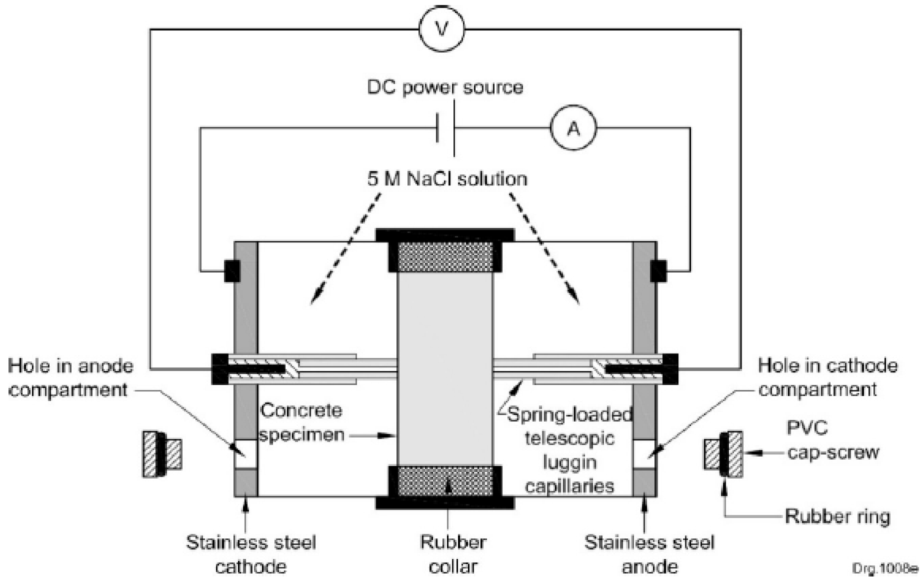


Figure 2.20: Schematic of chloride conductivity test
(SANS 3001-CO3-3, 2015)

The chloride conductivity value is defines as:

$$\sigma = \frac{id}{VA} \tag{2.7}$$

where: σ = chloride conductivity of specimen (mS/cm)

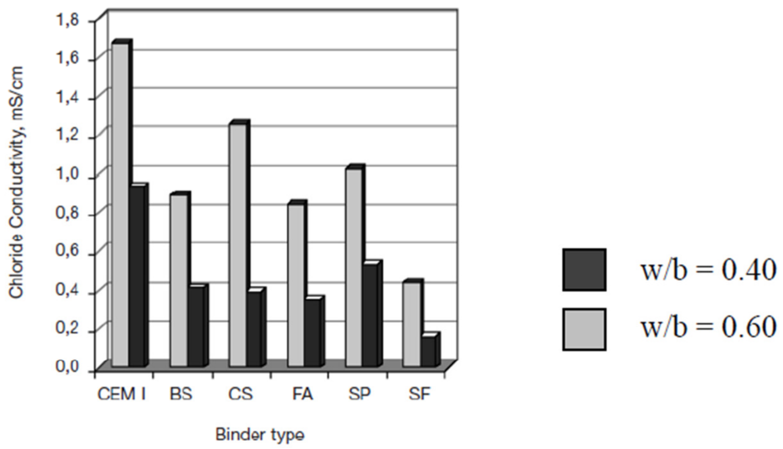
i = electric current (mA)

d = average thickness of specimen (cm)

V = voltage difference (V)

A = cross-sectional area of specimen (cm²)

CCI values for concrete typically range from 0.1 to 1.65 mS/cm for various blended cements at 28 days of age (Ballim et al., 2009). Figure 2.21 shows typical results for South African concretes, where higher concrete quality is indicated by lower values of conductivity.



CEM I = 100% PC
BS = 50% CEM I / 50% GGBS
CS = 50% CEM I / 50% GGCS
FA = 70% CEM I / 30% FA
SP = 85% CEM I / 15% Superpozz (FA)
= 93% CEM I / 7% CSF

Figure 2.21: Typical CCI results for South African concretes
(Ballim et al., 2009)

2.11 Case Studies

The following sections discuss four case studies, covering various areas of South Africa, chosen to represent the impact of w/b ratio and binder content on the strength, durability, constructability and overall project cost. Each case study is discussed and analysed to establish the role that w/b ratio and/or binder content play in current practice in producing economical and durable concrete structures.

2.11.1 Case Study 1: De Hoop Dam

De Hoop Dam is situated in the Steelpoort River, on route from the town of Stoffberg to Steelpoort, next to the existing provincial road R555. Construction of the dam was approved by the Cabinet of the Government of South Africa in June 2004 and the work commenced in June 2007. The dam is one of the largest in South Africa with a total concrete volume of more than 1 million m³ (Wright, 2009).

Roller Compacted Concrete (RCC) was employed for the dam which led to a vast simplification of the construction process. Significant improvements in the RCC mix design led to the development of immersion-vibrated roller compacted concrete (IVRCC) which allowed for concrete placement with both roller compaction and immersion vibration (Wright, 2009). This negated the need for grouting at the point of placement, improved the concrete quality and led to an acceptable surface finish.

Former RCC dams, constructed by the Department of Water Affairs, followed the low binder content approach at a water/binder ratio of 0.9. This resulted in the concrete segregating which lead to a poorer quality material than conventional mixes. As a result, higher paste contents were employed for the De Hoop Dam to mitigate these problems. The initial mix design specifications required a binder content of 180-190 kg/m³, consisting of 70% FA, a water/binder ratio of 0.62. This mix led to site compaction, workability and segregation difficulties (Wright, 2009).

In order to address these matters, the mix design was altered by modifying the aggregate grading, quantity and size and adjusting the binder content to 200 kg/m³. This eliminated the segregation of the mix and reduced the required compaction effort. The costs associated with the higher binder contents were offset by the reduced compaction effort requirements and shorter project timeframes. Quality improvements were noted with lower permeability for the hardened concrete structures.

2.11.2 Case Study 2: Port of Ngqura Administration Building

A five-storey high administration building was constructed at the Port of Ngqura for the Transnet National Ports Authority (TNPA) to house existing staff and allow for growth over the next 50 years. The building is divided into an east and west wing, separated by a foyer which extends the full height of the building. The total office area of the building is just under 10 000m² (Isaacs, 2016).

Due to the building being located within 15 km of the ocean and exposed to salt-laden air, its external environment was classified as ‘severe’ in accordance with SANS 10100:2 (1992). This constant exposure would result in chloride-induced corrosion causing expansion of the concrete and cracking of the cover-crete over time, leading to structural deterioration and unplanned maintenance (Isaacs, 2016).

In order to mitigate the deterioration the prescribed minimum requirements of SAND 10100:2 (1992) were adhered. The concrete strength was specified as 40MPa and the binder was composed of Portland cement with 30% FA replacement. In some of the mixes GGBS was used in-lieu of FA (Isaacs, 2016). These extenders were used to improve the resistance of the concrete to chloride penetration and reduce the Portland cement content in the mixes. No performance based criteria was applied to the structure which may have reduced the binder content and improved the usable life-span of the building. Prescriptive specifications were implemented with no clear deterioration prediction models or methods.

2.11.3 Case Study 3: Gautrain Precast Concrete Yard

The majority of the precast elements employed on the Gautrain project were produced in the Midrand precast yard. This included viaduct segments weighing up to 58 tons each, M-beams of up to 40 tons a piece and several other precast elements. On all of these elements, approximately 100 kg of cement per cube was saved since the first 400 elements came off the production line (Beer, 2009).

Initially 400 kg of cement, in combination with 100 kg of fly ash per cube of concrete, was used to achieve the high early strengths. Thereafter more accurate strength-testing procedures and improved mixes led to a reduced cement requirement of 300 kg of cement per cube of concrete whilst marginally increasing the fly ash requirement by 20kg (Beer, 2009). This represented a significant overall saving on material costs and overall carbon footprint of the project. Improved usage out of a given quantity of cement was the key driver at the yard.

These improvements were achieved by applying advanced recrystallization (ARC) technology. This allowed the yard to achieve average strengths of 74 MPa at 28 days using a w/b ratio of 0.45 with a FA replacement of 30%. Furthermore, the yard utilised CEM I 42.5 N cement instead of the conventional rapid-hardening CEM I 52.5 R cement at a rate of 400 kg per cube of concrete to achieve a 75 MPa rating. CEM I 42.5 N is not as refined as the rapid hardening cement.

ARC technology is based on the manner in which cement, water, aggregates and extenders react chemically. Unlike past practice where aggregates were considered as bulk material only, ARC considers their minerology and uses them as a chemical component of the mix as well, and in so doing enhances the strength and durability of concretes substantially (Beer, 2009). Along with achieving high early age strengths for demoulding purposes, permeability testing on all precast elements was another requirement for the yard. The 100-year durability specification required high levels of impermeability of the concrete. Both binder content and w/b ratio were important considerations for the concrete elements and the ARC technology.

2.11.4 Case Study 4: Gauteng Freeway Improvement Project

The South African National Roads Agency Limited (SANRAL) developed the Gauteng Freeway Improvement Project (GFIP) which involved upgrading the road network, improvement and construction of interchanges, and construction of median barriers. The project was initiated in 2007 and covered 560 km of the road network, with the first completed phase consisting of 185 km of the road network. The GIFP implemented performance based specifications for quality control by using measures of strength, durability indices (OPI and WSI) and concrete cover. Tables 2.5 and 2.6 outline the mix proportions of the concretes employed on the project.

Table 2.5: Summary of the range of concrete mix properties from four plants of the Readymix concrete producer
(Nganga, 2011)

Binder Content (kg/m³)				Water content (l/m³)	w/b ratio
Portland Cement	FA	GGBS	Total		
383-403	68-71	-	541-474		0.41-0.44
360-373	-	90-93	450-466	184-207	0.44-0.45

Table 2.6: Summary of mix proportions of concrete used in production of precast elements (Nganga, 2011)

Mix Constituents	Proportion (kg/m³)
Portland cement	410
FA	176
Total binder content	586
Water content	220
w/b ratio	0.38

Form the above mix proportions; Nganga (2011) made the following observations:

a) Low w/b ratios were used for all concrete elements. This is preferable as it results in a lower void volume in the hardened cement paste with an associated reduction in the penetrability of concrete.
b) High binder contents of up to 586 kg/m³ were used for the concrete mixes. SANRAL specifications permitted binder contents of up to 400 kg/m³ to address the durability requirements. Payment adjustments were made for binder contents in excess of 400 kg/m³ but below 450 kg/m³; however, no payments were made for binder contents exceeding 450 kg/m³.

Limiting values with reduced payment clauses were enforced on the OPI and cover depth readings. Table 2.7 outline the specific details for the OPI readings. For WSI, a limiting value of 10 mm/√hr was established; however, a reduction in payment was not applied.

Table 2.7: Limiting values used in DI based performance specifications and the reduced payments criteria applied
(Nganga, 2011)

Description of Test	OPI (Log Scale)	Percentage Payment
Full acceptance	> 9.70	100%
Conditional acceptance (with reduced payment)	> 8.75 ≤ 9.70	80%
Conditional acceptance (with remedial measures approved by engineer and reduced payment)	-	-
Rejection	< 8.75	Not applicable

Table 2.8 outlines the OPI and WSI results for various project phases of the GFIP. Data relating to in-situ structures was obtained from bridges, piers, abutments, wing walls, retaining walls, culverts and toll gantries. Data for precast items, project ID 9, was obtained from precast median barriers.

Table 2.8: Summary statistics of OPI and sorptivity values
(Nganga, 2011)

Project Phase ID	OPI (Log Scale)			WSI (mm/√hr)		
	Mean	Max	Min	Mean	Max	Min
1 (in-situ)	9.75	10.41	9.07	9.67	13.73	6.88
2 (in-situ)	9.91	10.42	9.37	9.36	13.21	6.04
4 (in-situ)	9.87	10.40	9.39	7.20	10.33	5.15
6 (in-situ)	10.06	11.10	8.83	7.13	10.35	5.20
9 (precast)	10.25	10.70	9.85	9.59	14.43	5.08

It can be seen by comparing the OPI values in Table 2.8 to the limiting values in Table 2.7 that the mean values for all the projects considered exceeded the limiting values. The minimum values still complied with the conditional acceptance criteria. However, it is also noted that the maximum recorded values were much higher than the full acceptance value of 9.70, considering that these values are on a log scale. The average WSI values for all the projects were below the limiting value of 10 mm/√hr.

Table 2.9: Summary statistics of compressive strength
(Nganga, 2011)

Project Phase ID	Strength (MPa)			
	Specified	Mean	Max	Min
4	30	37.9	48.8	25.0
	40	43.5	49.2	39.9
6	30	48.2	61.4	37.3
	40	56.1	71.5	42.8
	60	79.0	84.6	69.2
9	30	49.4	77.0	30.0

Strength results are summarised for the different project phases in Table 2.9. The mean strength values for all project phases exceeded the specified values. At times the maximum strength achieved far exceeded the specified values, with as much as 77 MPa having been recorded for a 30 MPa specified concrete for project 9.

From Tables 2.5 and 2.6 it is evident that concretes with high binder contents were specified for these projects. Contractors and precast manufacturers exceeded the binder content payment thresholds to ensure the required durability was achieved. Although some of the concretes failed to meet the acceptance criteria, most of the concrete mixes were overdesigned. High binder contents and low w/b ratios led to increased OPI and strength values but lower than required WSI values.

2.11.5 Brief Discussion of the Case Studies

From the case studies, it is evident that prescriptive approaches are unable to address modern requirements and developments in the concrete construction industry. The impacts of prescriptive parameters such as w/b ratio and binder content are not isolated and need to be considered along with other material properties and requirements. Performance-based specifications are able to address these shortcomings; however, continued reliance on prescriptive approaches and the lack of factual and investigative data leads to unnecessarily high binder contents. These high binder contents lead to uneconomical and overdesigned concrete mixes which do not fully address all the performance-based requirements. This emphasises the need to conduct further studies on the relative importance of concrete mix design parameters on the resulting performance-based criteria. This would ideally lead to the continued adoption and implementation of performance based approaches by understanding the contributory roles of the mix design parameters.

2.12 Summary

SCM are materials that, when blended with PC, contribute to the properties of concrete. FA and GGBS are the most common SCM's used in concrete. FA and GGBS are industrial by-products from varying processes. Due to the pozzolanic reaction in FA concretes, early age strength development is generally lower than those displayed by concretes made with PC, with strength maturing significantly in the long term. Moreover, FA refines the microstructure of the hydrated cement paste by transforming larger pores into finer ones which has a marked impact on the resulting concrete permeability and strength.

GGBS contributes to concrete strength by its steady hydration process which refines the pore structure over time. Lower early age strengths, as comparted to PC concretes, are generally reported but this improves over time. The benefit of GGBS in concrete lies in its chloride binding capabilities which leads to lower chloride diffusion coefficients as compared to PC only or FA extended concretes.

W/b ratio is generally regarded as the determining factor for strength and penetrability of the hydrated cement paste. The cement microstructure and associated mechanical properties are largely dependent on this ratio. For low water binder ratios, the hydrated cement paste obtains a dense microstructure due to the relatively small binder particle spacing. On the other hand, for high w/b ratios, the hydration products of the cement particles need to extend further for interaction which results in a weaker and dispersed microstructure. Furthermore, the excess water in the paste evaporates over time leaving large, interconnected capillary pores resulting in higher permeability. Therefore concretes with low w/b ratios have enhanced strength and durability properties as compared to those with high w/b ratios.

Strength is predominantly a function of the w/b ratio and is independent of binder content. However, for a low w/b ratio, an increase in binder content has a positive impact on strength. Thereafter, as the binder content increases, the opposite, less pronounced, effect is encountered. For a high w/b ratio, a similar tend holds true but the effect is less evident. This effect relates to the increase in paste volume which at first provides a beneficial aggregate binding role and thereafter results in increased pore spaces which is detrimental to concrete strength. Furthermore, binder content and associated paste volume increases, reduces concrete durability due to detrimental changes to the concrete transport properties. This is more prevalent at a high w/b ratio because an increase in the paste volume leads to an increase in the pore fraction present in the cement matrix.

Durability assessments need to account for the interaction between concrete as a system and its exposure environment. Factors influencing the concrete system relate to the concrete's ability to resist mechanisms of deterioration, whilst those related to the exposure environment influence the degree of aggressiveness that the concrete has to withstand. The quality of the near surface concrete is important to limit the ingress of deteriorating agents that leads to the depassivation and corrosion of the reinforcement. The quality of this layer determines the extent to which four transport mechanisms, namely permeation, sorption, diffusion and migration, allow the ingress of harmful substances into the concrete.

These concrete durability properties are assessed by a set of index tests which have been developed in South Africa, each related to a transport process in concrete. The set is comprised of the oxygen permeability index (gaseous diffusion), water sorptivity index (water absorption) and chloride conductivity index (ionic diffusion). The indices obtained from these tests are related to service life prediction models and generally need to comply with prescribed requirements and specifications.

The next chapter will cover the experimental details and methods used in this study.

CHAPTER 3

3 EXPERIMENTAL DETAILS

3.1 Introduction

This chapter outlines the pertinent details of the experiments performed during the study. Details of the variables, materials, mix designs, test specimens and methods are provided. A brief schematic is presented in Figure 3.1.

