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THE INFLUENCE OF MIX DESIGN PARAMETERS AND COMPRESSIVE STRENGTH ON DURABILITY INDICES

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ABSTRACT

Current concrete specifications used in mix design are mainly of the prescriptive type, i.e. recipe-based specifications that prescribe limiting values for certain mix design parameters such as minimum binder content, maximum water/binder (w/b) ratio and minimum compressive strength class. This has numerous economical, technical and environmental disadvantages and is one of the driving factors behind the development and promotion of performance-based specifications. These have the potential to lead to alternative methods of mix design to improve concrete structural performance.

In South Africa, the use of the Durability Index Approach in performance-based specifications has grown increasingly. Durability can be thought of as a materials concept for a structure in a given environment for the duration of its design life. As such, it can only be accurately described by considering it as a function of numerous intrinsic and extrinsic interrelated factors. Despite this, a dominant assumption in the industry is that concrete durability is directly proportional to its binder content and compressive strength, largely due to the misinterpretation of prescriptive specifications in depicting factors like binder content as the governing parameter of durability. This results in uneconomical and often non-durable concretes due to implications of high cement contents, such as high costs (cement is the most expensive constituent of concrete), high shrinkage, thermal effects and alkali-silica reactions.

This thesis presents a study on the influence of parameters of mix design, such as w/b ratio, binder content, binder type and curing regime, as well as compressive strength, on the durability of concrete as expressed by the Durability Index Approach. The objective of the investigation was to identify the issues behind specifications of minimum binder contents, as well as identify relationships between mix design parameters, compressive strength and durability indices. This was done by obtaining findings which would serve as a basis to potentially bring about sensible and justifiable changes to specifications. This could in turn lead to more durability-oriented mix design strategies.

In order to verify whether prescriptive specifications such as minimum binder contents are justifiable, various studies in literature were reviewed on the subject. In the literature review, it was identified that certain relationships exist between aspects of concrete durability and various parameters, among which are binder content, w/b ratio and compressive strength. It was found that the nature of these relationships cannot be generalised as each relationship needs to take into consideration a variety of additional influencing factors. One example is that the influence of increasing binder content on durability indicators is often detrimental and can seldom be associated with beneficial effects. This is because there are other factors such as increasing paste volume that need to be considered.

While there is ample literature that emphasises the numerous issues surrounding the specification of limiting parameters such as minimum binder content, it was also deemed necessary to compile an industry research section. This section aimed at identifying whether the trends being followed in industry with regard to mix design are closely linked with limiting values of prescriptive parameters. Research identified that concrete production occurs with excessively high binder contents. In the case studies presented in Chapter 3, the binder contents specified by the consulting engineers for the respective exposure environments were found to be higher than the minimum recommended values found in BS EN 206. In both cases, this led to an over-design with regard to both durability indicators and compressive strength. This resulted in concrete mixes that were more uneconomical than they needed to be, as well as possibly more susceptible to technical problems (shrinkage, thermal effects and alkali-silica reactions). The fundamental misunderstanding identified in industry was that high binder contents are associated with higher strength and higher durability, despite the ample evidence to the contrary in literature. This misunderstanding often leads to the use of excessively high binder contents, resulting in the aforementioned problems.

The experimental work conducted suggested that while compressive strength and durability are interlinked for both curing regimes investigated, the relationship between mix design parameters and durability indices is not a simple one. Increases in w/b ratio generally resulted in a deteriorating performance with respect to durability index values for all binder types. Increasing the binder content for a constant w/b ratio caused an increase in the paste volume of all concretes and the general trend observed for increases in paste volume on durability indices was that of a reduction in durability. These reductions differed in extent for each durability index investigated, depending on other factors such as w/b ratio, binder type and curing regime. Generally however, it was found that increases in paste volume caused more significant reductions in durability when the w/b ratio was higher. At low w/b ratios, increases in paste volume still caused reduction in durability, but the effects were not as pronounced. Hence the current trends being adopted in industry of increasing binder content for enhancing durability cannot be justified.

The general conclusion that can be drawn is that durability cannot be effectively described by the use of one sole determining parameter such as w/b ratio or minimum binder content, as is being interpreted by numerous professionals in the local industry who adopt prescriptive specifications. Rather it has to be analysed by simultaneously considering other mix design parameters and the results that changes in binder content have on them, thereby affecting durability. The results of this study suggest that the use of prescriptive specifications for the purpose of mix design is flawed and should be revisited.

PLAGIARISM DECLARATION

I know the meaning of Plagiarism and declare that all the work in the document, save for that which is properly acknowledged, is my own.

NAME	DATE	SIGNATURE
		Signed by candidate

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I dedicate this thesis to my family, in particular to its most recent addition; my nephew Eugenio Primo Guercia.

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1. INTRODUCTION

With the development and adoption of the Eurocodes, previously separated norms and regulations were conformed to a set of unified standards for all the countries in the European Union. In concrete and structural-related applications, an Annex of the standards local to the United Kingdom (BS EN 206-1:2000) pertains to the specification, performance, production and conformity of concrete. Since these newly developed standards will be used under different geographical and climatic conditions, different levels of protection, environmental exposure and different, well-established regional traditions and experience must accompany their usage (BS EN 206-1:2000). Furthermore, the standards also take great care in specifying the following important aspects:

- The nature and quantity of constituent materials in concrete may not be detrimental to its durability or cause corrosion of the reinforcement.
- Constituent materials should be suitable for the intended use of the concrete.
- Where general suitability is established for a constituent material, it does not imply an inherent suitability for every situation and every concrete composition.

During the development of these standards, serious considerations were made for the detailing of a performance-related approach to the specification of durability, which subsequently initiated a reviewing process of current performance-based tests and design methods. After thorough review, the European Committee for Standardisation (CEN) concluded that performance-based methods are “not yet sufficiently developed to be included in the standards” (BS EN 206-1:2000). As a result, the standards for concrete specification are mainly of the prescriptive type, with a main focus on limiting values of concrete composition to resist environmental actions. According to different exposure classes, limiting values of parameters are specified such as permitted types and classes of constituent materials, maximum water/binder (w/b) ratio, minimum binder content, minimum concrete compressive strength class (optional) and minimum air-content of concrete (if relevant). These requirements are largely based on previous practice and experience where the general consensus among many engineers is that high binder contents are synonymous with stronger, more durable concretes, and thus better performing structures. This is not always the case as high binder contents may not only result in unnecessarily uneconomical and unsustainable mixes, but also in various durability concerns such as Alkali-Silica reactions and thermal deformations.

There are three main factors controlling the quality of the surface zone of the concrete and thus its deterioration rate, namely the constituent materials, construction quality and the aggressiveness of the exposure environment. Since it is impractical to control the latter, alternative strategies for durability design should ideally focus on constituent materials and construction practices (Alexander et al. 2008). South Africa is at the forefront of concrete technology research, one of the motivations for wanting to adopt the use of the Eurocode within its borders. The most recent advance made in this field has been the development of a local alternative to the prescriptive approach of concrete design specifications, more commonly known as the “South African Durability Index Approach” or DI Approach.

Durability Indices are quantifiable parameters that are sensitive to materials processing and environmental factors. They are used to characterise the durability of concrete by measuring transport-related properties of the cover layer of both in-situ and laboratory-made concrete. Since it is this layer which has a direct impact on durability by controlling the movement of aggressive agents from the environment into the concrete (Alexander et al. 2008), the dual aspects of material potential and construction quality are emphasised significantly. Various specifying authorities, such as the South African National Roads Agency Ltd (SANRAL), have adopted the use of performance-based specifications in the form of the DI Approach. However, this has at instances resulted in inappropriate mix designs with excessively high binder contents for fear by part of the contractors of failing the durability criteria, despite previously published findings highlighting that binder content is wrongly perceived by many to be the governing parameter controlling concrete strength and durability (Yurdakul. 2010). Based on this perception, minimum binder contents and values of w/b ratio are often specified in quantities that overcompensate for the target strength.