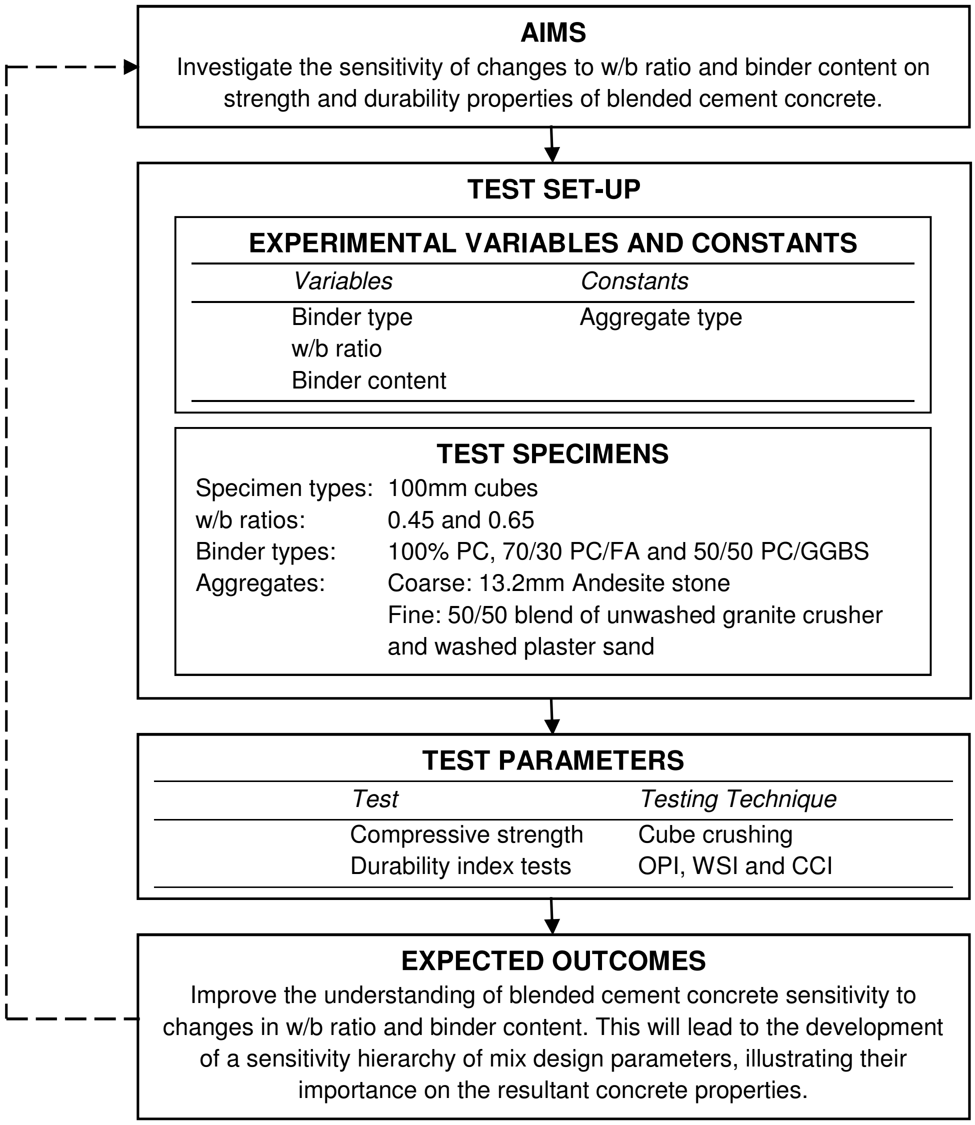


Figure 3.1: Experimental methodology flow chart

3.2 Experimental Variables and Constants

The influences of the following variables on blended cement concrete were considered significant in determining the sensitivity of strength and durability properties:

a) Binder type
b) Water/binder ratio
c) Binder content

The aggregate type remained constant in the study.

3.2.1 Binder Type

The binders used for this study consisted of plain Portland Cement (PC), fly ash (FA) and ground granulated blastfurnace slag (GGBS). Type 1 PC with a strength class of 52.5 R, denoted as CEM 1 52.5R, was used as it is roughly compositionally equivalent to PC and only contains up to 5% of minor additional constituents. The cement complies with the requirements of SANS 50197-1 (2013).

Class S, air classified FA was used and the material complies with the requirements of SANS 50450-1 (2014). GGBS, a latent hydraulic binder, was used and complies with the requirements of SANS 55167-1 (2011). The measured oxide composition and typical range of each binder is shown in Table 3.1 below.

Table 3.1: Chemical composition of binders
(Afrisam, 2013; Hovy, 2016; Grieve, 2009)

Oxide	*% Composition by mass*					
	PC		*FA*		*GGBS*	
	Measured	*Typical*	*Measured*	*Typical*	*Measured*	*Typical*
CaO	65.1	63.0-69.0	6.0-9.5	4.0-7.0	37.5	32.0-37.0
SiO_2	20.8	19.0-24.0	50.0-52.5	48.0-55.0	39.2	34.0-40.0
Al_2O_3	4.6	4.0-7.0	28.5-30.5	28.0-34.0	13.2	11.0-16.0
Fe_2O_3	2.7	1.0-6.0	2.0-3.0	2.0-4.0	-	-
SO_3	3.0	-	-	-	-	-
MgO	1.7	0.5-3.6	2.0-2.5	1.0-2.0	7.8	10.0-13.0
K_2O	0.5	0.2-0.8	<1.0	1.0-2.0	0.9	0.8-1.3

3.2.2 Water/Binder Ratio

Two water/binder (w/b) ratios of 0.45 and 0.65 were utilised. SANS 10100-2 (2014) states that the minimum water/binder ratio varies between 0.45 and 0.55, dependent on exposure conditions. Grieve (2009) records a typical range for w/b ratios, for conventional concrete, between 0.45 and 0.80. Previous research, as outlined in Chapter 2, typically considered w/b ratios from 0.40 to 0.70. There are structures and concrete applications that require 0.36 w/b ratio for high strength concrete applications.

A lower w/b ratio of 0.45 was used to investigate the influence of less permeable concrete on the strength and durability properties of concrete which aligns with the SANS requirements. The higher w/b ratio of 0.65 was used to supplement existing experimental data and limit the relative high water content associated to the set binder contents.

3.2.3 Binder Content

Two binder contents of 350 and 450 kg/m³ were used in the study. SANS 10100-2 (2014) notes that a binder content in excess of 550 kg/m³ of concrete should normally be avoided as it tends to lead to handling, placement and compaction difficulties (due to high cohesiveness). Minimum binder contents between 340 to 420kg/m³ is recommended for varying exposure environments. Previous research, as outlined in Chapter 2, typically considered binder contents from 260 to 490kg/m³. The selected binder contents comply with SANS requirements and are comparable to existing literature.

Erstwhile Cement and Concrete Institute (2009) provides guidelines on the selection of cementitious materials for concrete. 30% FA replacement and 40% to 50% GGBS replacement is the recommended practice for the concrete industry for various applications. Previous research, as outlined in chapter 2, typically considered 30% FA and 50% GGBS replacement percentages which aligns with industry practices and was considered for the study.

3.2.4 Aggregate

Coarse aggregate

Andesite is the name used for a family of fine-grained, extrusive igneous rocks that are usually light to dark grey in colour. The rock has a composition that is intermediate between basalt and granite (Rafferty, 2006). 13.2 mm Andesite stone was used as coarse aggregate as it is commonly available. The stone complies with the requirements of SANS 1083 (2014) and the grading curve is given in Figure 3.2. The grading curve indicates that the coarse aggregate sample contains varying sizes other than 13.2mm and is therefore not single sized.

Andesite is the name used for a family of fine-grained, extrusive igneous rocks that are usually light to dark grey in colour. The rock has a composition that is intermediate between basalt and granite (Rafferty, 2006).

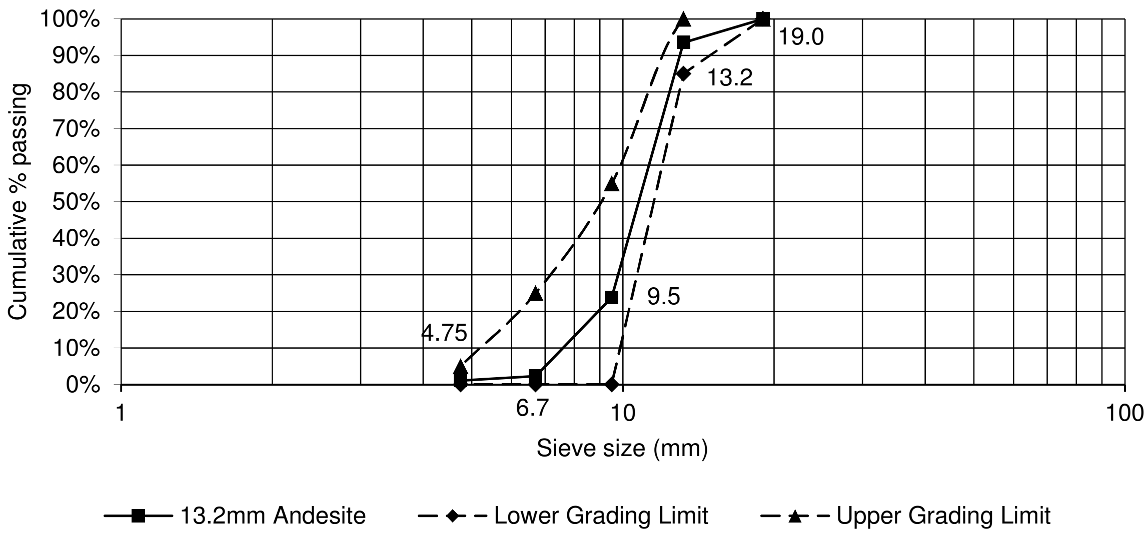


Figure 3.2: Grading curve of coarse aggregate (13.2mm Andesite)

Fine aggregate

Unwashed andesite crusher sand was initially considered as fine aggregate for the study as it is commonly available. However, after the grading analysis, as shown in Figure 3.3, the material was classified as very coarse with a fineness modulus (FM) of 4.02 and minimal fine content passing the 300 micron sieve (9.02%). The lack of cohesion in the trail mixes confirmed that the material was unsuitable for use (Addis, 1998).

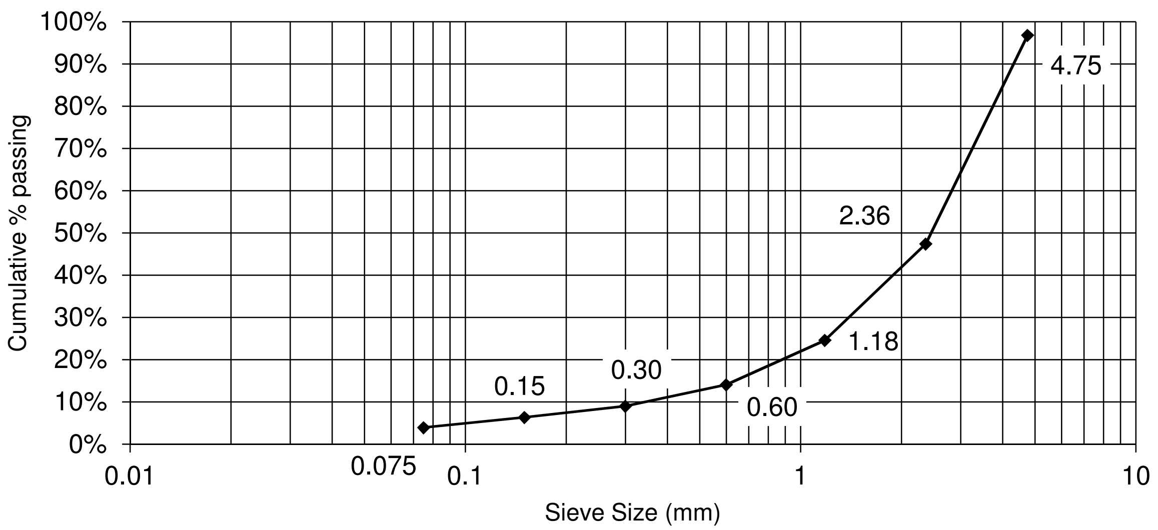


Figure 3.3: Grading curve of andesite fine aggregate

After a series of aggregate selection processes and trail mixes, a 50/50 blend of unwashed granite crusher sand and washed plaster sand was selected for the study. The granite crusher sand has an improved grading as compared to the andesite and the plaster sand functioned as filler for material passing the 600micron sieve. Figure 3.4 shows the grading curve for the materials.

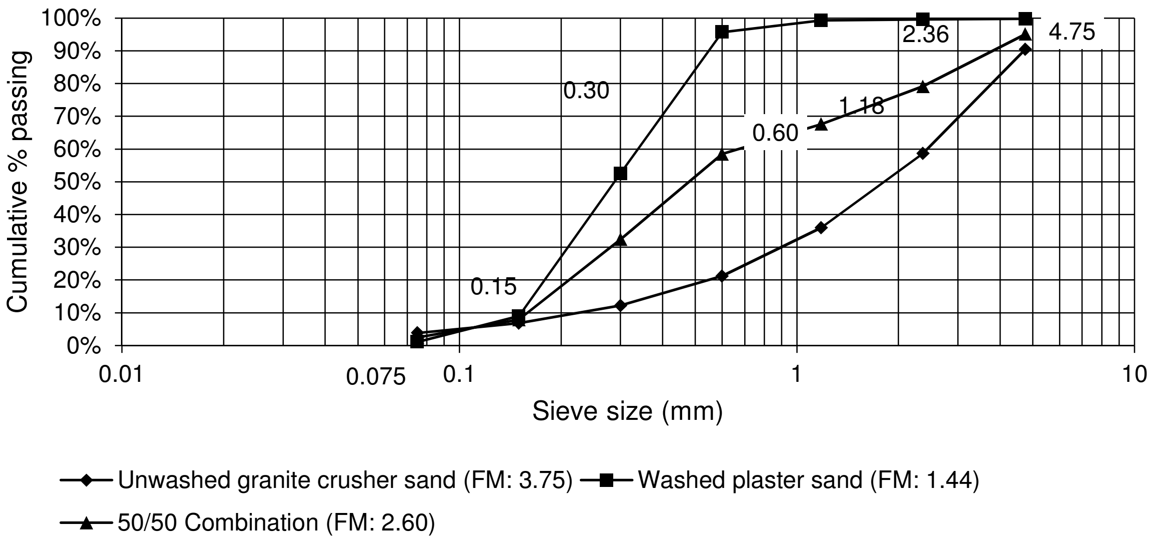


Figure 3.4: Grading curve of blended fine aggregate

Granite is widespread across South Africa but it is not more extensively used than other aggregates for concrete. This is generally due to the favourable location of other rock types that are equally suitable. However, the steady depletion of alternate rock supplies will probably lead to an increase in demand for granite (Owens, 2009). This is evident in the diminishing quartzite supplies in the Witwatersrand area where engineers are opting, amongst other, for granite supplies to the north of Johannesburg.

3.3 Concrete Mix Design and Mix Proportions

The study adopted the Concrete Institute of South Africa volumetric mix design method. This method is derived from the ACI Standard 211.1-91 (Addis & Goodman, 2009) and modified to suit South African practice. In this approach, mix constituents are calculated by mass, with the requirement that the absolute volumes should equate to the total volume of concrete. The method is based on the following concrete characteristics:

a) Strength, at a given age for fully compacted concrete with a defined water/binder ratio and type of cementitious material;
b) Amount of water required per unit volume of concrete;

c) Optimum stone content depending on stone and sand characteristics;
d) Volume of compacted concrete produced through a combination of materials.

The flow chart in Figure 3.5 outlines the modified mix design procedure employed during the study.

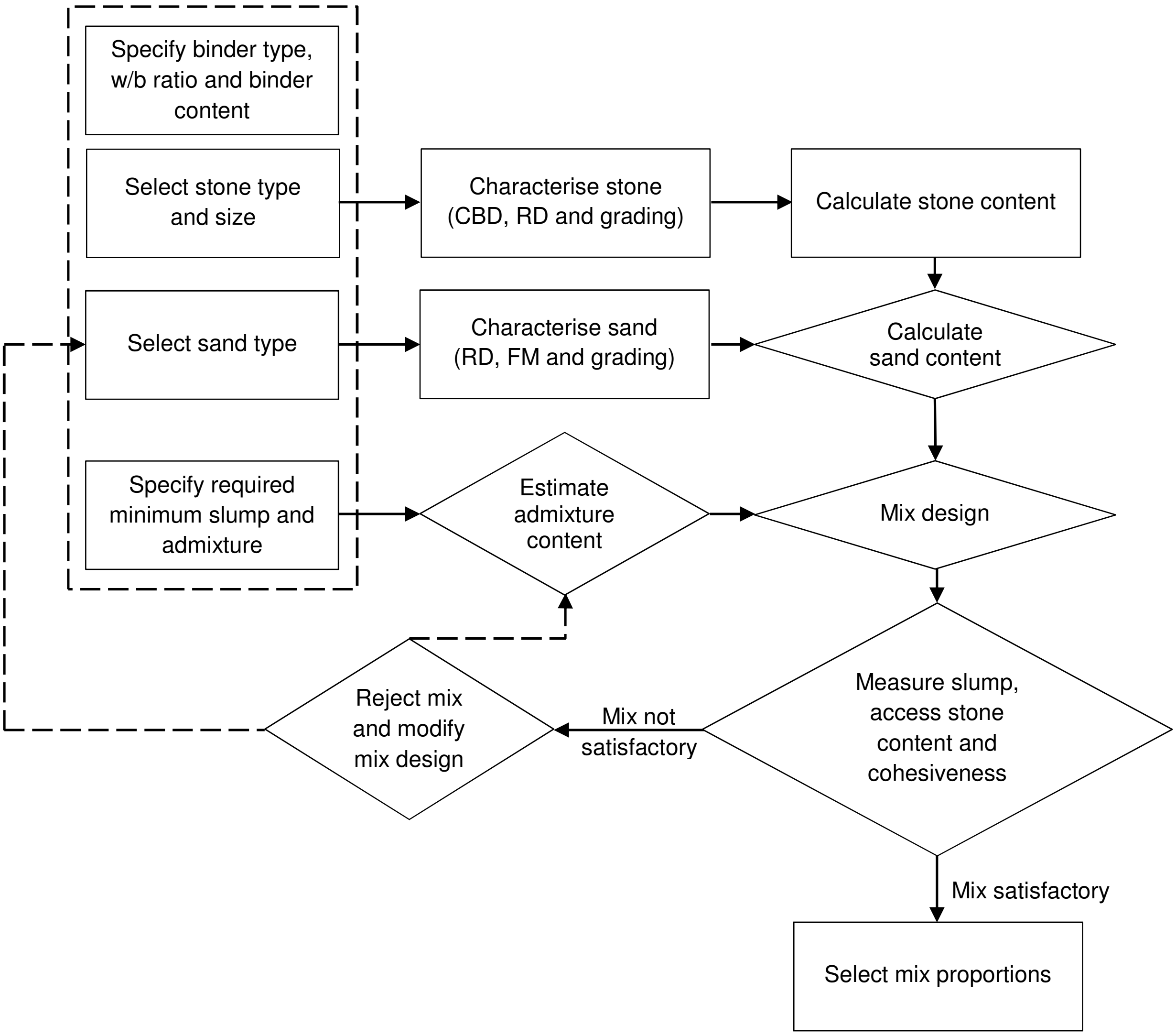


Figure 3.5: Concrete mix design flow chart
(adapted from Addis & Goodman, 2009)

A modified ploycarboxylate, high range water reducing superplasticiser admixture, Sika ViscoCrete -10, was used to improve the workability of the dry mixes. The admixture was systematically added to the mixes until a minimum slump of 75mm was obtained.

In total, twelve mix combinations were prepared for comparison in the study. These mixtures were identified according to the extender type and content, binder content and w/b ratio. Table 3.2 provides a summary of the mix proportions.

Table 3.2: Summary of concrete mix proportions

Material (kg/m³)	*Designation*											
	PC-350		*PC-450*		*FA-30-350*		*FA-30-450*		*GB-50-350*		*GB-50-450*	
w/b ratio	0.45	0.65	0.45	0.65	0.45	0.65	0.45	0.65	0.45	0.65	0.45	0.65
PC	350	350	450	450	245	245	315	315	175	175	225	225
FA	-	-	-	-	105	105	135	135	-	-	-	-
GGBS	-	-	-	-	-	-	-	-	175	175	225	225
Binder (Combined)	350	350	450	450	350	350	450	450	350	350	450	450
Crusher sand	528	435	425	306	488	395	381	262	522	429	418	298
Plaster sand	528	435	425	306	488	395	381	262	522	429	418	298
Fine aggregate (combined)	1056	870	850	612	976	790	762	524	1044	858	836	596
Coarse aggregate	973	973	973	973	1022	1022	1022	1022	973	973	973	973
Water Content	158	228	203	293	158	228	203	293	158	228	203	293
Admixture(1)	2.56	-	-	-	1.28	-	-	-	1.92	-	-	-

Notes (refer to Table superscript references):
1. Admixture units: l/m³ of binder

3.4 Test Specimens

3.4.1 Number of Specimens

The compressive strength tests required three 100mm cube specimens per mixture combination equating to 180 tests in total. The durability index tests required four 70mm by 30mm disc specimens per mixture combination equating to 96 tests per durability index, or 288 tests in total. The same specimens were used for the oxygen permeability and water sorptivity tests. The total number of cube specimens equated to 288, inclusive of a contingent amount, as outlined in Table 3.3.

Table 3.3: Number of specimens

Test	*Curing Period (days)*	*Mixture Combinations*	*Quantity per Test*	*Total quantity*			
				Disc(1)		*Cube*(2)	
Compressive strength:	3	12	3	-	-	36	180
	7		3	-		36	
	14		3	-		36	
	28		3	-		36	
	56		3	-		36	
Oxygen permeability:	28	12	4	48	96	24	48
	56		4	48		24	
Water sorptivity(3):	28	12	4	48	96	-	-
	56		4	48		-	
Chloride conductivity:	28	12	4	48	96	24	48
	56		4	48		24	
Contingency(4):							12
Cube total:							288

Notes (refer to Table superscript references):
1. Disc specimen size: 70 ± 2mm diameter by 30 ± 2mm thick.
2. Cube specimen size: 100mm. Disc-cube equivalent: 2 discs per cube.
3. Samples from oxygen permeability test reused for water sorptivity test.
4. One additional cube per mix.

3.4.2 Curing of Specimens

Curing of concrete is defined as providing adequate moisture, temperature, and time to allow concrete to achieve the desired properties for its intended use (Kosmatka et al., 2002). Strength and durability parameters are affected by the type and duration of curing (Ballim, 1994). Immediately after casting, the specimens were covered with polyethylene sheets for a period of 24 hours at room temperature to prevent moisture loss from the concrete. The specimens were then demoulded, labelled and placed into a water bath at 23 ± 2°C for curing. The cubes were cured for (a) 3, 7, 14, 28 and 56 days to obtain compressive strengths, and (b) 28 and 56 days to obtain the durability indexes.

3.5 Test Procedure

3.5.1 Compressive Strength

The compressive strength of the concrete was determined by performing standard cube (100mm) crushing tests in accordance with SANS 5863 (2006). The specimens were tested at 3, 7, 14, 28 and 56 days to determine the effect of the parameters on early and medium term strength of the materials.

All tests were performed using an automated hydraulic compression machine at a loading rate of 0.25MPa per second up to failure load. SANS 5863 (2006) recommends a loading rate of 0.3 ± 0.1MPa per second.

3.5.2 Durability Index Tests

Three durability index tests have been developed that measure the resistance of concrete to the transport of deteriorating substances (Alexander et al., 2001). These tests provide reliable values to be used for characterisation and likely material performance. The specimens were tested at 28 and 56 days. Figures 3.6 to 3.8 indicate the OPI, WSI and CCI test setups respectively.

Figure 3.6: OPI test setup

Figure 3.7: WSI test setup

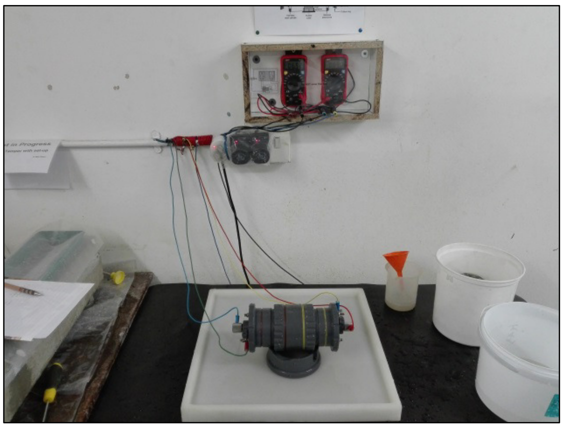


Figure 3.8: CCI test setup.

The next chapter will present the experimental results accompanied by the analyses and discussion thereof.

CHAPTER 4

4 RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results, analysis and discussion of the experimental work outlined in Chapter 3. Correlations between compressive strength and durability indices, in relation to w/b ratio and binder content, are investigated and discussed. This is achieved by analysing set binder contents and w/b ratios, for the three binder types, and assessing the associated impact on the selected strength and durability properties. The chapter begins by investigating the influence and sensitivity of w/b ratio and binder content on compressive strength. Thereafter, similar investigations are conducted on the durability indices.

It is widely documented that strength and durability properties of blended cement concretes are affected by changes in w/b ratio and binder content (Angelucci, 2013; Ballim, 1994; Ballim, 2009). However, the extent to which strength and durability are affected by a change in each of these parameters can only be established by conducting sensitivity analyses. These analyses were therefore carried out to quantify the impact of varying the w/b ratio and binder content on the resulting strength and durability properties, and which parameter had a greater influence on the resulting strength and durability properties.

Trends of the resulting data, from the sensitivity analyses, were then identified and discussed. These trends were then summarised, at the end of each section, and the practical implications for the concrete mix design process outlined.

The error bars, indicated on the respective figures, are a graphical representation of the variability of the data and indicate the uncertainty of the reported measurements. They represent the 95% confidence interval, refer to Appendix A for calculation details, which provides an acceptable range for the samples and any data points falling outside of these ranges are defined and outliers and rejected. Figure 4.1 defines the graphical representation of the error bars where d is the sample deviation as outlined in Appendix A.

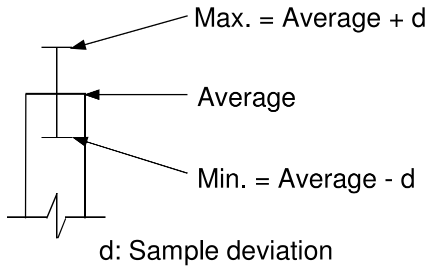


Figure 4.1: Error bar legend

4.2 Compressive Strength

The mix design process is generally governed by attaining a specified target value by adjusting the w/b ratio of the mix. Furthermore, prescriptive specifications impose minimum binder content requirements to seemingly enhance the strength and durability of the resulting product (SANS 10100-2, 2014). This section investigates the impacts and sensitivity of these parameters on compressive strength.

4.2.1 Effect of w/b Ratio and Binder Content on Strength

Figures 4.2 and 4.3 present the early age and long term compressive strength results for the PC and blended cement concretes with two different binder contents and w/b ratios. Figure 4.4 presents the strength development of the concretes, up to 56 days.

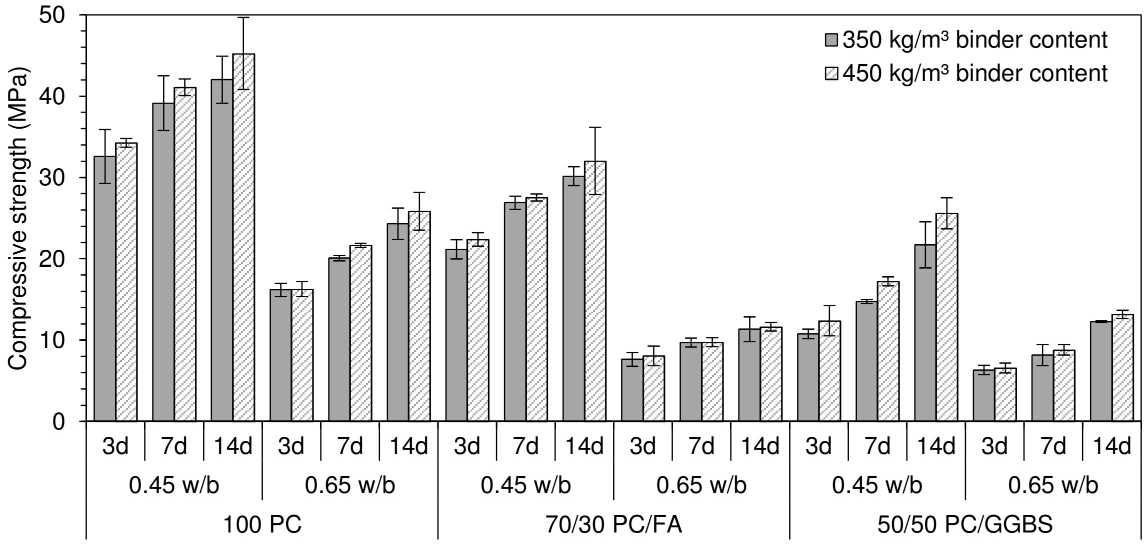


Figure 4.2: Early age average compressive strength results

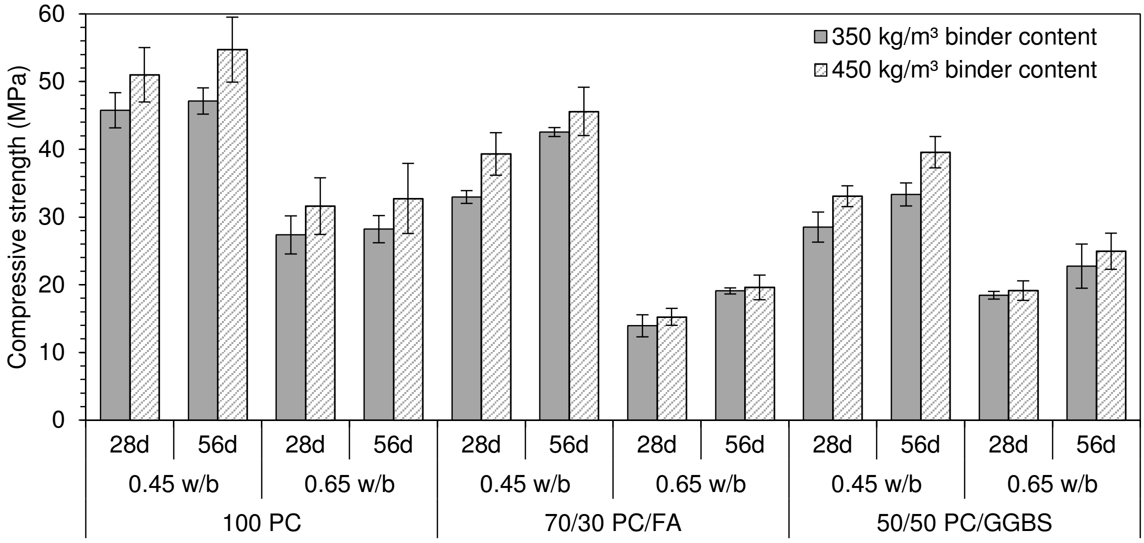


Figure 4.3: Long term average compressive strength results

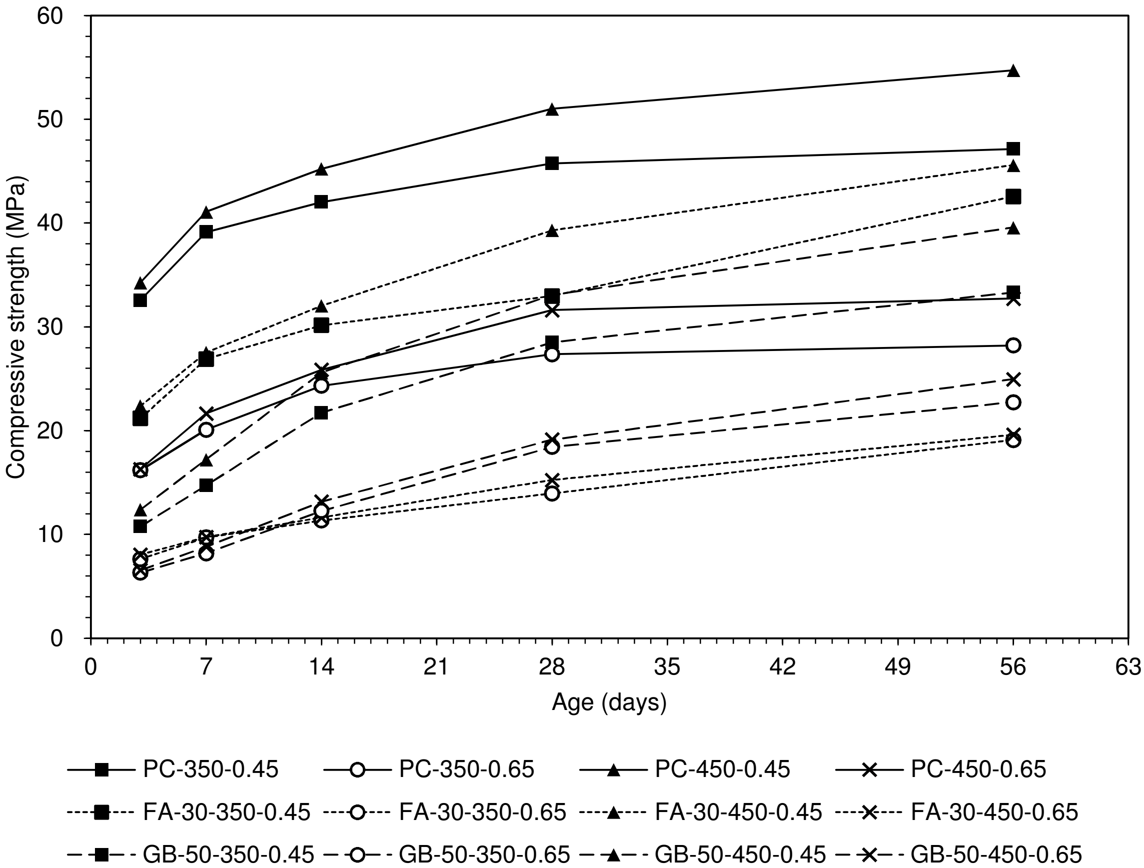


Figure 4.4: Average compressive strength development

When evaluating the influence of the w/b ratio on the compressive strength results, for a given binder type, the 0.45 w/b ratio mixes yielded higher strength values than the 0.65 w/b ratio mixes, these reductions correspond to numerous literature sources (Yang et al., 2010;

Mukadam, 2014). This result is related to the larger binder inter-particle spacing that leads to the hydration products extending further to interact with one another and results in a less dense hydrated cement microstructure. Porosity is also increased, for the 0.65 w/b ratio, due to the excess water that is not consumed by the hydration process which leads to the formation of pores in the resulting structure (Malhotra, 1994).

Compressive strength values generally increased along with binder content which align with the findings of Bertolini et al. (2013). This may be due to the associated increases in paste volume available to bind the aggregate which leads to strength improvements. However, this trend will not continue indefinitely as continued binder and associated paste increases will lead to higher pore spaces and associated reductions in compressive strength as reported by Angelucci (2013).

Improvements in strength were also noted as the concrete age increased due to the beneficial role of prolonged curing. This is predominantly due to the ongoing hydration process of the cementitious material whereby the porosity and interconnectivity of pores decreases with time (Ballim, 1993).

The compressive strength values recorded for FA concretes were lower than those achieved by PC concretes. This coincides with literature published by Thomas (2007), where it was found that FA tends to delay the early strength development of concrete. Given that FA is a pozzolan, it forms cementing compounds, calcium silicate hydrate, in water by reacting with calcium hydroxide from the PC hydration process. This is due to the surplus amount of silica, alumina and iron oxide in FA available for the reaction (Arel and Yazici, 2012). Thus, there is a delay in strength development as the calcium hydroxide from the PC hydration process needs to be available first before the FA contributes to strength (Van Dam, 2013).

Apart from the 0.65 w/b ratio mixes, compressive strength results for the GGBS concretes were the lowest of the binder combinations investigated. These lower early age strengths of the GGBS concretes is due to the latent hydraulic reaction of the GGBS, which lowers the heat of hydration and slows the production of calcium silicate hydrates (CSH). Lower early age results align with the findings presented by Angelucci (2013) but contradict those of Elliot (2017). This variability mainly relates to the fineness of the GGBS used in the two studies as outlined by (Divsholi et al., 2014). The GGBS used in this study is comparable to that of Angelucci (2013) and has a relatively low Blaine fineness of 275 m^2/kg, which yielded the lower strength results (Afrisam, 2013).