Previous studies have been conducted to determine the relevance and usefulness of specifying minimum binder contents as a requirement for concrete mix design. In one such study, Wasserman et al. (2009) investigated the effects brought about by changes in cement content on mechanical and durability properties of concrete. The results obtained in the study are summarised in this dissertation and they suggested that the effect of cement content is different for various properties of concretes. As such, it cannot be specified simply in terms of minimum requirements and specifications dealing with such criteria should be revisited. The fundamental misunderstanding identified in the specification of minimum binder contents is that concrete durability depends not only on a wide variety of factors and mix design parameters, binder content being one such parameter, but also on their interaction. The effects on each property when changing one mix design parameter will be different depending on which parameters are also changed indirectly and which others remain unchanged. There is thus a need for the establishment of a general and empirical relationship that seeks to define aspects of durability in terms of various concrete properties through the use of mix design parameters such as binder content, water content and water/binder ratio. This relationship will aim to provide the better understanding necessary to construct a sound basis for future trends in codes and specifications for concrete mix design. This may in turn lead to the development of a hybrid approach, where an integrated framework of performance-based specifications will be used in conjunction with those prescriptive specifications that are deemed sensible.

1.1 Problem Statement

The specifications that are mostly adhered to in concrete mix design are of the prescriptive type, focusing mainly on minimum binder contents and maximum w/b ratios. The use of these specifications, however, often occurs without understanding, resulting in the use of high quantities of binder. This can lead to various technical problems (high heat of hydration, shrinkage, cracking, alkali-silica reactions), as well as economical and environmental problems (higher costs, increased pollution due to higher cement production, unnecessarily high strengths). Hence the assumption that high binder contents and high strengths result in good durability not only undermines the importance of other influencing parameters such as exposure environment and construction practices, but also emphasises the misunderstanding of the link between durability and mix design parameters. What is needed in order to promote an understanding of concrete durability deeper than that conveyed by prescriptive specifications is a study that will investigate the influence of mix design parameters (such as binder content and w/b ratio) and compressive strength on concrete durability. This will establish a clear and well-defined relationship between durability, compressive strength and mix design parameters, which will in turn bring about justifiable and sensible changes to current trends in concrete specifications for mix design.

1.2 Research Objectives

The objectives of this research are to investigate the influence of compressive strength and various mix design parameters on durability. The experimental parameters in question are the following:

- Binder Content
- Water/Binder Ratio
- Binder Type
- Compressive Strength
- Curing

The investigation is aimed at determining whether the industry trends identified in Chapter 3 related to increasing binder content to enhance durability are justifiable. The research will serve as a basis to promote a deeper understanding of concrete durability, as well as a stepping stone towards a more thoroughly promoted and formalised use of the DI Approach. The research output will result in the identification of trends and relationships between the experimental variables and display them in an effective and diagrammatic way.

1.3 Scope and Limitations

The scope of the study focuses on durability as described quantitatively by the measurable parameters that constitute the DI Approach and that are commonly specified: oxygen permeability, water sorptivity and chloride conductivity. Furthermore, the experimental variables that are investigated in the study deal mainly with the intrinsic factors (constituent materials and proportions) that influence durability.

1.4 Plan of Development

The investigation begins with a Literature Review chapter that identifies previously published findings relevant in achieving the set out objectives. A chapter on Industry Research highlights the lack of justification in the adherence to limiting values of parameters such as binder content and w/b ratio by referring to South African case studies. A description of the experimental methodology consisting of mix design and testing procedures is followed by a discussion and analysis of the results obtained. Lastly, conclusions are drawn and recommendations are made based on the results.

2. LITERATURE REVIEW

In this chapter, the literature that was reviewed consisted of previously conducted research which investigated the influence of parameters present in prescriptive specifications (binder content, w/b ratio) and the resulting compressive strength on concrete durability. The aim of the chapter was to identify whether previously published findings coincided with the general assumption imparted by limiting parameters found in prescriptive specifications, namely that high binder content and high compressive strength are associated with high durability.

The chapter starts by introducing the reader to concrete specifications, what they entail and some concerns with present prescriptive approaches in mix design. Benefits of alternative performance-based approaches of design are then identified, giving a South African example of such a method. The chapter then goes on to describe various aspects of concrete microstructure in order to link the understanding of microstructure to the successful use of performance-based design methods. The concept of penetrability of the microstructure is then introduced and a link is identified between penetrability and the selection of mix design parameters, affecting the development of strength and durability properties of concrete. Hence the literature review discusses the influence of mix design parameters such as binder content, w/b ratio and binder type combination on compressive strength and durability. The chapter then concludes by aiming to identify a relationship between compressive strength and durability properties.

2.1 Introduction to Concrete Specifications

With the recent conformity of standards from various European countries into one unique set of guidelines (Eurocode 2), various benefits are anticipated (Wieland. 2009):

- Europe - wide consistent design criteria.
- Coordination of different national codes in the form of National Annexes.
- Consistent base for research and development.

Eurocode 2 deals with the structural design and use of concrete, specifies prescriptive criteria for durability of concrete structures. It imposes requirements on constituent materials, construction practice and structural details on the basis of exposure environment, expected service life and intended service life condition of the structure. To ensure adequate durability, Eurocode 2 stipulates that the following interrelated factors should be considered:

- **Environmental exposure** – Chemical attack (acids, chlorides, ASR etc.), as well as physical attack (temperature changes, abrasion, water penetration etc.).
- **Strength class** – The choice of sufficiently durable concrete for protection of reinforcement against corrosion and protection of concrete against attack requires careful consideration of concrete composition. A denser microstructure can potentially result in a higher strength and a higher resistance to deterioration.
- **Concrete cover** – Minimum cover to reinforcement needs to be provided in order to ensure safe transmission of bond forces, corrosion protection of steel and adequate fire resistance.

Numerous clauses in Eurocode 2 refer to BS EN 206, which deals more specifically with specification, performance, production and conformity of concrete. In BS EN 206, durability is dealt with in such a way that the nature and quantity of constituent materials in concrete may not be detrimental to it or cause corrosion of the reinforcement. Also, constituent materials should be suitable for the intended use of the concrete and where general suitability is established for a constituent material, it does not imply an inherent suitability for every situation and every concrete composition. Such guidelines aim at standardising the processes of design of structural concrete so as to try and reproduce concrete of similar quality in multiple occasions when required.

2.1.1 Reasoning behind the Specification of Concrete

The fundamental philosophy behind the specification of concrete is that if it is known exactly what concrete is required for a specific purpose and exactly how to make it, the tendency is to be able to reproduce it as many times as required (Day, 2006). A prescriptive specification would thus be written in such a way so as to result in the concrete always being produced in precisely that way. There is however an inherent variability involved in the production of concrete, whereby two mixes generated with the same proportions of ingredients and in the same controlled conditions may display different mechanical and durability characteristics. Nevertheless, with accumulation of sufficient field data through the generation of numerous trial mixes involving various projects, specification becomes an obvious step to follow. A conventional way in which specification is carried out for strength-specific targets is through what are commonly known as “Standard Mixes”. Most standard mixes used in South Africa are based on proportioning of mass and volume of constituent materials for a specific target strength, with water being added until workability is judged to be satisfactory by eye (Addis. 2008). An example of trial mixes is given in the following table:

Table 1: Typical proportions and ingredients for trial mixtures based on target strength (Trial concrete mixes: proportions and quantities for ordering, C&CI, 2010)

Concrete Strength at 28 days (MPa)	Mass or Volume	9,5 mm or 13,2 mm stone			19,0 or 26,5 mm stone		
		Cement	**Sand**	**Stone**	**Cement**	**Sand**	**Stone**
10	***Mass/ 50 kg bag***	50 kg	238 kg	128 kg	50 kg	230 kg	196 kg
	Volume/ 50 kg bag	50 kg	0,175 m^3	0,095 m^3	50 kg	0,170 m^3	0,145 m^3
	Mass/m^3	250 kg	1190 kg	640 kg	225 kg	1030 kg	890 kg
	Volume/m^3	5,0 bag	0,88 m^3	0,47 m^3	4,5 bag	0,76 m^3	0,66 m^3
15	***Mass/ 50 kg bag***	50 kg	175 kg	106 kg	50 kg	170 kg	164 kg
	Volume/ 50 kg bag	50 kg	0,130 m^3	0,080 m^3	50 kg	0,125 m^3	0,120 m^3
	Mass/m^3	315 kg	1100 kg	670 kg	280 kg	950 kg	920 kg
	Volume/m^3	6,3 bag	0,82 m^3	0,50 m^3	5,6 bag	0,70 m^3	0,68 m^3
20	***Mass/ 50 kg bag***	50 kg	138 kg	92 kg	50 kg	130 kg	138 kg
	Volume/ 50 kg bag	50 kg	0,100 m^3	0,070 m^3	50 kg	0,095 m^3	0,100 m^3
	Mass/m^3	375 kg	1030 kg	690 kg	340 kg	880 kg	940 kg
	Volume/m^3	7,5 bag	0,76 m^3	0,51 m^3	6,8 bag	0,65 m^3	0,700 m^3

Table 1 displays mix design proportioning usually found on cement bags and commonly used for on-site batching. “Recipes” such as the one depicted in Table 1 specify aggregate and cement quantities for different target strengths. One common aspect of such proportioning methods such as the one depicted in Table 1, however, is that they do not account for the differences between different types of extenders and aggregates. Such methods simply give an outline of the constituent proportions based on aggregate size and specific mass or volume of cement for a target strength. Concrete Suppliers such as readymix companies have the choice of either adhering to such guidelines developed over time by institutions such as the Cement and Concrete Institute or use their own in-house mix designs developed over time through extended gathering of data, mainly involving specification of constituents based on achieving target strengths. Some problems with this were highlighted by Ballim (1993):

- It is often difficult to ensure that the prescribed procedure is being adhered to in practice.
- Even with rigid control procedures, the designer is unable to establish if the desired properties have been achieved without implementing specific testing procedures.
- Due to the uncertainty associated with prescriptive approaches, there is a tendency towards over-specification, leading to the result that concretes that are exposed to innocuous environments are often required to be treated in the same way as concretes exposed to aggressive environments.

Another problem that can be identified is that because the mix design process revolves around catering for a target strength, durability considerations are not an integral part of the process but are often seen as a secondary outcome. It is clear to see that nowadays, compressive strength cannot be considered on its own in the mix design process. Depending on the project at hand, durability requirements may take preference as governing mix design parameters, and with increasing demands for durable, economical and sustainable concrete mixes, prescriptive design specifications do not suffice. In BS EN 206, reference is made to performance-based related design methods. These methods consider in a quantitative way each relevant deterioration mechanism, the working life of the element/structure and the criteria that define the end of its working life. A comparison of prescriptive and performance-based specifications is given in the following sub-section.

2.1.2 Prescriptive Specifications vs Performance-Based Specifications

Prescriptive specifications involve the selection of material through consideration of factors like the structure's environmental exposure class and service life span. They are "recipe-based specifications", where different limits are set on specific parameters i.e. minimum binder contents, maximum water/binder (w/b) ratio and minimum compressive strength to achieve desired durability for different exposure classes (Ballim et al, 2009). Table 2 is extracted from BS EN 206 and represents some of the latest specification criteria proposed for new European National Standards, which to a large extent summarises the data present in the British Standards. In Table 2, mix design parameters are specified according to the three main parameters (maximum w/b ratio, minimum cement content and minimum strength class) as a function of different exposure classes. There is little evidence in literature which deals with the reasoning behind limiting parameters and its link to enhanced durability. Work carried out by Wasserman et al. (2009), however, identified three main arguments behind the presence of one such parameter, namely minimum cement requirements, which may link in terms of ensuring durability to the other limiting parameters present in the code:

- **Assurance of maximum w/b ratio** – a traditional approach resulting from old practices when admixtures were not used like they are today and the only means of controlling water/binder ratio while maintaining workability was by altering the binder (cement) content.
- **Minimum fines content** – a minimum content of particles finer than 0.075 mm to ensure workability and the development of proper bond between the concrete and reinforcing steel

- **Steel Protection** – enough cement is provided to bind CO_2 and chlorides that penetrate into the concrete

Table 2: Extract from British Standards Tables – BS EN 206 Part 1 (Annex F to be used in conjunction with Eurocode 2, 2006)

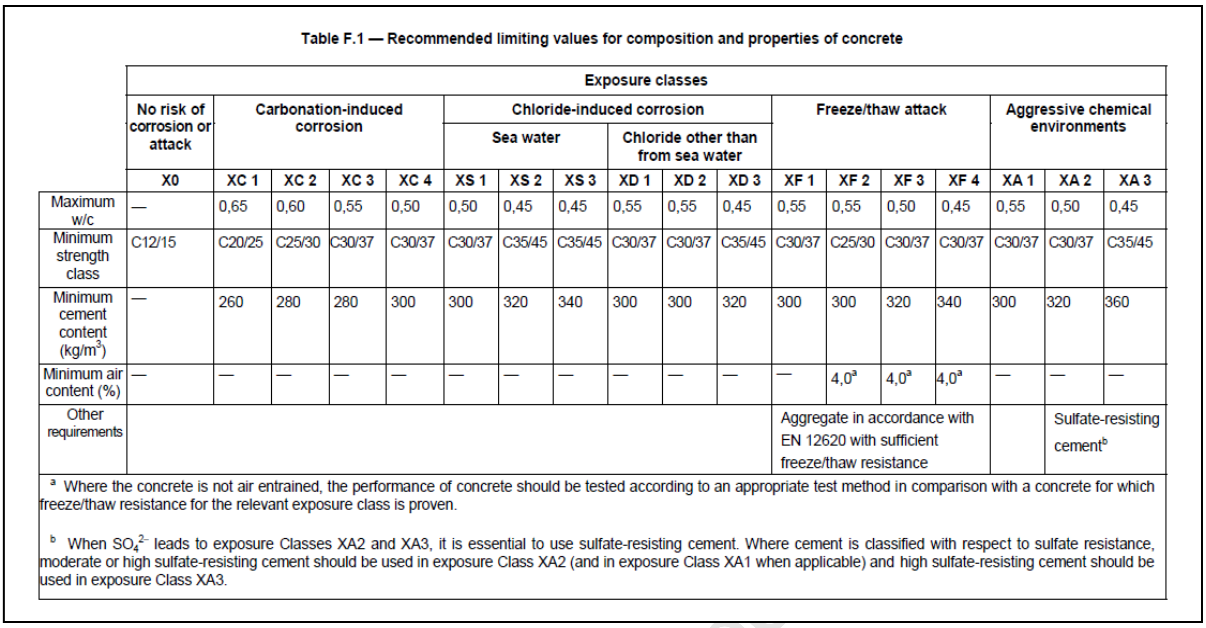


Table F.1 — Recommended limiting values for composition and properties of concrete

	Exposure classes																	
	No risk of corrosion or attack	Carbonation-induced corrosion				Chloride-induced corrosion						Freeze/thaw attack				Aggressive chemical environments		
						Sea water			Chloride other than from sea water									
	X0	XC 1	XC 2	XC 3	XC 4	XS 1	XS 2	XS 3	XD 1	XD 2	XD 3	XF 1	XF 2	XF 3	XF 4	XA 1	XA 2	XA 3
Maximum w/c	—	0,65	0,60	0,55	0,50	0,50	0,45	0,45	0,55	0,55	0,45	0,55	0,55	0,50	0,45	0,55	0,50	0,45
Minimum strength class	C12/15	C20/25	C25/30	C30/37	C30/37	C30/37	C35/45	C35/45	C30/37	C30/37	C35/45	C30/37	C25/30	C30/37	C30/37	C30/37	C30/37	C35/45
Minimum cement content (kg/m^3)	—	260	280	280	300	300	320	340	300	300	320	300	300	320	340	300	320	360
Minimum air content (%)	—	—	—	—	—	—	—	—	—	—	—	—	4,0[a]	4,0[a]	4,0[a]	—	—	—
Other requirements												Aggregate in accordance with EN 12620 with sufficient freeze/thaw resistance					Sulfate-resisting cement[b]	

[a] Where the concrete is not air entrained, the performance of concrete should be tested according to an appropriate test method in comparison with a concrete for which freeze/thaw resistance for the relevant exposure class is proven.