4.2.2 Sensitivity of Strength to Change in w/b Ratio and Binder Content

Figures 4.5 and 4.6 show comparisons of compressive strength results, up to 56 days, for specimens prepared using different w/b ratios and binder contents.

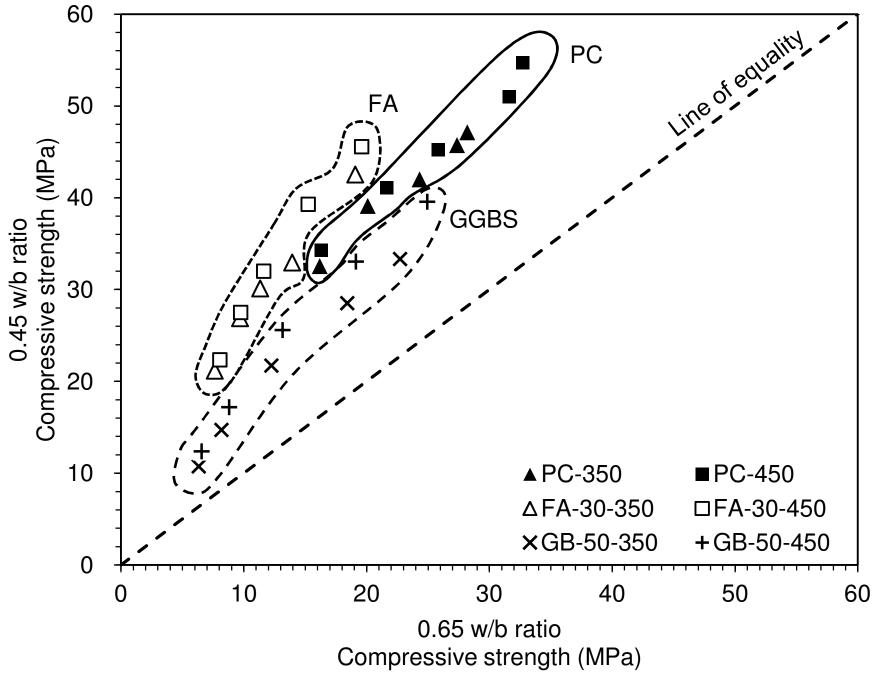


Figure 4.5: Effect of w/b ratio on compressive strength

Data points on Figure 4.5 that fall on the line of equity, 45 degree line passing through the origin, indicate that the compressive strength results obtained for the 0.45 w/b ratio are the same as the results obtained for the 0.65 w/b ratio, for a given binder type and content. However, all the data points lie above this line which indicates that higher compressive strength results were obtained for the 0.45 w/b ratio as compared to the 0.65 w/b ratio.

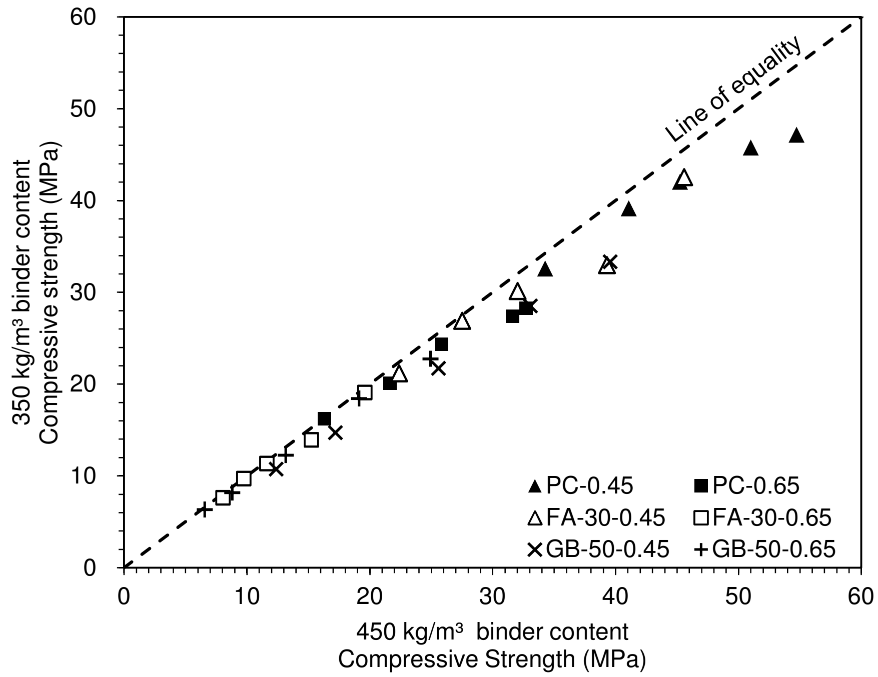


Figure 4.6: Effect of binder content on compressive strength

Data points in Figure 4.6 that fall on the line of equity, 45 degree line of equity passing through the origin, indicate that the compressive strength results obtained for the 350 kg/m³ binder content are the same as the results obtained for the 450 kg/m³ binder content, for a given binder type and w/b ratio. However, all the data points lie below this line which indicates that higher compressive strength results were obtained for the 450 kg/m³ binder content as compared to the 350 kg/m³ binder content for both w/b ratios. The figures further show that strength values are more sensitive to changes in w/b ratio than binder content as the data points, in Figure 4.5, are further offset from the line of equity than those in Figure 4.6. This indicates that changes in w/b ratio have greater influence on the resulting compressive strength as compared to changes in binder content.

The sensitivity of compressive strength to changes in w/b ratio and binder content is presented in Figures 4.7 and 4.8. The figures outline the percentage change in compressive strength after individual increases in the parameters, up to 56 days. Figure 4.7 shows that an increase in w/b ratio has a negative impact on compressive strength for reasons outlined in the previous paragraph. The extent to which a change in w/b ratio affects concrete strength generally decreases with age, although this trend is not clearly defined at early ages. Furthermore, FA concretes were most affected by a change in w/b ratio.

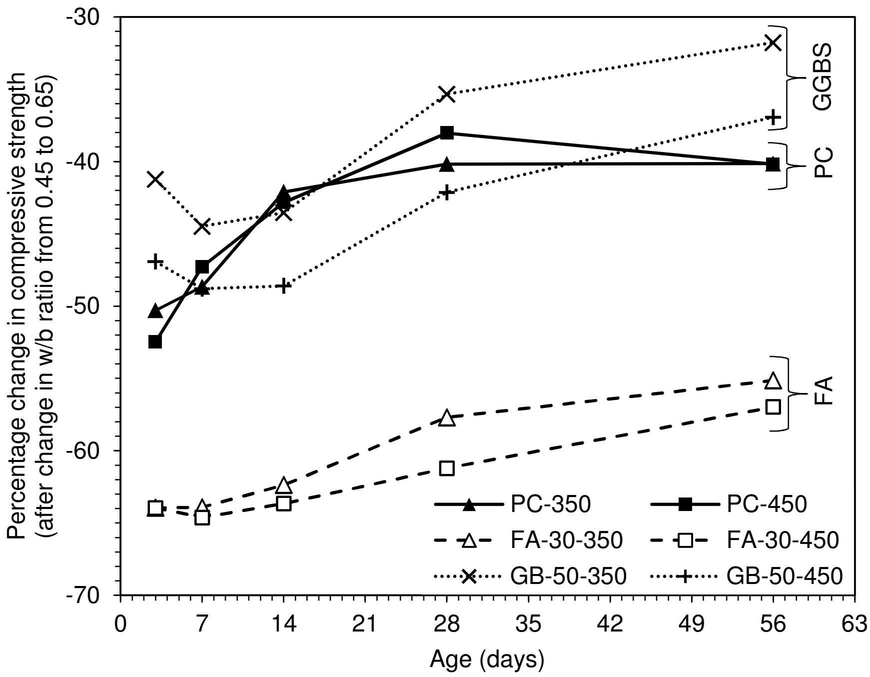


Figure 4.7: Sensitivity of compressive strength to change in w/b ratio from 0.45 to 0.65

The percentage change of compressive strength of PC concretes increased from just below -50% at 3 days, to around -40% at 28 days and thereafter a minor decrease is noted at 56 days. The percentage change therefore decreases with age up to 28 days and thereafter remains reasonably constant. This is due to the to the relatively large cement particle spacing for the 0.65 w/b ratio which requires the hydration products to extend further to interact (Malhotra, 1994). During early ages the interaction is considered to be minimal but improves with time. For PC concretes, the effect of binder content on this trend is minimal.

The percentage change of compressive strength of FA concretes decreases marginally from -64% at 3 days, to around -65% at 7 days and thereafter increases to -55% and -57% at 56 days, for 350 kg/m³ and 450 kg/m³ binder contents respectively. A change in w/b ratio therefore has the highest effect on the compressive strength of FA concretes. This is predominantly due to the dilution of the calcium hydroxide concentration (Biernacki et al., 2001), at the 0.65 w/b ratio, as a result of the increased water content but fixed binder content. The rate of calcium hydroxide consumption and the rate of hydrate formation are functions of the calcium hydroxide/fly ash ratio. In particular, there is more hydrate formed and more calcium hydroxide consumed per gram of starting fly ash per unit time when the mixtures contain more calcium hydroxide (Biernacki et al., 2001).

GGBS concretes follows similar trends to FA concretes where the percentage change of compressive strength decreases from 3 to 7 days and thereafter increases to 56 days. The percentage change is around 6% higher for 350 kg/m³ specimens as compared to 450 kg/m³ specimens. Therefore the higher the paste volume, the greater the change in compressive strength due to a variation in w/b ratio. As per PC concretes, the larger particle spacing, for the 0.65 w/b ratio, impacts the interaction of the hydration products. This improved with time but given that GGBS is a latent hydraulic binder, requiring an activator, the hydration process is extended and therefore the percentage change continues to decline with age (Elliot, 2007).

As the percentage change in compressive strength, after a change in binder content from 350 kg/m³ to 450 kg/m³, is positive, an increase in binder content improves the compressive strength of concrete, as shown in Figure 4.8. For PC concretes, the extent to which a change in binder content affects compressive strength is not well defined at early ages; however, from 14 days onward, an increase is evident. This trend applies to mixes with w/b ratios of 0.45 and 0.65.

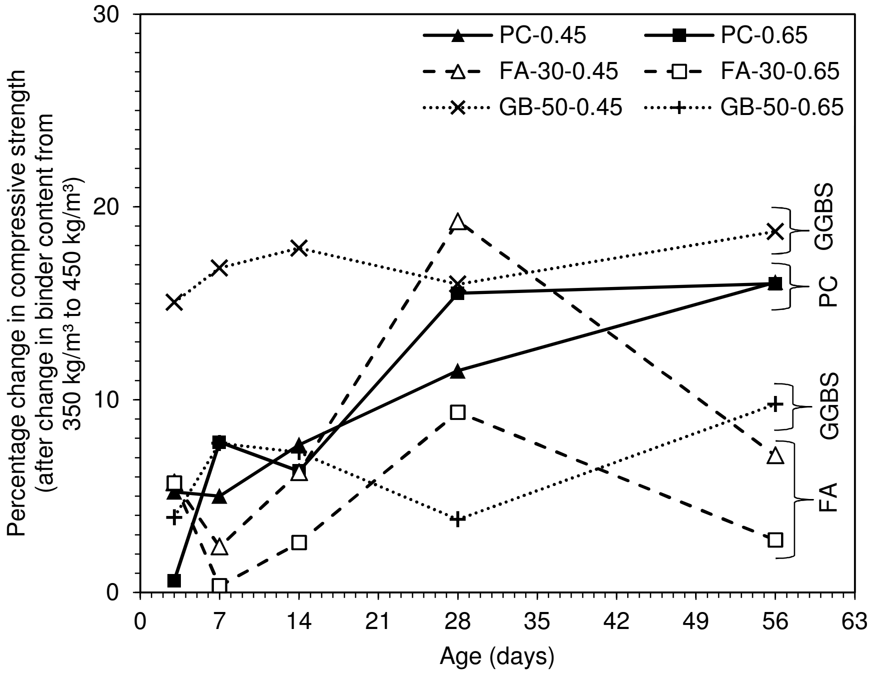


Figure 4.8: Sensitivity of compressive strength to change in binder content from 350 kg/m³ to 450 kg/m³

The percentage change of FA concretes fluctuates with age as follows; (a) from 3 to 7 days, the percentage change decreases from around 6% to 2% and 0% for the 0.45 and 0.65 w/b ratio mixes respectively, then (b) up to 28 days, an increase is noted to 19% and 9% for the 0.45 and 0.65 w/b ratio mixes respectively, thereafter (c) the percentage change returns to within 4% of the 3 day value at 56 days, to 7% and 3% for the 0.45 and 0.65 w/b ratio mixes respectively.

The percentage change of GGBS mixes at the 0.45 w/b ratio fluctuates with age as follows; (a) from 3 to 14 days the percentage change increases from 15% to 17%, then (b) up to 28 days, a decrease is noted to 16%, thereafter (c) the percentage change increases to 19% at 56 days. A similar trend is evident for the GGBS mixes at the 0.65 w/b ratio apart from the time period between 7 to 14 days, where the percentage change decreases, and the corresponding values which are around 10% lower than the 0.45 w/b ratio mixes.

4.2.3 Summary and Practical Implications for Concrete Mix Design

The extent to which a change in w/b ratio affects compressive strength is greater than the extent to which a change in binder content affects compressive strength for w/b ratios of 0.45 and 0.65, binder contents of 350 kg/m^3 and 450 kg/m^3 and PC and blended cement concretes forming part of this study. This implies that the compressive strength of concrete is more sensitive to changes in w/b ratio than binder content and aligns with the findings of Angelucci (2013). This is most prevalent for FA concretes.

An increase in w/b ratio has a signification negative influence on concrete strength, whereas an increase in binder content has a marginal positive influence on concrete strength as outlined in the previous section. Angelucci (2013) reported similar findings for an increase in w/b ratio; however, for an increase in binder content, negligible and slight negative influences on compressive strength were noted. This contradiction may be related to the binder and water content variances between the studies as Angelucci (2013) did not consider fixed binder contents but rather fixed water contents of 155 l/m^3 to 195 l/m^3. In addition, the proportions of coarse aggregates in the mixes of Angelucci (2013) are higher than those employed in this study and hence more paste content may be required to bind the finer particles, as outlined in section 2.8.2, before the effects of increased binder contents become negative.

From a practical viewpoint, it is therefore crucial that the correct w/b ratio be selected and used based on the concrete strength and durability requirements. This is of particular importance to mixes containing FA as these concretes are the most affected by changes in w/b ratio as compared to PC and GGBS concretes. Furthermore, it is therefore crucial that the practice of adding additional water to concrete on site to “improve workability” be addressed and that the industry be informed and educated accordingly. This may be in the form of industry wide training initiatives to upskill site personnel regarding the detrimental impacts of this practice. The 28-day sensitivity of compressive strength to increases in w/b ratio, which is representative of increasing the water content of the concrete, is on average -39% for PC concretes, -59% for FA concretes and -39% for GGBS concretes. This is indicative of the detrimental effect on concrete compressive strength of this practice.

Strength improvements were noted for binder content increases but this trend does not continue indefinitely as reported by Angelucci (2013). The industry perception of increasing binder contents to address durability concerns therefore may negatively influence the strength development of concretes due to the associated increases in paste content. Therefore this prescriptive trend may have detrimental impacts on concretes and needs to be addressed by the adoption of performance based criteria.

4.3 Oxygen Permeability Index

The oxygen permeability index (OPI) represents the negative logarithm of the coefficient of oxygen permeability (k). Low coefficients of permeability, high OPI values, indicate less permeable concrete, whereas high coefficients of permeability, low OPI values, indicate more permeable concrete with a high portion of interconnected pores.

4.3.1 Effect of w/b Ratio and Binder Content on OPI

Figure 4.9 presents the average OPI results for the PC and blended cement concretes with two different binder contents and w/b ratios.

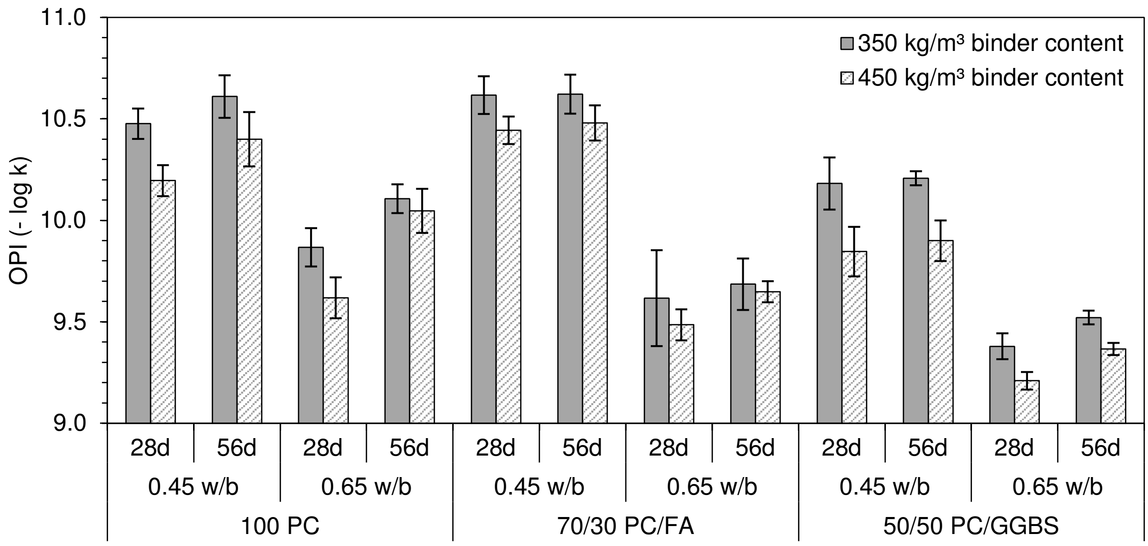


Figure 4.9: Average OPI results

These results show that concretes with higher w/b ratios displayed higher permeability and in turn lower OPI values. This is explained by the excess water that is present in the hydrated cement paste, for higher w/b ratios, which later evaporates and leaves large, well connected capillary pores, resulting in a higher permeability as compared to lower w/b ratios (Mackechnie, 1996).