[b] When SO_4^{2-} leads to exposure Classes XA2 and XA3, it is essential to use sulfate-resisting cement. Where cement is classified with respect to sulfate resistance, moderate or high sulfate-resisting cement should be used in exposure Class XA2 (and in exposure Class XA1 when applicable) and high sulfate-resisting cement should be used in exposure Class XA3.

These arguments are based on previous practice and experience. They may have been relevant in earlier concretes when there was no availability of chemical admixtures to enable low w/b ratio concretes with adequate workability, or when the need for fines could not be met by the use of fillers currently available in industry (Wasserman et al, 2009), and when alternative materials such as extenders that provide additional binding potential were not common. Despite modern advances in admixtures and cementitious materials technology, current specifications are predominantly of the prescriptive type i.e. they have not kept up with development. Furthermore, strict adherence to these specifications is aided by the general opinion among professional engineers that high cement contents are a guarantee for higher durability. Such specifications do not prove to be favourable. Minimum binder contents provide a lower limit for the design of 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 needed (Wasserman et al, 2009). Various problems can arise from this (Wasserman et al, 2009 & Fowler et al, 2010):

- **Economical considerations** - cement is the most expensive constituent of concrete mixtures. Higher cement content results in higher cost.
- **Technical considerations** – higher cement content may result in higher strengths, depending on the w/b ratio, but it may also result in a higher paste volume, thus making the mixture more susceptible to cracking caused by shrinkage, thermal effects, Alkali-Silica Reactions (ASR) and other durability concerns.
- **Environmental considerations** – production of cement involves high levels of Carbon Dioxide gas (CO_2) emissions and consumed energy. As such, there is a need to reduce the cement content in concrete.

The problems mentioned above highlight the need for a shift away from prescriptive specifications and towards performance-based specifications. Performance-based specifications seek to ensure adequate performance by taking into consideration exposure conditions and measured material characteristics. Their guiding principle is the relationship between measured durability parameters and the environmental load on the structure, thus enabling the quantification of structural deterioration through the use of appropriate models (Ballim et al, 2009). The main objective of performance-based specifications is thus to enable the design and specification of concrete mixes based on factors such as local material availability, functional demand, type of application and exposure environment. This would contribute to the concept of "tailor-made concrete" and would thus increase the safety of design and improve the economics and efficiency of mixes from project to project (Utsi. 2008). The use of prescriptive codes and standards nowadays is somewhat conservative due to the fact that they are based solely on strength requirements. Depending on the intended application, concrete composed from said codes and standards may result in unnecessarily expensive and inefficient solutions (Utsi, 2008). Despite such considerations, current specifications for concrete durability in both South Africa Standards and European Standards follow the prescriptive type. However the increasing argument among various engineers and researchers is that aspects like durability, which is a material performance concept for a structure in a given environment (Ballim et al. 2009), cannot be determined accurately through the simple prescription of mix parameters. Instead, a more holistic approach is needed where the relationships between mix design parameters and properties (functions of constituent materials and their proportions) and durability properties need to be thoroughly investigated and clearly understood. This would pave the way for the development of an efficient framework of performance-based mix design specifications in order to achieve sustainable, economical and durable concrete mixes. In South Africa, such a performance-based method is increasingly being implemented and is known as the Durability Index (DI) Approach.

2.1.3 The South African Durability Index Approach

The basis of the DI Approach is to enable the quantification of relevant parameters in order to yield a suitable description of concrete quality. This is obtained through the measurement of transport-related properties of the cover layer of both in-situ and laboratory-made concrete. The measurements characterise concrete quality through the use of durability indices, which are quantifiable parameters that are sensitive to material, processing and environmental factors, thus highlighting both material potential and construction quality (Alexander et al, 2008). Testing methods and procedures have been developed to determine quantifiable parameters that allow the quantitative description of concrete deterioration processes that are closely linked to transport mechanisms such as gaseous and ionic diffusion and water absorption. These testing methods and procedures, known as Durability Index Tests, have been shown to be sensitive to material, construction and environmental factors that influence durability, characterising concrete quality by a variety of factors that include material and mix proportions (Ballim et al, 2009). Durability Index Tests comprise three measurable parameters that are associated with transport mechanisms within the concrete; namely, oxygen permeability, chloride conductivity and water sorptivity (Ballim et al, 2009).

Since details of testing equipment and procedures are well covered in literature, a summary of the basic principles of each Durability Index Test is provided in the following sections.

Oxygen Permeability Index

The principle behind this testing procedure is to measure the decay of oxygen pressure through the concrete sample with time by means of a falling head permeameter (Mackechnie et al. 2001a:2). The oxygen permeability index is defined as the negative log of the coefficient of permeability, which itself depends on the concrete microstructure, material moisture condition and nature of permeating fluid. Figure 9 depicts a typical arrangement of a test set-up.

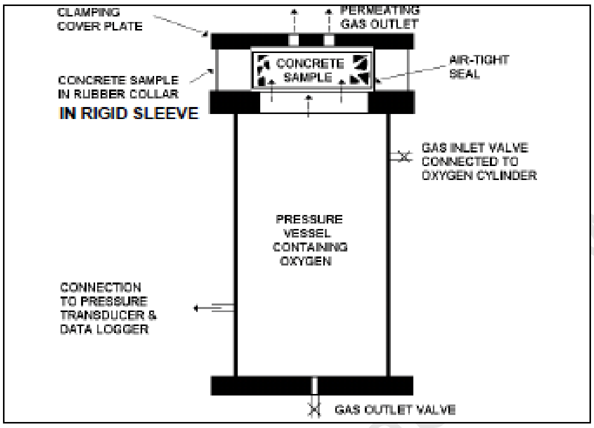


Figure 1: Permeability cell arrangement (Durability Index Testing Procedure Manual, 2010)

The nature of this testing procedure ensures that specimen moisture and permeating fluid are controlled parameters, leaving concrete microstructure as the parameter to be investigated during analysis of results (Mackechnie et al, 2001a). Figure 2 alongside displays some typical results for OPI values of South African concretes. A higher value is indicative of a concrete of potentially higher quality. The most significant aspect of this test is that it serves as an assessment tool for the overall micro and macrostructure of the outer surface of cast concrete, being very sensitive to “short circuits” for permeating gases (voids and cracks) (Ballim et al, 2009).

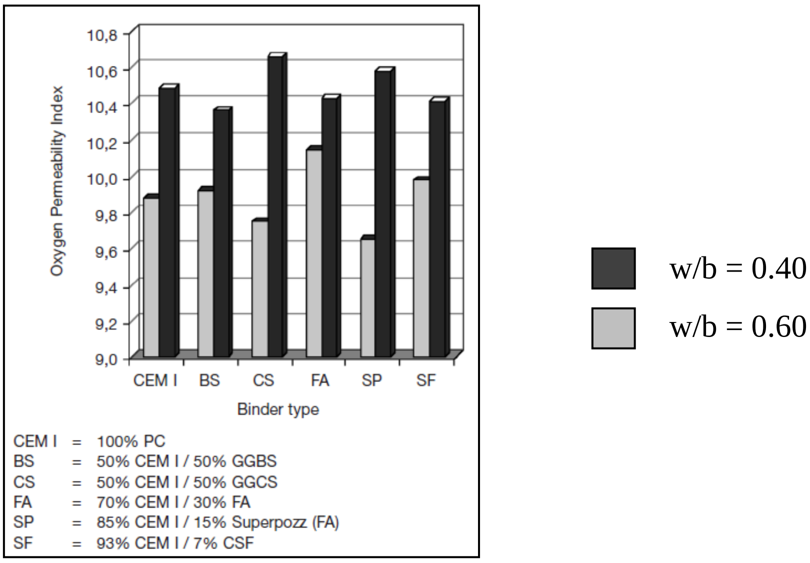


Figure 2: Typical OPI results for South African concretes, measured on water-cured samples at 28 days (Ballim et al, 2009)

Water Sorptivity

In this test, the absorption rate and porosity of the concrete sample are determined by immersing the concrete samples in water at regular time intervals and then placing the samples in a vacuum allowing them to saturate for 18 ± 1 hour. This testing procedure was developed not only to allow the measurement of a specimen's porosity, but also to enable the quantification of the rate of absorption so as to differentiate between bulk effects and surface effects (Ballim et al, 2009), something testing methods prior to the water sorptivity test failed to achieve. Differing from the OPI test, lower sorptivity values indicate a higher quality of concrete cover. The test has been found to be sensitive to the nature and extent of early curing of the cover concrete, making it very useful for construction quality assessment (Ballim et al, 2009). Figure 3 shows typical results for South African concretes.

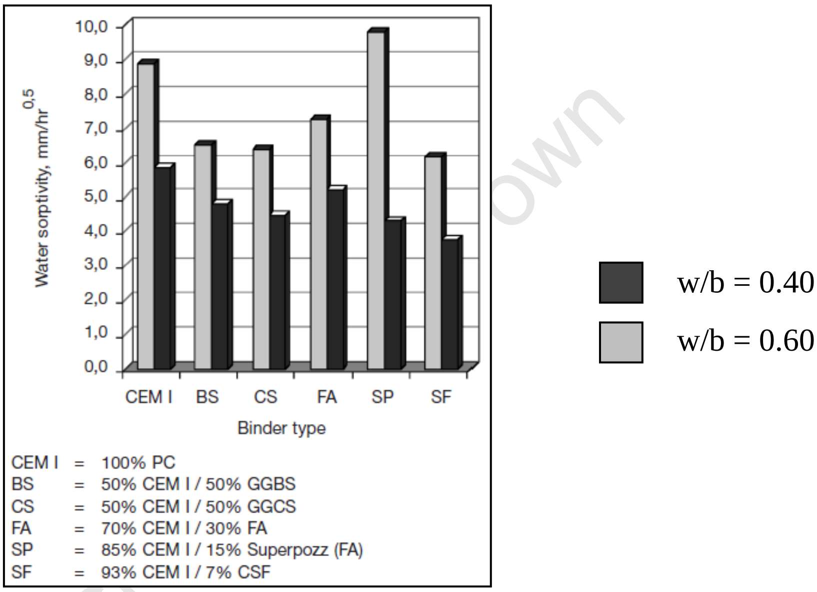


Figure 3: Typical water sorptivity results for South African concretes, measured on water-cured samples at 28 days (Ballim et al, 2009)

Chloride Conductivity

Diffusion is a transport mechanism that becomes of crucial importance, especially in marine concrete, and its rate is dependent on a variety of factors such as temperature, saturation level, type of diffusing substance and inherent material diffusion capacity (Mackechnie et al. 2001a). Various accelerated tests such as the Chloride Conductivity Test have been developed to measure diffusion rates due to the time-consuming nature of similar procedures used previously. In this testing procedure, concrete samples are placed in a two-cell conduction rig containing a sodium chloride solution and a potential difference of 10 V is applied.

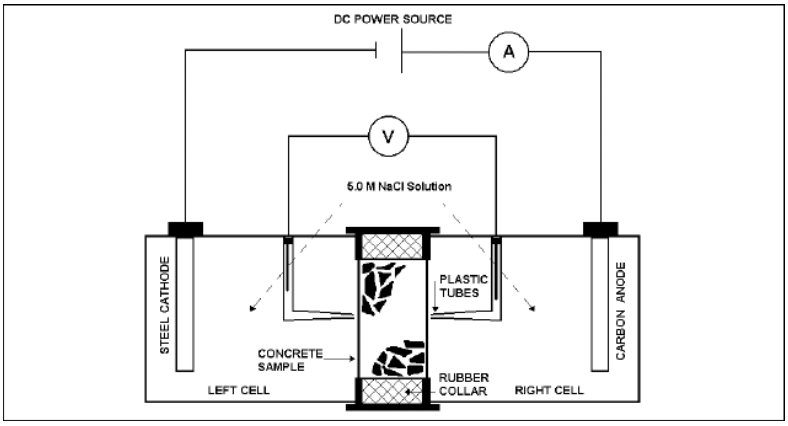


Figure 4: Chloride conductivity test apparatus (Durability Index Testing Procedure Manual, 2010)

This test set-up allows for an accurate and rapid assessment method as laboratory conditions are controlled and results are obtained instantaneously. Each test method is associated with a specific transport mechanism, thus the suitability of each test type for assessment of concrete properties will depend on which property is being considered (Ballim et al, 2009). Figure 5 again shows typical results for South African concretes, where a higher concrete quality is indicated by higher values of conductivity. Darker colour represents w/b ratio of 0.4 while the lighter colour depicts results for concretes with w/b ratio of 0.6 (Ballim et al, 2009).

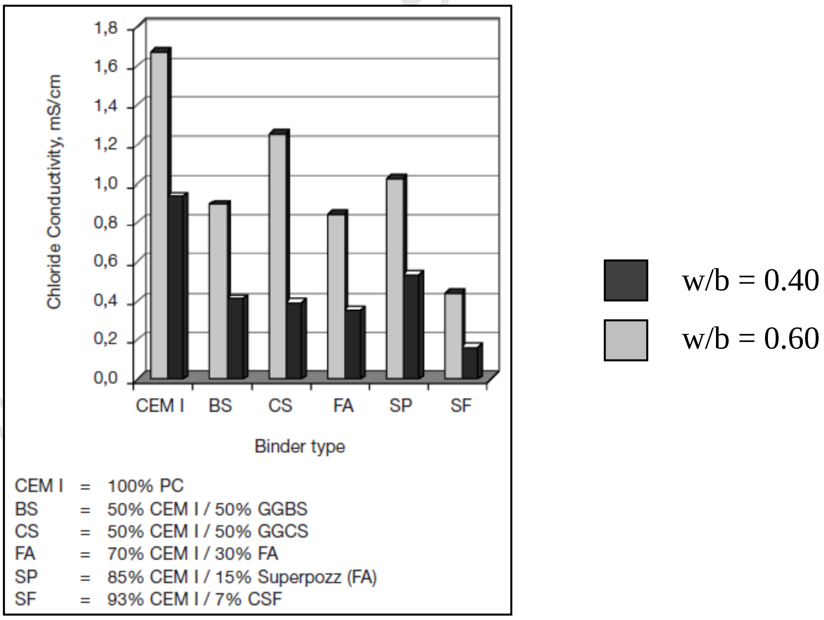


Figure 5: Typical chloride conductivity results for South African concretes, measured on water-cured samples at 28 days (Ballim et al, 2009)

2.1.4 Link between DI Approach and Concrete Microstructure

The relatively common application of Durability Index tests as site quality control tools in South Africa due to their sensitivity to construction and material factors is now also finding a niche in the optimisation of material processes, such as mix design. Thanks to the use of the DI Approach in South Africa, rational durability design and performance-based specifications are being developed and, at instances, applied in actual construction (Alexander et al, 2008). Specifying authorities such as SANRAL make use of Durability Indices for both the assessment of existing structures, as well as the design of new ones.