Similarly, higher binder contents also lead to increased permeability and lower OPI values as reported by Angelucci (2013). These changes are due to the associated increases in paste volume, which is the most significant contributor to porosity and permeability of the concrete system (Kolias et al., 2005). As with compressive strength, permeability improvements were noted as the concrete age increased due to the beneficial role of prolonged curing as explained in Section 4.2.1.

OPI values of FA concretes at the lower w/b ratio were higher than those of PC concretes. This supports the findings of Mukadam (2014) and is due to the fact that the pozzolanic reaction of FA refines the microstructure of the hydrated cement paste by transforming larger pores into finer ones, increasing the matrix density (Thomas and Matthews, 1992). However, OPI values of FA concretes at the higher w/b ratio tended to be lower than those of PC concretes. This phenomenon of increased permeability for FA concretes at higher w/b ratios, in relation to comparable PC concretes, was reported by Kanjee (2015) and Mukadam (2014) and is related to the dilution of the available calcium hydroxide, and subsequent retardation of the FA pozzolanic reactions, due to the increased water content (Biernacki et al., 2001).

GGBS concretes had the lowest OPI values, at all ages, and this align with findings reported by Du Preez (2002). This is due to the high replacement percentage and low Blaine fineness of the GGBS, as compared to the PC and FA specimens, which influences the rate of reaction of the concrete and resulting permeability (Divsholi et al., 2014).

4.3.2 Sensitivity of OPI to Change in w/b Ratio and Binder Content

Figures 4.10 and 4.11 are comparisons of the OPI results, for 28 and 56 days, for specimens prepared using different w/b ratios and binder contents. Section 4.2.2 defines the purpose of the line of equity indicated on the figures. It is evident that all the data pints lie above the line of equity on Figure 4.10 which indicates that higher OPI results were obtained for the 0.45 w/b ratio as compared to the 0.65 w/b ratio. These improvements are as a result of the lower water content and resulting connected capillary pores, after evaporation, as described in Section 4.3.1.

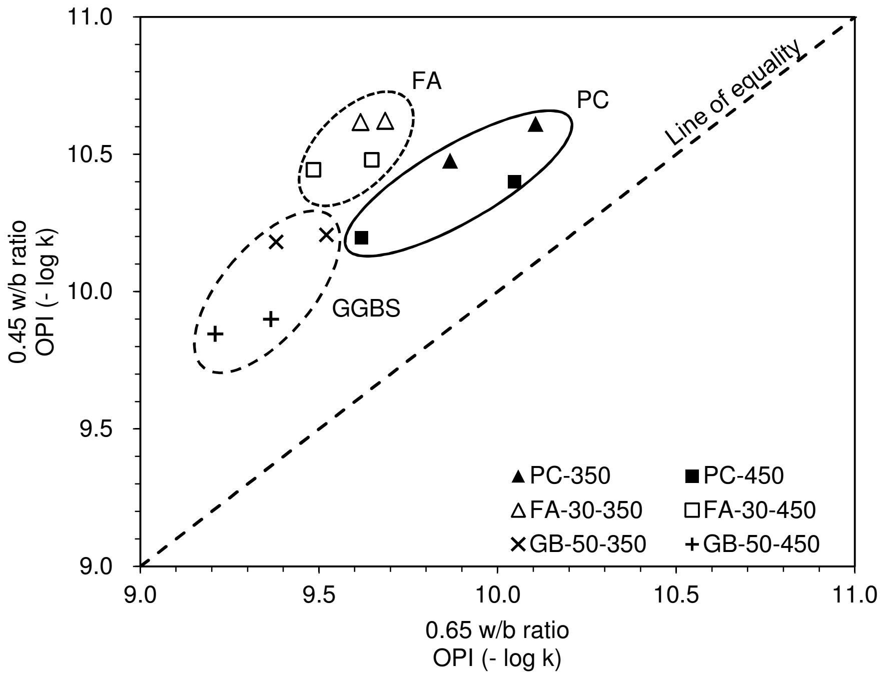


Figure 4.10: Effect of w/b ratio on OPI

A similar trend is observed for Figure 4.11, where all the data points lie above the line of equity indicating that higher binder contents have detrimental effects on permeability due to the increased paste content, associated porosity and interconnectivity of pores as outlined in Section 4.3.1. From the figures it is evident that OPI values are more sensitive to variances in w/b ratio than binder content as the data points are further offset from the line of equity in Figure 4.10 as compared to Figure 4.11. These offsets and variances are expressed as comparable percentages in the subsequent paragraphs. This aligns with the compressive strength findings.

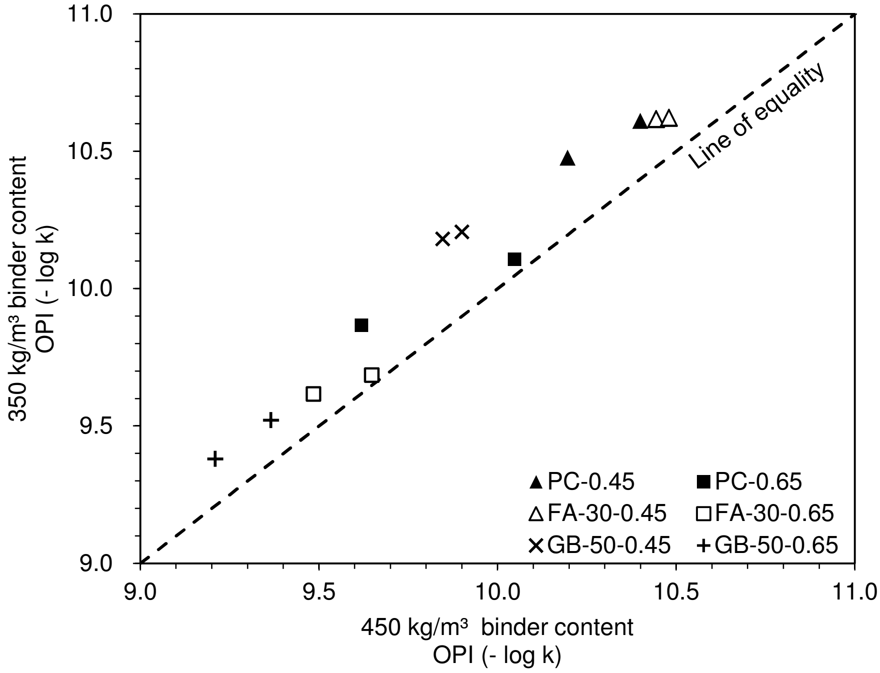


Figure 4.11: Effect of binder content on OPI

The sensitivity of the OPI results to changes in w/b ratio and binder content are displayed in Figures 4.12 and 4.13. The figures outline the percentage change in OPI after individual increases in the parameters for 28 and 56 days. Figure 4.12 shows that an increase in w/b ratio impacts OPI negatively for reasons outlined in the previous paragraph. The extent to which a change in w/b ratio affects OPI decreases with age and is due to the improved interaction of hydration products, for the higher w/b ratio, at later ages as outlined in section 4.2.2. The extent to which a change in w/b ratio affects OPI decreases as binder content increases. This is not expected as a higher binder content result in increased paste content and associated variability. FA concretes were the most affected by a change in w/b ratio.

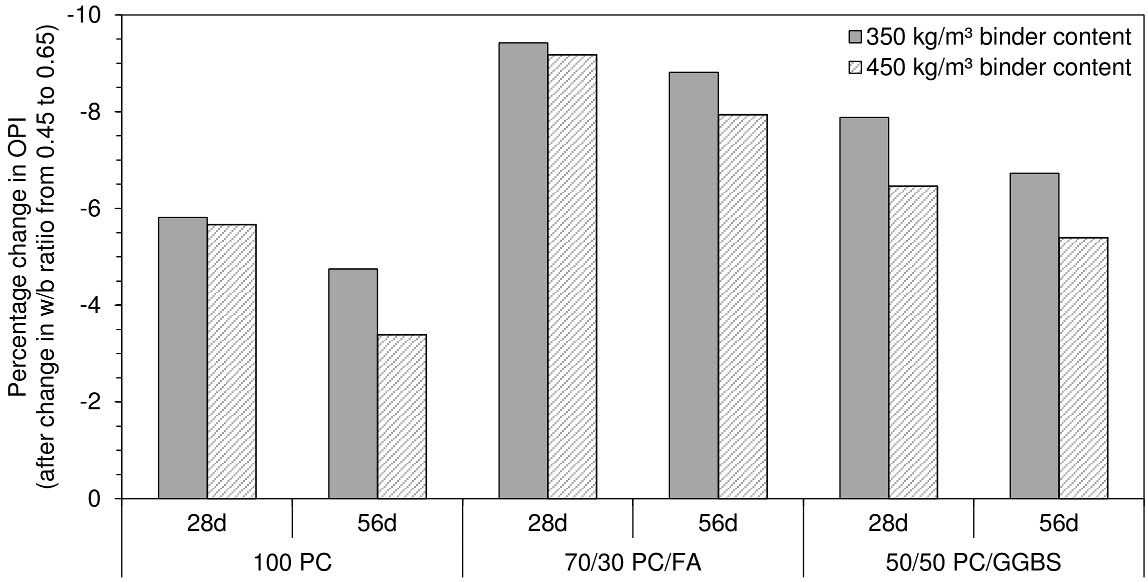


Figure 4.12: Sensitivity of OPI to change in w/b ratio from 0.45 to 0.65

From -5.8% and -5.7%, there was a 1.0% and 1.8% increase in the percentage change of OPI when comparing the 28 and 56 day values for the 350 kg/m³ and 450 kg/m³ PC mixes respectively. Increases of 0.1% and 0.9% were recorded when comparing the 350 kg/m³ and 450 kg/m³ PC mix values for 28 and 56 days respectively. FA concretes followed similar trends to PC concretes but yielded lower percentage change values, varying from the PC mixes by between -3.5% to -4.0%. This is likely due to the dilution of the calcium hydroxide concentration at higher water contents, as outlined in section 4.2.2, which impacts permeability variations in the long term (Biernacki et al., 2001). GGBS concretes also followed similar trends with the percentage change values falling between those of PC and FA concretes.

An increase in binder content has a detrimental effect on the OPI of concrete as outlined in Figure 4.13. The extent to which a change in binder content affects OPI decreases with age and w/b ratio. GGBS concretes have the highest percentage change and hence sensitivity to changes in binder content, followed by PC and FA concrete respectively. This implies that the paste variability of GGBS concretes are more pronounced than FA and PC concretes. Due to the high replacement percentage and low Blaine fineness of the GGBS, as compared to the PC and FA specimens, the rate of reaction of the concrete and resulting permeability is affected (Divsholi et al., 2014). This impact is more pronounced and prevalent with increasing paste content for GGBS concretes.

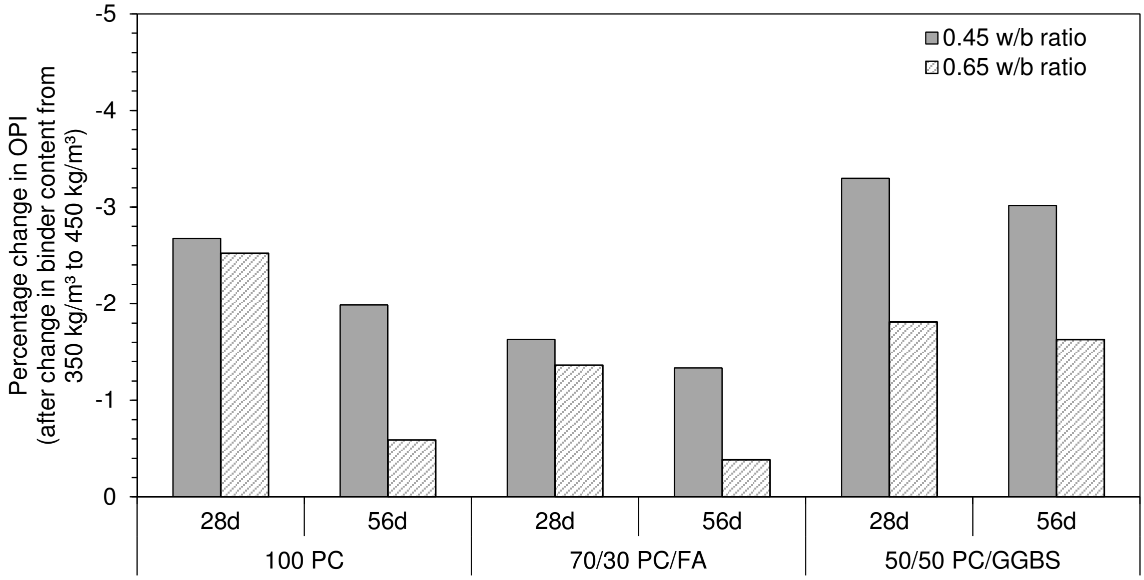


Figure 4.13: Sensitivity of OPI to change in binder content from 350 kg/m³ to 450 kg/m³

4.3.3 Summary and Practical Implications for Concrete Mix Design

The extent to which a change in w/b ratio affects OPI values is greater than the extent to which a change in binder content affects these values for w/b ratios of 0.45 and 0.65, binder contents of 350 kg/m³ and 450 kg/m³ and PC and blended cement concretes forming part of this study. This implies that the OPI index values of concrete tend to be more sensitive to changes in w/b ratio than binder content. Furthermore, FA concretes have the highest sensitivity to changes in w/b ratio whereas GGBS concretes exhibit the highest sensitivity to changes in binder content. However, Angelucci (2013) reported that OPI index values were more sensitive to changes in binder content than w/b ratio and may be related to the factors outlined in section 4.2.3. The extent to which a change in w/b ratio and binder content affects OPI therefore varies depending on the water, binder and coarse aggregate content ranges. It is therefore necessary to relate the sensitivity of OPI to changes in w/b ratio and binder content to the applicable water, binder and coarse aggregate content ranges.

An increase in both w/b ratio and binder content lead to lower OPI values (higher permeability) which aligns with the findings of Angelucci (2013). Given that the comparable percentage change in OPI, for changes in w/b ratio and binder content, are on average within 5.0% of each other, both these parameters are important and relevant to OPI. Therefore, when designing concrete mixes to minimise permeability, both w/b ratio and paste content needs to be considered. Once again, the industry perception of increasing binder content to address durability concerns is not founded and emphasises the need to promote the continued adoption of performance based criteria. Increasing the binder content will impact the microstructure of the hardened concrete matrix but these effects cannot be deemed as beneficial or detrimental without investigating other parameters affected by the change (Du Preez, 2002).

The DI approach enables the characterisation of concrete quality through the quantification of parameters obtained from the measurement of transport related properties. The impact of mix design parameters, such as binder content, can only be categorised under material potential and its content specification does not solely determine durability (Angelucci, 2013). Durability is related to several factors such as mix design parameters, mechanical properties and extrinsic influences and needs to be considered holistically by considering the combined effect of these influences and not just isolated parameters. Performance based approaches therefore need to replace prescriptive approaches to ensure the required durability is achieved.

4.4 Water Sorptivity Index

Sorptivity is defined as the progression of a wetting front though a porous material due to capillary action (Alexander et al., 1999). The water sorptivity test is based on measuring the unidirectional ingress of water into a preconditioned concrete disk specimen (Beushausen & Alexander, 2008). This is largely influenced by the pore geometry including the orientation and connectivity. The lower the sorptivity the more resistant the material is to the ingress of moisture.

4.4.1 Effect of w/b Ratio and Binder Content on WSI

Figure 4.14 presents the average water sorptivity results for the PC and blended cement concretes with two different binder contents and w/b ratios.

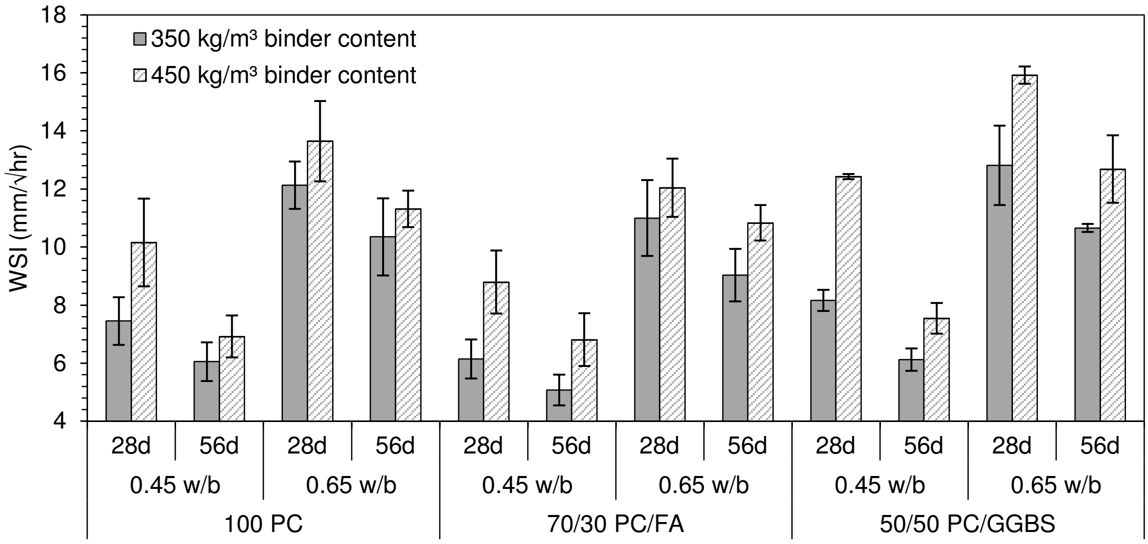


Figure 4.14: Average WSI Results

When evaluating the influence of w/b ratio on sorptivity it is evident that for all three concretes investigated, the sorptivity properties increased with increasing w/b ratio. This is attributed to the increased pore refinement as the w/b ratio decreases (Mackechnie, 1996). A sorptivity increase was noted for all concrete specimens with an increase in binder content. These results imply that concretes with higher binder contents will experience greater rates of water absorption into the concrete through capillary action. These increases are due to the associated increases in paste volume, which is the main contributor of pore geometry, size, orientation and connectivity (Du Preez, 2002).

Figure 4.14 further illustrates the beneficial role of FA in decreasing the sorptivity properties of concrete as compared to PC specimens. Due to its pozzolanic reaction, FA refines the capillary pores, lowering the sorptivity of the concrete. Furthermore, the fine filler effect of FA leads to an improved packing configuration of the particles in the hardened cement paste (Yahia et al., 2005). This results in a more dense microstructure which reduces the overall concrete sorptivity (Mackechnie, 1996).

GGBS concretes yielded the highest sorptivity results, indicating increased near surface absorption rates. This can be explained by the coarse binder particles, as compared to PC and FA, and the associated high replacement levels, refer to Section 4.3.1 for the supporting rationale. Furthermore, GGBS concretes are sensitive to curing due to the slow latent hydraulic reactions that modify the concrete structure with age. Thus, there is a delay in the formation of cementing compounds as the activators from the PC hydration process needs to be available first before the GGBS contributes to refining the concrete microstructure.

4.4.2 Sensitivity of WSI to Change in w/b Ratio and Binder Content

Comparisons of WSI results for specimens tested at 28 and 56 days, using different w/b ratios and binder contents, are outlined in Figures 4.15 and 4.16. The line of equity is explained in section 4.2.2. All the data points are located below the line of equity which implies higher WSI results were obtained for the 0.65 w/b ratio as compared to the 0.45 w/b ratio (Figure 4.15). This is due to the improved pore refinement for the lower water binder ratio (Mackechnie, 1996).

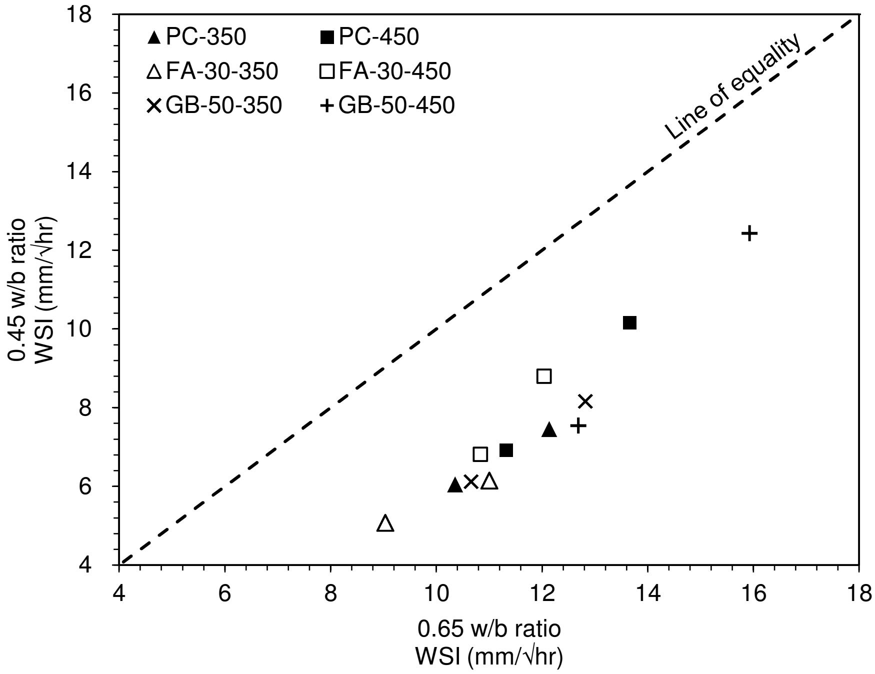


Figure 4.15: Effect of w/b ratio on WSI

All the data points on Figure 4.16 lie below the line of equity indicting the detrimental effect of increases in binder content and associated increases in paste content on WSI. From the Figures it is evident that WSI is more sensitive to changes in w/b ratio than binder content as the data points in general are further offset from the line of equity in Figure 4.16 as compared to Figure 4.15. These offsets are quantified and discussed in the following paragraphs.

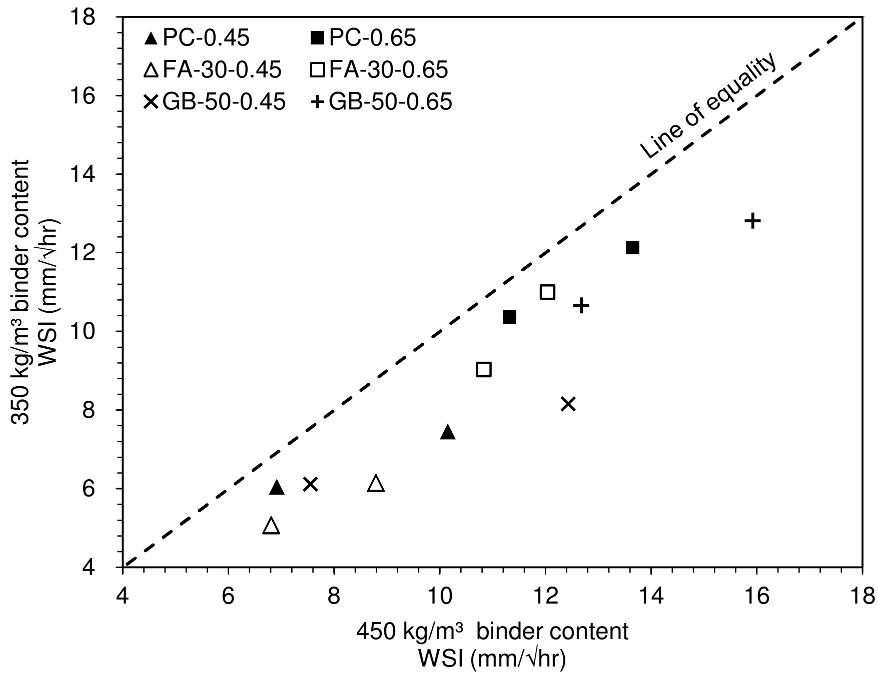


Figure 4.16: Effect of binder content on WSI

WSI sensitivity to changes in w/b ratio and binder content is shown in Figures 4.17 and 4.18. The figures outline the percentage change in WSI after individual increases in the parameters for 28 and 56 days. Figure 4.17 indicates that WSI increases along with w/b ratio and that the extent to which a change in w/b ratio affects WSI increases with age, apart from the FA specimens with 350kg/m³ binder content where a slight decrease is noted. This indicates that the effect of the ongoing hydration process (Ballim, 1993) on WSI is more prevalent and beneficial with age for the lower w/b ratio.

The extent to which a change in w/b ratio affects WSI decreases as binder content increases. This differs from the OPI findings as these two indices measure different characteristics of the pore structure of concrete. The influence of tortuosity and the ITZ on WSI is different to that of OPI (Elahi et al., 2010). FA concretes were the most affected by a change in w/b ratio, for the 350 kg/m³ binder content, and the 28 days results, for the 450 kg/m³ binder content, whereas GGBS exhibited the highest 56 day sensitivity, to a change in w/b ratio, for the 450 kg/m³ binder content.

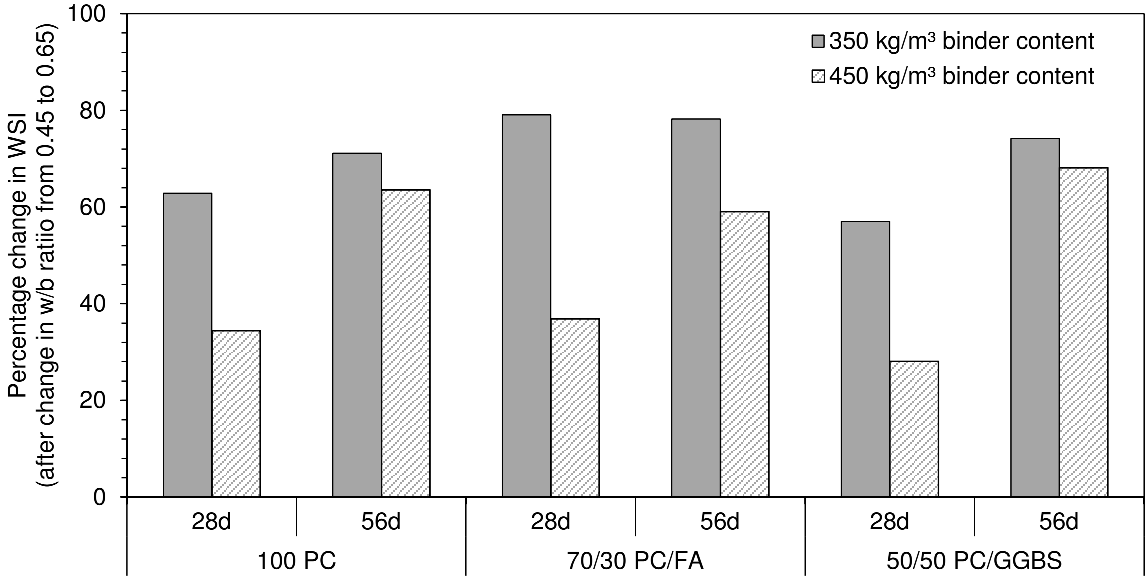


Figure 4.17: Sensitivity of WSI to change in w/b ratio from 0.45 to 0.65

The WSI sensitivity of PC concretes, to changes in w/b ratio, increases with age by 8% and 17% for the PC and GGBS concretes at the 350 kg/m³ binder content whereas a decrease of 1% is noted for the comparable FA concretes. For the 450 kg/m³ mixes, the extent to which a change in w/b ratio effects WSI increases with age by 30%, 23% and 40% for the PC, FA and GGBS concretes respectively. Sensitivity therefore increases with age and this generally holds true for all binder combinations apart from the FA concretes at the 350kg/m³ binder content. This however contradicts the OPI findings, where sensitivity decreases with age, and is possibly due to the indices measuring different characteristics of the concrete pore structure.

Figure 4.18 shows that binder content increases have negative impacts on the WSI of concrete. The extent to which a change in binder content affects WSI decreases with age and w/b ratio apart from FA concretes at the 0.65 w/b ratio where an increase is noted. For PC concretes, the percentage change decreases with age from 37% and 13% to 14% and 9%, for the 0.45 w/b ratio and 0.65 w/b ratio respectively. Similar trends are evident for the GGBS concretes and the percentage changes values are between 9% to 16% higher than PC concretes. FA concretes, at the lower w/b ratio, also follow similar trends to the PC concretes; however, the percentage change increases with age from 9% to 19% for 0.65 w/b ratio mixes.

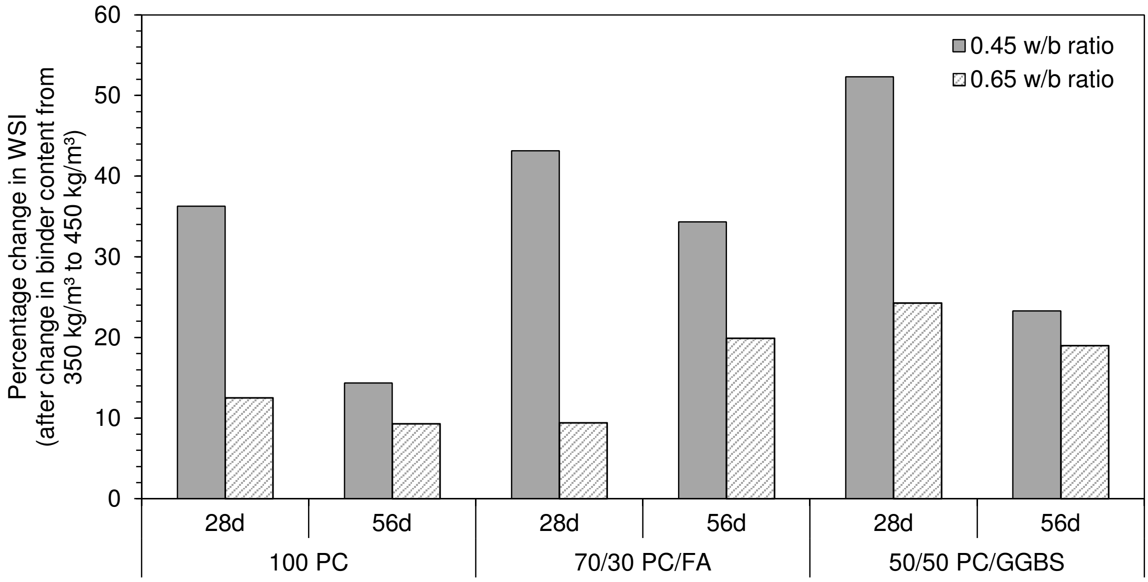


Figure 4.18: Sensitivity of WSI to change in binder content from 350 kg/m³ to 450 kg/m³

4.4.3 Summary and Practical Implications for Concrete Mix Design

The extent to which a change in w/b ratio affects WSI is greater than the extent to which a change in binder content affects WSI for w/b ratios of 0.45 and 0.65, binder contents of 350 kg/m³ and 450 kg/m³ and PC and blended cement concretes forming part of this study. This implies that the WSI of concrete is more sensitive to changes in w/b ratio than binder content. This is most prevalent for blended cement concretes.

Increases in w/b ratio and binder content lead to associated increases in near surface concrete porosity. Angelucci (2017) reported similar findings for an increase in binder content. From a practical point of view, it is therefore important that the w/b ratio and binder content be kept to a minimum as far as possible to ensure the required durability is achieved. This is particularly relevant to blended cement concretes which exhibit the highest sensitivity to change in these parameters.

4.5 Chloride Conductivity Index

Resistance to chloride conductivity is both a physical and chemical mechanism. Chloride ions pass through the concrete by means of diffusion which is regarded as a physical process, however, a fraction of these ions are bound by the aluminates in the binder which is classified as a chemical process (Angelucci, 2013). The Chloride Conductivity Index, CCI, provides a measure of the resistance of a material to the ingress of chlorides by diffusion. Low CCI values are indicative of a concrete specimen's increased resistance to ionic ingress, whereas the opposite holds true for high CCI values (Mackechnie, 1996).

4.5.1 Effect of w/b Ratio and Binder Content on CCI

Figure 4.19 outlines the average CCI results of the prepared concrete specimens. The concrete mixes can be arranged from the lowest to the highest CCI values as GGBS, FA and PC. This applied to both the 28 day and 56 day results although the 56 day results are lower than the 28 day results. This is due to the continued hydration process resulting from prolonged curing (Ballim, 1993).

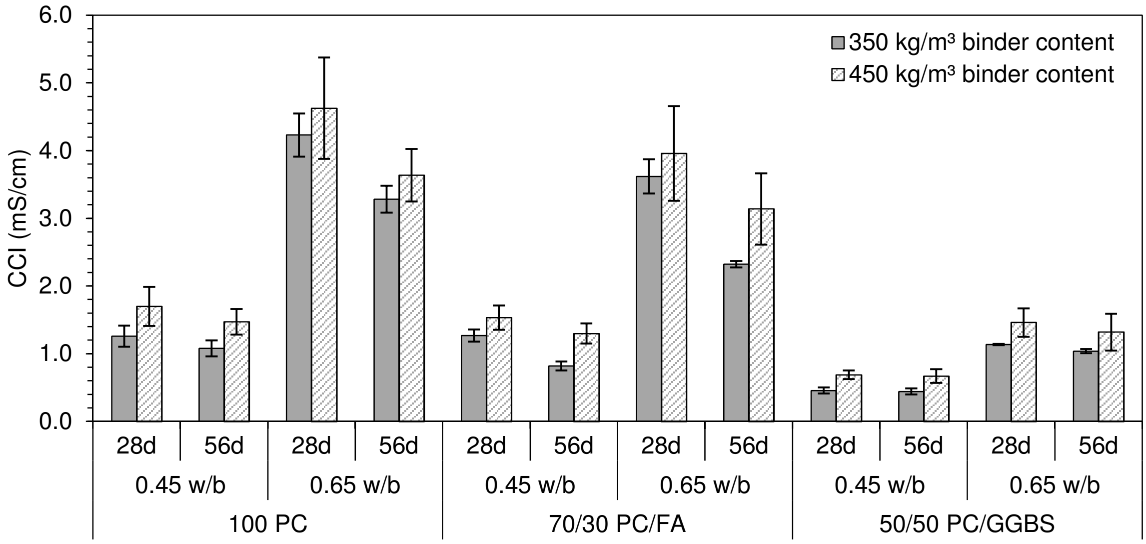


Figure 4.19: Average CCI Results

From Figure 4.19 the use of a higher w/b ratio of 0.65 resulted in higher CCI values, for all binder combinations when compared to the 0.45 mixes. This is attributed to the decrease in capillary porosity of the concrete as the w/b ratio increases (Malhotra, 1994). Similarly, higher binder contents also lead to increased CCI values due to the associated paste volume increases (Kolias et al., 2005).

It can be seen that the inclusion of GGBS in concrete provides improvements in CCI values when compared to PC and FA mixes. This is especially prevalent at the higher w/b ratio where the GGBS specimens showed 360% and 420% decreases in CCI values when compared to the FA and PC concretes respectively. This trend of attaining low CCI values in GGBS concretes is attributed to the chloride binding capabilities of the binder (Ballim, 1994). Moreover, GGBS refines the pore structure of the hardened concrete matrix due to the formation of the secondary calcium silicate hydrate gel from the pozzolanic reaction of the slag (Hadjsadok et al., 2012).

Moreover, FA also had a beneficial effect on the CCI values as compared to PC only mixes but this was less notable than the GGBS concretes. This is related to the concrete pore refinement effect of the FA which lowers the rate of diffusion of substances into the concrete (Nikam and Tambvekar, 2003).

4.5.2 Sensitivity of CCI to Change in w/b Ratio and Binder Content

Comparisons of CCI results for specimens tested at 28 and 56 days, using different w/b ratios and binder contents, are outlined in Figures 4.20 and 4.21. The line of equity is explained in section 4.2.2. For Figure 4.20, all the data points are located below the line of equity which implies higher CCI results were obtained for the 0.65 w/b ratio as compared to the 0.45 w/b ratio. Increases in w/b ratio therefore lead to lower concrete chloride resistance.