Despite the increased use of the DI Approach, durability remains a primary concern, with as-built concrete quality being inadequate in many cases (Alexander et al, 2008). This is due to the continuing dominance of prescriptive specifications, with many engineers still making use of them as more than just a guideline. Current specifications for concrete durability in both South African Standards and European Standards follow the prescriptive type, but the increasing argument among various engineers and researchers is that aspects like mix durability, which is a material performance concept for a structure in a given environment (Ballim et al, 2009), cannot be determined accurately through the simple prescription of mix parameters. Instead, a more holistic approach is needed where the relationships between mix design parameters, compressive strength and durability properties need to be thoroughly investigated and clearly understood. In order to develop useful and meaningful tools for mix design using Durability Indices, it is crucial to be aware of numerous parameters and their effects on mechanical and durability properties of the concrete. Durability Index test results are usually affected by aspects such as exposure conditions, site practices and material properties of the sample. Since it is possible to control exposure conditions in a testing environment, and since site practices are not a controllable parameter during mix design, it is evident that understanding of the microstructure of the concrete system becomes the key parameter behind the effective use of Durability Index Tests. Hence the following section of the Literature Review aims to give the reader an overview of various aspects of concrete microstructure and to, in later sections, relate these aspects to changes in mix design parameters and their resulting effect on compressive strength and durability.

2.2 Microstructure of the Concrete System

Concrete can be described as a composite material that consists of a binding medium within which are found embedded fragments or particles of aggregate. The binding medium is a mixture of water and, most commonly, cement, but increasingly more a combination of cement and supplementary cementitious materials (Mehta & Monteiro, 2006). Based on the above description, the microstructure of concrete can be divided into three main components:

- Cement Paste
- Interfacial Transition Zone
- Aggregates

In this section a summary of these phases is given, outlining each phase’s influence on compressive strength and durability properties of concrete through a description of their structure. This summary is then referred to from Section 2.3 onwards, where an outline of the influence of mix design parameters on compressive strength and durability is given.

2.2.1 Hardened Cement Paste

The hydration reactions between water and the calcium silicates and calcium aluminates present in Portland cement produce the binding medium known as cement paste. The paste itself can be regarded as a system of constituents forming a microstructural framework through which the transfer of loads takes place (Hover, 1998). The main constituents of hardened cement paste are the following (Addis, 2008. Grieve, 2009):

- **Calcium-Silicate-Hydrate (CSH) gel** - It is the main "glue" which binds the aggregate particles together and the main contributor of the strength of hardened cement paste. CSH gel grows outward from the surfaces of unhydrated cement particles to form a rigid structure of microscopic rods and platelets joined at points of contact.
- **Calcium Hydroxide (CH)** - Also known in cement chemistry as Lime or Portlandite, it occurs in the form of relatively large crystals that are embedded in the CSH gel, with some also found in solution in the pore water. While it does not contribute to strength, it is mainly responsible for raising the internal pH of concrete to prevent depassivation of the steel.
- **Ettringite (CASH)** - When mixing water leaches alkalis from the cement grains and aluminates pass into the solution, they react with the dissolved gypsum to form a precipitate known as Calcium Aluminosulphate or Ettringite. Although it is an expansive product, it also attaches itself to the aluminate preventing access of water to it and thus the too rapid setting of cement.

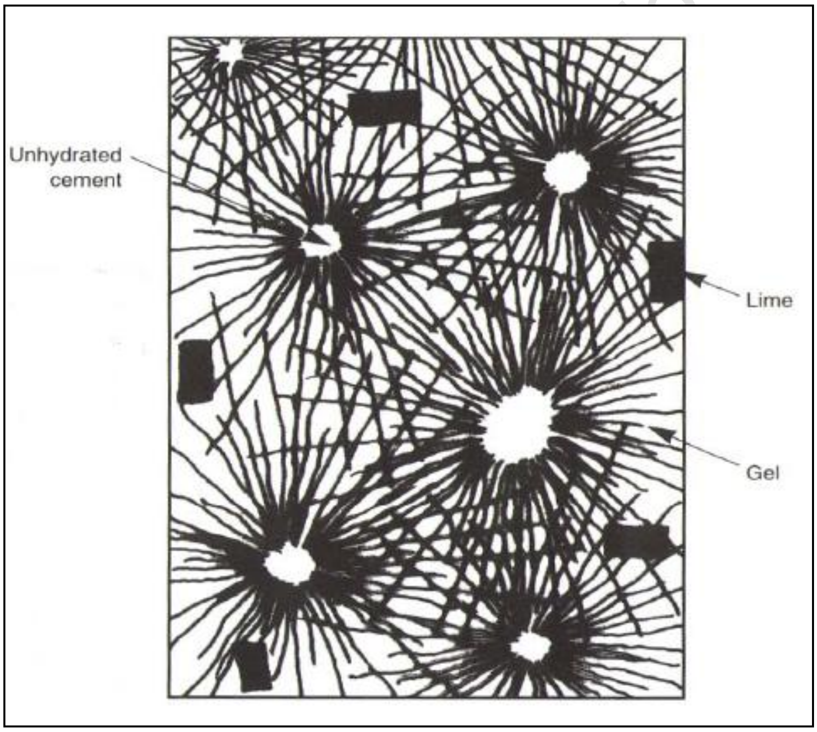


Figure 6: Structure of hardened cement paste (Addis, 2008)

The structure of the hardened cement paste is as depicted in Figure 6. It consists predominantly of a gel made up of platy particles colloidal in size (Grieve, 2009). Large Portlandite crystals are embedded in the gel, along with residues of unhydrated cement. Although the gel is characteristically two thirds solids and one third pores, regardless of its density and extent of hydration, its low permeability is attributed to the comparatively small size of the gel pores, which are about two orders of magnitude smaller than the capillary pores. These capillary pores form as the residue of spaces in the fresh paste that were previously filled with water (Grieve, 2009). The larger volume of capillary pores acts as an optimum medium for movement of deleterious gases, liquids and dissolved solids (Hover, 1998), and is the main reason for the highest porosity contribution of the concrete hailing from the paste. However, as hydration proceeds, further formation of the gel results in the blocking of these pores. From Figure 6, it is thus clear to see that both compressive strength and durability properties are dependent to a significant extent on the structure of the cement paste, which is dictated by the proximity of the cement particles. The closer the cement particles are together, the less porous the paste will be due to the framework of interconnecting platelets and rods formed by denser hydration products, resulting in more effective blocking of the pores (Hover, 1998).

2.2.2 Interfacial Transition Zone

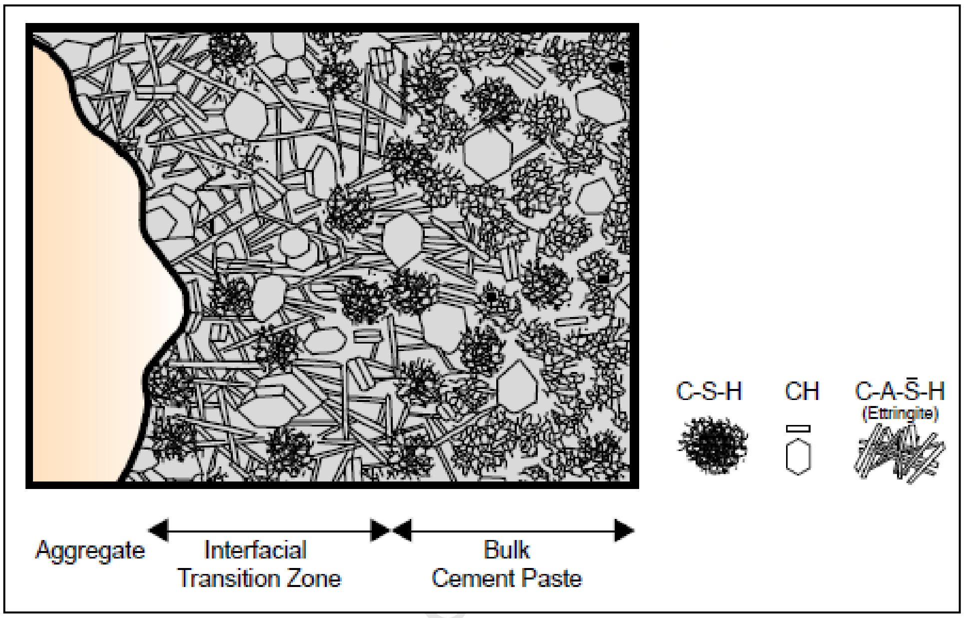


Figure 7: Interfacial Transition Zone (Mehta & Monteiro, 2006)