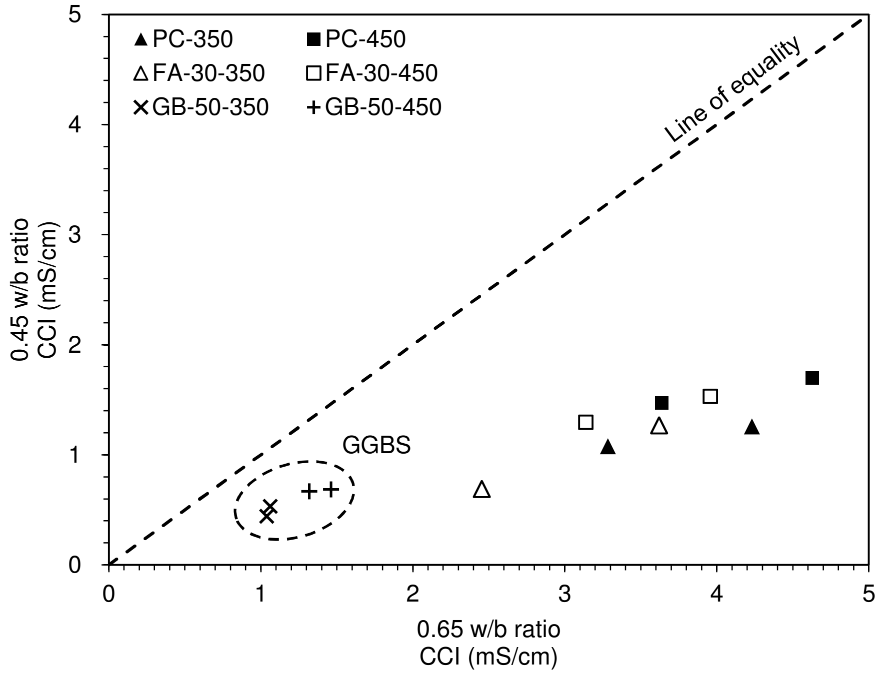


Figure 4.20: Effect of w/b ratio on CCI

Similarly, all the data points on Figure 4.21 also lie below the line of equity indicting the detrimental effect of increases in binder content on CCI. From these figures it is evident that CCI is more sensitive to changes in w/b ratio than binder content as the data points in general are further offset from the line of equity in Figure 4.20 as compared to those in Figure 4.21. These offsets are quantified and discussed in the following paragraphs.

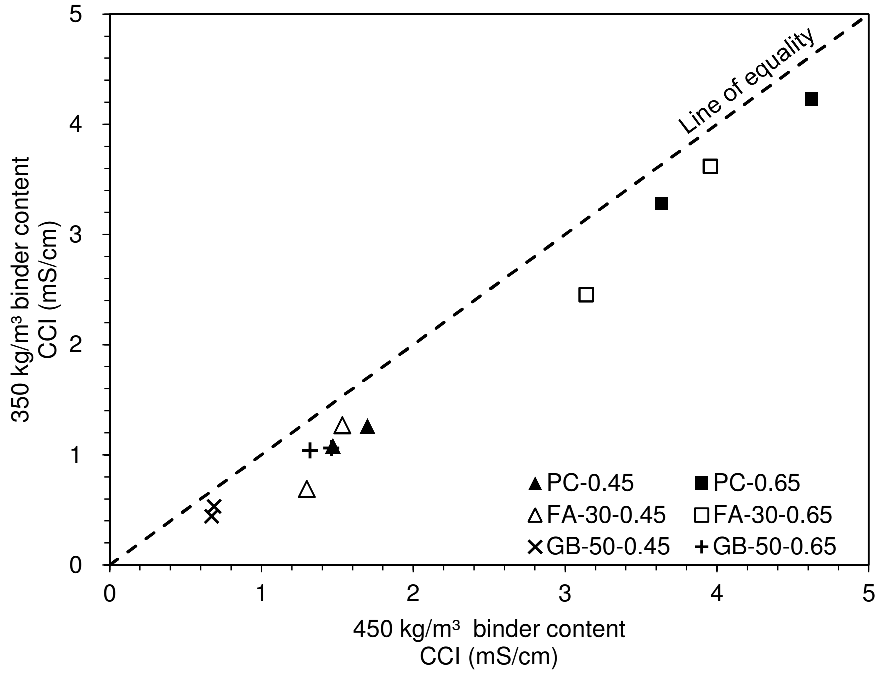


Figure 4.21: Effect of binder content on CCI

The sensitivity of the CCI results to changes in w/b ratio and binder content are displayed in Figures 4.22 and 4.23. The figures outline the percentage change in CCI after individual increases in the parameters for 28 and 56 days. Figure 4.22 shows that an increase in w/b ratio has a negative impact on the chloride resistance of concrete. The extent to which a change in w/b ratio affects CCI decreases with age. This is due to the ongoing hydration of the cementitious material whereby the porosity and interconnectivity of pores decreases with time (Ballim, 1993).

PC concretes were the most affected by a change in w/b ratio followed by FA and GGBS concretes. The lower sensitivity of GGBS concretes to changes in w/b ratio may be attributed to its refined pore structure due to the formation of secondary calcium silicate hydrate gel which is particularly beneficial at higher w/b ratios (Hadjsadok et al., 2012). Similarly, for FA concretes, this lower sensitivity to changes in w/b ratio can be related to the beneficial effect of pore refinement in the paste fraction of the concrete, which reduces the rate of diffusion of the chlorides into the concrete (Nikam and Tambvekar, 2003). These beneficial effects are not present in PC concretes and hence a higher w/b ratio would have a marked effect on the variance of the resulting OPI values.

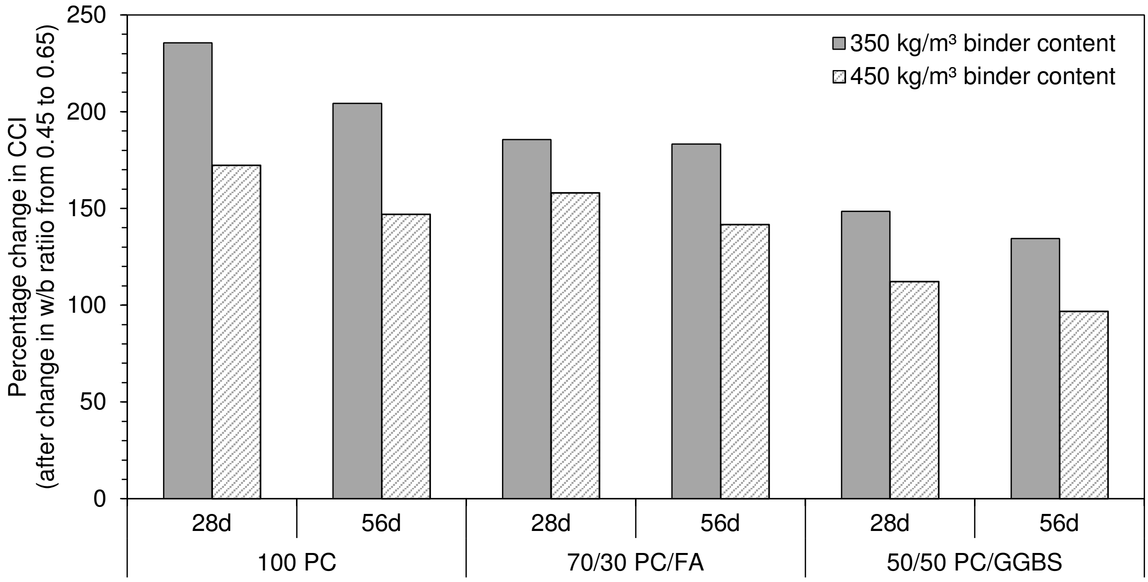


Figure 4.22: Sensitivity of CCI to change in w/b ratio from 0.45 to 0.65

The percentage change of CCI of PC concretes increases with age from 236% and 172%, at 28 days, to 204% and 147%, at 56 days, for the 350 kg/m³ and 450 kg/m³ binder combination mixes respectively. FA and GGBS concretes follow similar trends with the percentage change being on average 23% and 67% lower than the comparable PC mixes respectively.

An increase in binder content increases the CCI of concrete as shown in Figure 4.23 for reasons outlined in section 4.5.1. The extent to which a change in binder content affects CCI generally increases with age apart from the 0.65 w/b ratio GGBS concretes which exhibits a marginal decrease. For PC concretes, the percentage change increases with age from 35% and 9% to 36% and 11%, for the 0.45 w/b ratio and 0.65 w/b ratio respectively. Similar trends are evident for the FA concretes and the percentage change increases with age from 21% and 9% to 58% and 35%, for the 0.45 w/b ratio and 0.65 w/b ratio respectively. GGBS concretes, at the lower w/b ratio, also follow similar trends to the PC concretes; however, the percentage change decreases with age from 29% to 27% for 0.65 w/b ratio mixes.

The variances with age for PC and GGBS concretes are considered to be marginal, around 2%, and indicate that the sensitivity of CCI to changes in binder content is not directly governed by curing. However, marked increases with age of up to 37% are noted for FA concretes. This implies that the sensitivity of CCI of FA concretes to changes in binder content is governed by curing. As the paste variability increases with age, so does the pore refining effects of the FA pozzolanic reactions, depending on binder content.

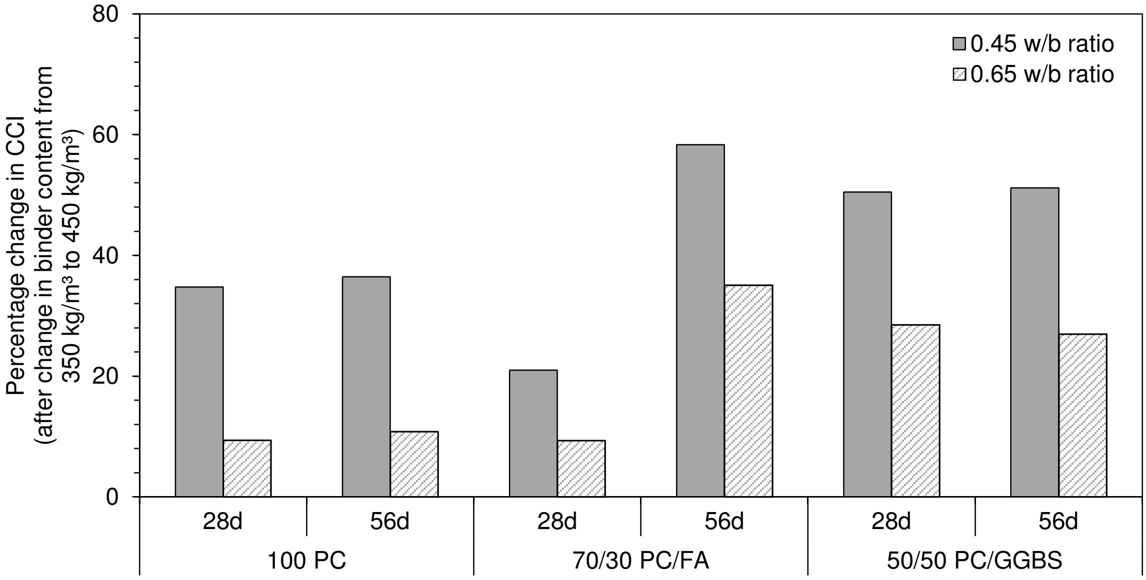


Figure 4.23: Sensitivity of CCI to change in binder content from 350 kg/m³ to 450 kg/m³

4.5.3 Summary and Practical Implications for Concrete Mix Design

The extent to which a change in w/b ratio affects CCI is greater than the extent to which a change in binder content affects CCI for w/b ratios of 0.45 and 0.65, binder contents of 350 kg/m³ and 450 kg/m³ and PC and blended cement concretes forming part of this study,. This implies that the CCI of concrete is more sensitive to changes in w/b ratio than binder content which contradicts the findings of Angelucci (2013) and may be related to the concrete mix proportion variances outlined in section 4.2.3. The extent to which a change in w/b ratio and binder content affects CCI therefore varies depending on the water, binder and coarse aggregate content ranges.

From a practical perspective, the mix design process should aim to achieve a sufficiently dense concrete microstructure, by minimising the w/b ratio, whilst limiting the paste content of mixes. This again emphasises the importance of the continued wide scale adoption of the performance based design criteria incorporating the DI tests.

The DI tests provide a means of characterising the quality of the concrete cover layer, using parameters that reflect the deterioration process acting on the concrete (Alexander, 2001). The tests ‘index’ the concrete in terms of its ability to resist the ingress of aggressive agents and these index values are matrixed with design and construction-related factors such as mix materials and proportions, nature and time of curing and thickness of the cover layer (Alexander, 2004). In order to promote the adoption of the DI tests, the framework needs to be extended by incorporating early age material indexing, direct durability testing, and observations of long term durability performance.

CHAPTER 5

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The objective of this study was to investigate the sensitivity of strength and durability properties of blended cement concrete to changes in w/b ratio and binder content. The results indicate that changes in these parameters affect the strength and durability properties of concrete. Furthermore, changes in w/b ratio have the greater influence on the resulting strength and durability properties of concrete as compared to changes in binder content. This chapter outlines the results and discussions, presented in Chapter 4, along with the conclusions of the sensitivity analyses for the individual concrete strength and durability properties.

5.1.1 Compressive Strength

The results show that compressive strength decreases with increasing w/b ratio but increases with increasing binder content. However, strength improvements related to binder content increases are dependent on the paste content range, aggregate content and grading. This trend will therefore not continue indefinitely as continued binder and associated paste content increases will lead to higher pore spaces and associated reduction in compressive strength (Angelucci, 2013). Strength improvements are also evident with age and PC concretes yield the highest compressive strengths followed by FA and GGBS concretes. However, long term strength results of FA and GGBS concretes may be higher than the comparable PC concretes.

The extent to which a change in w/b ratio affects compressive strength is greater than the extent to which a change in binder content affects compressive strength. FA concretes are the most affected by a change in w/b ratio. The sensitivity of PC and GGBS concretes to a change in w/b ratio fluctuates with age but by 56 days PC concretes exhibit a higher sensitivity to a change in this parameter compared to GGBS concretes. In general, the sensitivity of concretes to a change in w/b ratio decreases with age.

The sensitivity of PC concretes to changes in binder content generally increases with age. The extent to which a change in binder content affects FA concretes decreases from 3 to 7 days, then increases to 28 days and thereafter returns to approximately the 3 day value at

56 days. GGBS concretes follow the inverse of this trend whereby the sensitivity to changes in binder content increases from 3 to 7/14 days then, decreases to 28 days and thereafter returns to approximately the 7/14 day value at 56 days.

From a practical viewpoint, it is therefore important that the correct w/b ratio be selected and used based on the concrete strength requirements. This is of particular importance to mixes containing FA. Furthermore, the practice of adding additional water to concrete on site to "improve workability" needs to be put to an end by industry wide training initiatives.

Moreover, the industry perception of increasing binder content to address durability concerns have negative influences on the strength development of concretes due to the associated increases in paste content. This prescriptive trend is detrimental to compressive strength and needs to be addressed by the adoption of performance based criteria.

5.1.2 Oxygen Permeability

Permeability tends to increase with an increase in w/b ratio and binder content. As with compressive strength, permeability improvements are evident with prolonged curing. For the 0.45 w/b ratio, the OPI values of FA concretes tend to be higher than those of the PC concretes due to the pozzolanic reaction of FA, which refines the microstructure of the hydrated cement paste by transforming larger pores into finer ones, increasing the matrix density. However, OPI values of FA concretes at the 0.65 w/b ratio tend to be lower than those of the PC concretes. This phenomenon of increased permeability for FA concretes at higher w/b ratios, in relation to comparable PC concretes is due to the dilution of the available calcium hydroxide, and subsequent retardation of the FA pozzolanic reactions, due to the increased water content. GGBS concretes have the lowest OPI values.

The extent to which a change in w/b ratio affects OPI is greater than the extent to which a change in binder content affects OPI. The sensitivity of OPI to changes in w/b ratio increases in the following order, PC < GGBS < FA, whereas the OPI of GGBS concretes exhibit the highest sensitivity to changes in binder content followed by PC and FA concretes. In general, the sensitivity of concretes to a change in w/b ratio and binder content decreases with age.

Considering that the comparable sensitivity of OPI, to changes in w/b ratio and binder content, are on average within 5.0% of each other, both these parameters govern OPI. Thus, w/b ratio and paste content needs to be controlled during the mix design process when considering OPI. The industry perception of increasing binder content to address durability concerns is not founded and the continued adoption of performance based criteria needs to be promoted.

5.1.3 Water Sorptivity

Sorptivity properties increase with increasing w/b ratio and binder content. Sorptivity improvements are also evident with age and FA concretes yield the lowest WSI results followed by PC and GGBS concretes.

The extent to which a change in w/b ratio affects WSI is greater than the extent to which a change in binder content affects WSI. FA concretes are the most affected by a change in w/b ratio, for the 350 kg/m³ binder content, and the 28 days results, for the 450 kg/m³ binder content, whereas GGBS exhibited the highest 56 day sensitivity for the 450 kg/m³ binder content. The sensitivity of concretes to a change in w/b ratio increases with age, apart from the FA specimens with 350kg/m³ binder content where a slight decrease is noted

Apart from the 56 day results for FA concretes, the WSI of GGBS concretes display the highest sensitivity to changes in binder content followed by PC and FA concretes. The extent to which a change in binder content affects WSI decreases with age and w/b ratio, apart from FA concretes at the 0.65 w/b ratio where an increase is noted.

In practice, it is therefore recommended that the w/b ratio and binder content be kept as low as possible to ensure the required WSI is achieved whilst complying with the strength and further durability requirements. This is of particular importance to concretes containing FA and GGBS as they exhibit the highest sensitivity to changes in these parameters.

5.1.4 Chloride Conductivity

The results show that CCI increases with increasing w/b ratio and binder content. Furthermore, CCI decreases with age and GGBS concretes yield the lowest CCI values followed by FA and PC concretes.

The extent to which a change in w/b ratio affects CCI is greater than the extent to which a change in binder content affects CCI. The sensitivity of CCI to changes in w/b ratio increases in the following order: GGBS < FA < PC. In general, the sensitivity of CCI to a change in w/b ratio decreases with age.