Figure 7 shows the zone in the concrete system known as the Interfacial Transition Zone, or ITZ, which represents a small region next to the particles of coarse aggregate. It is usually 10 µm to 50 µm thick and constitutes the lesser of the strength component of the concrete than either of the main components of the concrete system (Mehta & Monteiro, 2006). Development of the ITZ in concrete happens in the following manner (Mehta & Monteiro, 2006. Grieve, 2009):

- When the concrete is freshly compacted, a thin film of water forms around the larger aggregate particles.
- This results in a water/binder ratio comparatively higher around the aggregates than in the bulk cement paste, which ultimately results in the formation of larger crystals of Portlandite and Ettringite as well as a higher capillary porosity.

The outcome is a framework that is highly porous. This porosity of the ITZ is one of the main reasons why it is the weakest constituent in the concrete system. Both the cement paste and the aggregates behave linearly until failure, yet the behaviour of the concrete system is not a linear one leading up to failure:

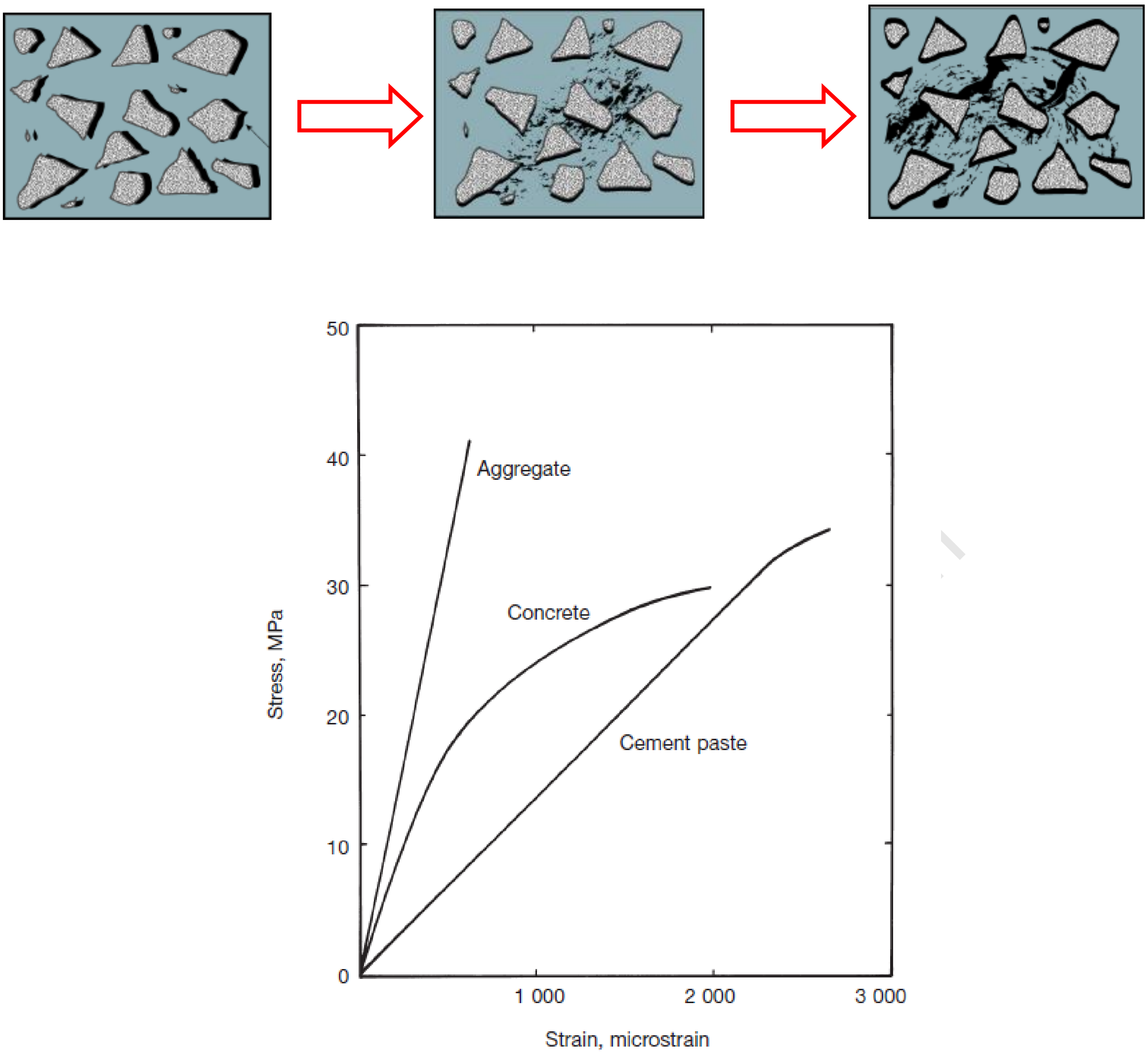


Figure 8: Influence of ITZ on non-linear behaviour of concrete leading up to failure (Mehta & Monteiro, 2006 & Grieve, 2009)

Figure 8 depicts the non-linear behaviour of concrete leading up to failure, which occurs firstly in the ITZ in the form of microcracks that subsequently spread throughout the hardened paste. Thus, despite its relatively small size, the ITZ significantly influences the compressive strength and durability properties of the concrete system due to the development and propagation of these microcracks (Mehta & Monteiro, 2006).

2.2.3 Aggregates

The role of aggregates in concrete was initially perceived to be one of provision of bulk, economy and dimensional stability to the mix (Alexander, 1998). The general opinion of many engineers and designers was that aggregates used in concrete were chemically inert and thus exercised little influence on properties of the mix. More recently their effects on concrete properties have become well known, such as the deleterious reactions with specific hydration products, as well as their beneficial interaction with cement paste to improve concrete strength and stiffness (Alexander, 1998). Considering the fact that aggregates make up approximately 70% of the volume of concrete, their properties have a significant effect on the properties of the concrete system (Addis, 2008). Compared to the average capillary porosity of hardened cement paste (30% - 40%), the volume of capillary pores present in aggregates is usually in the region of 3% and rarely exceeds 10%. Values of permeability coefficients for aggregates, however, display variability similar to those for cement pastes with water/binder ratio in the region of 0.38 to 0.71 (Mehta & Monteiro, 2006). The reason why aggregates may display a higher permeability than the cement paste is that capillary pores in the aggregates are much larger in size (most capillary pores in mature cement pastes are in the range of 10 to 100 nm, while aggregate pore sizes are on average larger than 10 µm) (Mehta et al, 2006). The porosity inherent in aggregates is another determining factor of durability properties and compressive strength of concrete.

2.2.4 Brief Summary

It is clear that all three constituent phases of concrete are associated with a certain degree of porosity inherent in their microstructure, which can play a significant role in the development of compressive strength and durability properties of the concrete system. A higher pore fraction results in more discontinuities within the cement matrix, thus leading to a larger area of susceptibility with regards to crack development and propagation, as well as ingress of deleterious substances (Hover, 1998). Harmful substances gain access to the concrete system through various transport mechanisms within it. The ease with which this ingress occurs depends largely on the penetrability of the concrete system.