Excluding the 56 day results for FA concretes, GGBS concretes display the highest sensitivity to changes in binder content followed by PC and FA concretes respectively. The extent to which a change in binder content affects CCI generally increases with age apart from the 0.65 w/b ratio GGBS concrete which exhibited a marginal decrease.

These findings again highlight the importance of limiting the paste content and minimising the w/b ratio when considering concrete DI properties. Given the beneficial effect of GGBS on chloride conductivity, adopting the highest replacement levels will yield the most beneficial results but also the highest sensitivity to paste content.

5.2 Recommendations

The following recommendations for further work are put forward based on this study:

a) This study can be extended by increasing and refining the experimental variable ranges (w/b ratio, binder content and binder type/proportional replacement). The focus should be to further the understanding of the correlation between these variables and the sensitivity of the resulting concrete strength and durability parameters across broadened variable ranges.

b) In this study, the binder fineness and composition was not quantified and these characteristics were purely based on the supplier’s provisions. Given the variability of the materials, it would be interesting to carry out an assessment of these characteristics using methods such as X-ray diffraction (a method used in the identification of fine grained, crystalline compounds). This will further the understanding of the material behaviour and influence on the resulting concrete properties.

c) The influence of the proportions and grading of coarse and fine aggregates, on the strength and durability properties of concrete, were not directly investigated in this study. It would be of interests to expand the investigation to include concrete mixes with various proportions of coarse and fine aggregates, with various gradings, to further the understanding of the aggregate/paste content requirements and the effects on the resulting concrete properties.

d) Further research should also consider durability properties defined by other means such as carbonation and chloride ingress rates and the influence that mix design parameters have on these properties.

e) Further studies should attempt to correlate fresh properties of concrete, i.e. rheology, slump, with the durability indexes for various w/b ratios and binder contents.

CHAPTER 6

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APPENDIX A

TESTING AND VARIABILITY

An outlier is an observation point that is distant from other observations and does not appear to fall within the expected distribution of a data set. An outlier can cause serious problems in statistical analyses. This may be due to variability in the measurement or it may indicate some form of defined experimental error such as cross contamination or improper calibration. In the latter case, these outliers may be excluded from the data set (Grubbs, 1969). Statistically sound tests need to be implemented for the detection of outliers, due to variability in measurement, such as the t-distribution test.

W.S. Gosset developed the t-distribution for statistical tests using small samples. This method takes into account the sample size which affects the shape of the distribution curve. It tends to be heavier-tailed than the normal distribution, for smaller sample sizes, and becomes progressively closer as the sample size is increased (Underhill and Bradfield, 2013). The confidence interval provides an acceptable range for the sample and any data point falling outside of this range is defined as an outlier and rejected. The confidence interval is defined by the following equation:

$$\left(\bar{x} - t^*_{n-1}\frac{s}{\sqrt{n}}, \bar{X} + t^*_{n-1}\frac{s}{\sqrt{n}}\right) \tag{A.1}$$

where:
- $\bar{x}$ = sample mean
- t^* = t-value obtained from the t-tables. For 95% confidence intervals, use the column headed 0.025
- s = sample standard deviation
- n = sample size

For simplicity the deviation is defined as (Underhill and Bradfield, 2013):

$$d = t^*_{n-1}\frac{s}{\sqrt{n}} \tag{A.2}$$

The sample standard deviation is calculated as follows:

$$s = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad \text{(A.3)}$$

where: x_i = individual test results

References

Grubbs, F.E. (1969) Procedures for detecting outlying observations in samples. *Technometrics,* 11 (1), pp. 1-21.

Underhill, L. and Bradfield, D. (2013). Introstat. Department of Statistical Sciences, University of Cape Town.

APPENDIX B

COMPRESSIVE STRENGTH AND DENSITY RESULTS

Table B.1: Compressive strength and density results for PC concretes.

Designation	Age (days)	Average[1]		Std. Dev.	Deviation[2]	Range	
		Density (kg/m³)	Strength (MPa)			Min (MPa)	Max (MPa)
PC-350-0.45	3	2401	32.6	1.3	3.30	29.3	35.9
	7	2388	39.1	1.4	3.36	35.8	42.5
	14	2457	42.0	1.2	2.91	39.1	44.9
	28	2443	45.8	1.1	2.61	43.1	48.4
	56	2418	47.1	0.8	1.94	45.2	49.1
PC-350-0.65	3	2409	16.2	0.3	0.80	15.4	17.0
	7	2414	20.1	0.1	0.33	19.8	20.4
	14	2412	24.3	0.8	1.93	22.4	26.3
	28	2372	27.4	1.1	2.82	24.5	30.2
	56	2430	28.2	0.8	2.00	26.2	30.2
PC-450-0.45	3	2450	34.3	0.2	0.53	33.7	34.8
	7	2474	41.1	0.4	1.01	40.1	42.1
	14	2399	45.2	1.8	4.42	40.8	49.7
	28	2445	51.0	1.6	4.02	47.0	55.0
	56	2422	54.7	1.9	4.80	49.9	59.5
PC-450-0.65	3	2317	16.3	0.4	0.92	15.4	17.2
	7	2292	21.7	0.1	0.25	21.4	21.9
	14	2304	25.9	0.9	2.33	23.5	28.2
	28	2320	31.6	1.7	4.20	27.4	35.8
	56	2278	32.7	2.1	5.18	27.6	37.9

Notes (refer to Table superscript references):

1. Average of three readings.
2. t-value selected for a 95% confidence level, t-value = 4.303. Number of specimens tested, n = 3.

Table B.2: Compressive strength and density results for FA concretes.

Designation	Age (days)	Average(1)		Std. Dev.	Deviation(2)	Range	
		Density (kg/m^3)	Strength (MPa)			Min (MPa)	Max (MPa)
FA-30-350-0.45	3	2428	21.2	0.5	1.18	20.0	22.4
	7	2421	26.9	0.3	0.82	26.1	27.7
	14	2458	30.2	0.5	1.15	29.0	31.3
	28	2441	33.0	0.4	0.94	32.0	33.9
	56	2445	42.6	0.3	0.67	41.9	43.2
FA-30-350-0.65	3	2367	7.6	0.3	0.84	6.8	8.5
	7	2404	9.7	0.2	0.55	9.2	10.3
	14	2330	11.3	0.6	1.52	9.8	12.9
	28	2328	13.9	0.7	1.64	12.3	15.6
	56	2329	19.1	0.2	0.45	18.6	19.5
FA-30-450-0.45	3	2420	22.4	0.3	0.82	21.6	23.2
	7	2402	27.5	0.2	0.42	27.1	28.0
	14	2407	32.0	1.7	4.13	27.9	36.2
	28	2409	39.3	1.3	3.15	36.2	42.5
	56	2382	45.6	1.4	3.56	42.0	49.1
FA-30-450-0.65	3	2307	8.1	0.5	1.22	6.8	9.3
	7	2364	9.7	0.2	0.56	9.2	10.3
	14	2295	11.6	0.2	0.53	11.1	12.2
	28	2292	15.3	0.5	1.24	14.0	16.5
	56	2300	19.6	0.7	1.81	17.8	21.4

Notes (refer to Table superscript references):

1. Average of three readings.
2. t-value selected for a 95% confidence level, t-value = 4.303. Number of specimens tested, n = 3.

Table B.3: Compressive strength and density results for GGBS concretes.

Designation	Age (days)	Average(1)		Std. Dev.	Deviation(2)	Range	
		Density (kg/m^3)	Strength (MPa)			Min (MPa)	Max (MPa)
GB-50-350-0.45	3	2393	10.8	0.2	0.60	10.2	11.4
	7	2421	14.7	0.1	0.25	14.5	15.0
	14	2399	21.7	1.1	2.84	18.9	24.6
	28	2399	28.5	0.9	2.23	26.3	30.8
	56	2415	33.3	0.7	1.70	31.6	35.0
GB-50-350-0.65	3	2389	6.3	0.2	0.57	5.8	6.9
	7	2329	8.2	0.5	1.30	6.9	9.5
	14	2348	12.3	0.0	0.10	12.2	12.4
	28	2369	18.4	0.2	0.55	17.9	19.0
	56	2356	22.7	1.3	3.26	19.5	26.0
GB-50-450-0.45	3	2397	12.4	0.8	1.87	10.5	14.3
	7	2432	17.2	0.2	0.55	16.7	17.8
	14	2421	25.6	0.8	1.91	23.7	27.5
	28	2419	33.1	0.6	1.53	31.5	34.6
	56	2393	39.6	0.9	2.32	37.2	41.9
GB-50-450-0.65	3	2257	6.6	0.3	0.62	6.0	7.2
	7	2253	8.8	0.3	0.66	8.2	9.5
	14	2271	13.2	0.2	0.52	12.6	13.7
	28	2298	19.1	0.6	1.45	17.7	20.6
	56	2333	25.0	1.1	2.67	22.3	27.6

Notes (refer to Table superscript references):

1. Average of three readings.
2. t-value selected for a 95% confidence level, t-value = 4.303. Number of specimens tested, n = 3.

APPENDIX C

DURABILITY INDEX TEST RESULTS

C.1: OPI Test Results

Table C.1: Coefficient of oxygen permeability test results.

Designation	Age (days)	Average(1) (m/s(3))	Std. Dev.	Coeff. of Variation (%)	Deviation(2)	Range	
						Min. (m/s(3))	Max. (m/s(3))
PC-350-0.45	28	3.36	0.37	11.13	0.59	2.76	3.95
	56	2.48	0.39	15.69	0.62	1.86	3.09
PC-350-0.65	28	13.68	1.92	14.02	3.05	10.63	16.74
	56	7.86	0.81	10.36	1.30	6.57	9.16
PC-450-0.45	28	6.40	0.72	11.24	1.14	5.26	7.54
	56	4.04	0.77	19.16	1.23	2.81	5.28
PC-450-0.65	28	24.30	3.50	14.40	5.57	18.73	29.87
	56	9.07	1.42	15.64	2.26	6.81	11.33
FA-30-350-0.45	28	2.43	0.34	14.13	0.55	1.89	2.98
	56	2.41	0.35	14.37	0.55	1.86	2.96
FA-30-350-0.65	28	25.18	7.48	29.71	11.90	13.28	37.08
	56	20.90	3.76	18.01	5.99	14.91	26.88
FA-30-450-0.45	28	3.61	0.36	9.87	0.57	3.05	4.18
	56	3.33	0.39	11.70	0.62	2.71	3.95
FA-30-450-0.65	28	32.89	3.72	11.30	5.91	26.98	38.80
	56	22.54	1.68	7.45	2.67	19.87	25.22
GB-50-350-0.45	28	6.67	1.20	17.97	1.91	4.76	8.57
	56	6.21	0.30	4.86	0.48	5.73	6.69
GB-50-350-0.65	28	41.88	3.80	9.07	6.04	35.84	47.92
	56	30.19	1.46	4.83	2.32	27.87	32.51
GB-50-450-0.45	28	14.43	2.60	18.01	4.13	10.30	18.57
	56	12.70	1.86	14.62	2.95	9.75	15.66
GB-50-450-0.65	28	61.84	3.79	6.12	6.02	55.82	67.86
	56	43.13	1.83	4.24	2.91	40.22	46.04

Notes (refer to table superscript references):

1. Average of four readings.
2. t-value selected for a 95% confidence level, t-value = 3.182. Number of specimens tested, n = 4.
3. x 10^{-11} m/s.

Table C.2: OPI test results.

Designation	Age (days)	Average[1]	Std. Dev.	Coeff. of Variation (%)	Deviation[2]	Range	
						Min.	Max.
PC-350-0.45	28	10.48	0.05	0.45	0.07	10.40	10.55
	56	10.61	0.07	0.62	0.11	10.50	10.72
PC-350-0.65	28	9.87	0.06	0.60	0.09	9.77	9.96
	56	10.11	0.04	0.44	0.07	10.04	10.18
PC-450-0.45	28	10.20	0.05	0.47	0.08	10.12	10.27
	56	10.40	0.08	0.81	0.13	10.27	10.53
PC-450-0.65	28	9.62	0.06	0.66	0.10	9.52	9.72
	56	10.05	0.07	0.68	0.11	9.94	10.15
FA-30-350-0.45	28	10.62	0.06	0.55	0.09	10.52	10.71
	56	10.62	0.06	0.57	0.10	10.53	10.72
FA-30-350-0.65	28	9.62	0.15	1.54	0.24	9.38	9.85
	56	9.69	0.08	0.82	0.13	9.56	9.81
FA-30-450-0.45	28	10.44	0.04	0.41	0.07	10.38	10.51
	56	10.48	0.05	0.52	0.09	10.39	10.57
FA-30-450-0.65	28	9.48	0.05	0.50	0.08	9.41	9.56
	56	9.65	0.03	0.34	0.05	9.60	9.70
GB-50-350-0.45	28	10.18	0.08	0.79	0.13	10.05	10.31
	56	10.21	0.02	0.21	0.03	10.17	10.24
GB-50-350-0.65	28	9.38	0.04	0.42	0.06	9.32	9.44
	56	9.52	0.02	0.22	0.03	9.49	9.55
GB-50-450-0.45	28	9.85	0.08	0.78	0.12	9.72	9.97
	56	9.90	0.06	0.64	0.10	9.80	10.00
GB-50-450-0.65	28	9.21	0.03	0.30	0.04	9.17	9.25
	56	9.37	0.02	0.20	0.03	9.34	9.40

Notes (refer to Table superscript references):

1. Average of four readings.
2. t-value selected for a 95% confidence level, t-value = 3.182. Number of specimens tested, n = 4.

C.2: WSI Test Results

Table C.3: WSI test results.

Designation	Age (Days)	Average(1) mm/√hr	Std. Dev.	Coeff. of Variation (%)	Deviation(2)	Range	
						Min. mm/√hr	Max. mm/√hr
PC-350-0.45	28	7.45	0.52	6.92	0.82	6.63	8.27
	56	6.05	0.42	6.92	0.67	5.38	6.71
PC-350-0.65	28	12.13	0.51	4.24	0.82	11.31	12.95
	56	10.35	0.84	8.07	1.33	9.02	11.68
PC-450-0.45	28	10.15	0.95	9.35	1.51	8.64	11.66
	56	6.92	0.45	6.58	0.72	6.19	7.64
PC-450-0.65	28	13.65	0.87	6.37	1.38	12.27	15.04
	56	11.32	0.40	3.50	0.63	10.69	11.95
FA-30-350-0.45	28	6.14	0.42	6.90	0.67	5.47	6.82
	56	5.07	0.33	6.56	0.53	4.54	5.60
FA-30-350-0.65	28	11.00	0.82	7.48	1.31	9.69	12.31
	56	9.03	0.57	6.26	0.90	8.13	9.93
FA-30-450-0.45	28	8.79	0.68	7.78	1.09	7.70	9.88
	56	6.81	0.57	8.39	0.91	5.90	7.72
FA-30-450-0.65	28	12.04	0.63	5.23	1.00	11.04	13.04
	56	10.83	0.38	3.54	0.61	10.22	11.44
GB-50-350-0.45	28	8.16	0.23	2.80	0.36	7.80	8.52
	56	6.12	0.24	3.99	0.39	5.73	6.51
GB-50-350-0.65	28	12.81	0.86	6.72	1.37	11.44	14.19
	56	10.66	0.09	0.81	0.14	10.52	10.80
GB-50-450-0.45	28	12.43	0.06	0.45	0.09	12.34	12.52
	56	7.54	0.33	4.44	0.53	7.01	8.08
GB-50-450-0.65	28	15.92	0.19	1.19	0.30	15.62	16.22
	56	12.68	0.73	5.77	1.16	11.52	13.85

Notes (refer to Table superscript references):

1. Average of four readings.
2. t-value selected for a 95% confidence level, t-value = 3.182. Number of specimens tested, n = 4.

C.3: CCI Test Results

Table C.4: CCI test results.

Designation	Age (Days)	Average[1] mS/cm	Std. Dev.	Coeff. of Variation (%)	Deviation[2]	Range	
						Min. mS/cm	Max. mS/cm
PC-350-0.45	28	1.26	0.10	7.76	0.16	1.10	1.42
	56	1.08	0.07	6.88	0.12	0.96	1.20
PC-350-0.65	28	4.23	0.20	4.75	0.32	3.91	4.55
	56	3.28	0.12	3.80	0.20	3.08	3.48
PC-450-0.45	28	1.70	0.18	10.71	0.29	1.41	1.99
	56	1.47	0.12	8.11	0.19	1.28	1.66
PC-450-0.65	28	4.63	0.47	10.17	0.75	3.88	5.37
	56	3.64	0.24	6.70	0.39	3.25	4.02
FA-30-350-0.45	28	1.27	0.06	4.45	0.09	1.18	1.36
	56	0.82	0.04	4.98	0.06	0.76	0.89
FA-30-350-0.65	28	3.62	0.16	4.41	0.25	3.36	3.87
	56	2.32	0.03	1.29	0.05	2.28	2.37
FA-30-450-0.45	28	1.53	0.11	7.31	0.18	1.35	1.71
	56	1.30	0.09	7.29	0.15	1.15	1.45
FA-30-450-0.65	28	3.96	0.44	11.10	0.70	3.26	4.66
	56	3.14	0.33	10.56	0.53	2.61	3.67
GB-50-350-0.45	28	0.46	0.03	6.30	0.05	0.41	0.50
	56	0.44	0.03	6.34	0.04	0.40	0.49
GB-50-350-0.65	28	1.14	0.01	0.54	0.01	1.13	1.15
	56	1.04	0.02	1.93	0.03	1.01	1.07
GB-50-450-0.45	28	0.69	0.04	5.84	0.06	0.62	0.75
	56	0.67	0.06	9.56	0.10	0.57	0.77
GB-50-450-0.65	28	1.46	0.13	9.11	0.21	1.25	1.67
	56	1.32	0.17	12.90	0.27	1.05	1.59

Notes (refer to Table superscript references):

1. Average of four readings.
2. t-value selected for a 95% confidence level, t-value = 3.182. Number of specimens tested, n = 4.