2.2.5 The Role of Mix Design in determining Concrete Penetrability

Penetrability can be described as a function of pore structure and pore interconnectivity.

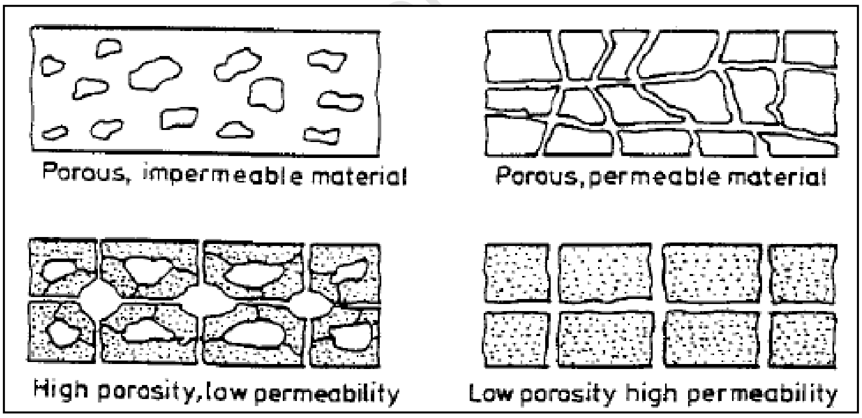


Figure 9: Concrete penetrability is a function of porosity and permeability (Hearn et al, 1994)

From Figure 9, it can be seen that it is possible to obtain various levels of penetrability through different degrees of porosity and permeability. These cause changes in the extent of the three main transport mechanisms highlighted in literature through which aggressive agents and harmful substances are transported into and within the concrete, namely permeation, absorption and diffusion (Ballim et al, 2009), discussed in more detail in Section 2.4. From the above observations, it is clear to see that the penetrability of the concrete system is largely dictated by the porosity of the constituent phases (particularly the cement paste and the ITZ) and thus it can largely determine the development of properties of the concrete system. As such it must be carefully considered during the mix design process. This can be achieved by ensuring a sufficiently dense concrete microstructure through the appropriate selection of mix design parameters such as w/b ratio, binder type combination, and binder content, as well as adequate site practices such as compaction and curing. Appropriate selection of such mix design parameters can ensure effective composition of the constituent phases, which can in-turn lead to satisfactory development of mechanical and durability properties in the concrete system. Mix design parameters can thus be used to quantitatively describe and assess changes in concrete microstructure. Any changes in concrete performance expressed in terms of compressive strength and durability indices can be related to the selection of different values of mix design parameters and result in a quantitative description aimed at assessing concrete quality. In the following sections, compressive strength and durability are introduced and the influence of mix design parameters on these properties is described in detail. This allows the reader to be familiarised with how changes in each different mix design parameter affect the concrete system as a whole, while also enabling the reader to determine whether present trends in mix design specifications are sensible and can be justified.

2.3 Compressive Strength of Concrete

The strength of a material is defined as the ability of the material to resist a specific level of stress without failure (Perrie, 2009). Strength in concrete is time-dependent, as its value gradually increases with time, and can be determined in various modes i.e. compressive, tensile and shear. Compressive strength is the most frequently specified property, being the most crucial parameter for the design of structural concrete. While there are other parameters that are often more critical to the assessment of concrete quality, strength is still commonly used for this purpose, especially in structural applications (Yurdakul. 2010). Concrete strength is affected by a variety of parameters, both intrinsic and extrinsic in nature. Figure 10 depicts a schematic representation of such influencing parameters:

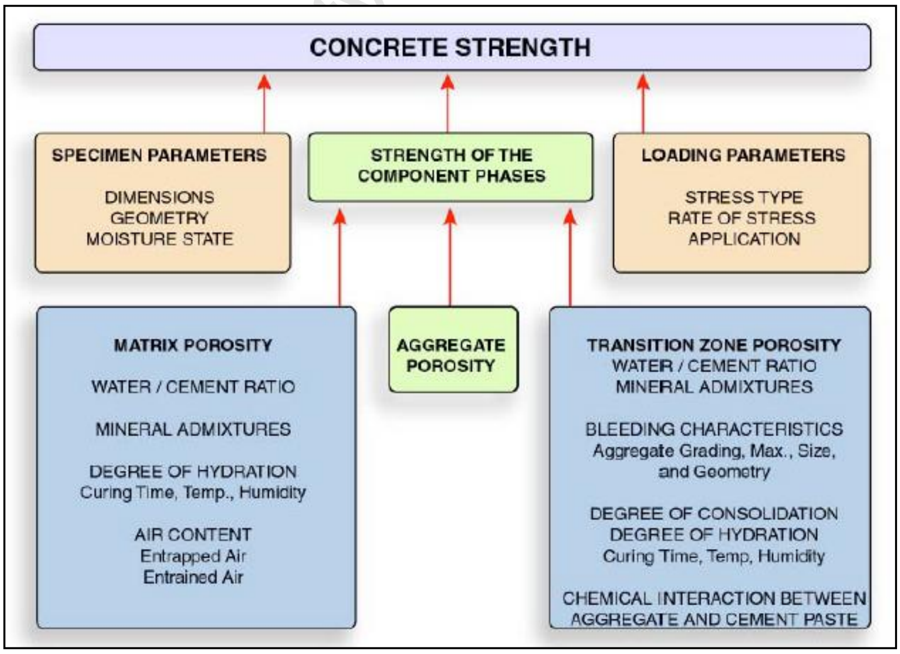


Figure 10: Factors affecting concrete strength (Mehta & Monteiro, 2006)

Concrete strength is determined by the strength of its weakest constituent phase. Due to its inherent brittle nature, tensile failure modes under an applied load are usually favoured. The strength of each constituent phase is largely determined by their porosity (noted in Section

2.2 and further emphasised in Figure 10), which is in turn a function of both constituent material types and proportions. This again highlights the significance of understanding the functioning of the concrete system through its constituent phases and materials. Concrete's inherent heterogeneity results in a non-uniform stress development upon loading, leading to higher stress concentrations in certain locations (Perrie, 2009). Strength thus depends on the influence that various factors have on each of the three component phases, namely the aggregates, the aggregate-paste interface and the hardened cement paste:

- **Aggregates** – the influence of aggregates on concrete strength increases with increasing concrete strength (Perrie, 2009). This is seen by the difference between normal strength concrete and high-performance concrete, where aggregate strength is a crucial consideration. Various parameters have an influence on strength and durability properties, such as aggregate size, mineralogy, porosity, grading, microfines content etc. (Fowler et al, 2010 & Koehler et al, 2007). While these factors are not analysed in-depth as they fall out of the scope of this investigation, they always need to be taken into consideration during mix design.

- **Aggregate-Paste Interface and Hardened Cement Paste** – Since the factors that influence both phases and their resulting effect on strength are closely linked, the two are mentioned simultaneously. The interface is generally the concrete's weakest area, while the hardened cement paste is the largest contributor to concrete strength (Perrie, 2009). Presence of unhydrated cement, pore size and distribution are factors that influence concrete strength and which are in turn influenced by the mix design process and the selection of appropriate mix design parameters.

2.3.1 Water/Binder Ratio

At any degree of completion of the hydration reaction between Portland cement and water, or the pozzolanic reaction between hydration products and cement extenders, the microstructure of the paste will depend largely on the w/b ratio of the mixture. W/b ratio is regarded as the determining factor of both strength and permeability of the cement paste and refers to the ratio of total water to total binder present (Grieve, 2009). The microstructure of the hydrated cement paste and its resulting mechanical properties depend largely on the proportions of the two constituents. Figure 11 depicts two cement pastes with two different water/binder ratios of 0.65 and 0.25. In the 0.25 paste, products of cement hydration will fill up the gaps between cement particles fairly rapidly, achieving a strong, dense microstructure. In such a case, the proportion of cement gel required to ensure a strong and impervious microstructure is not high. Hydration begins very rapidly and occurs via diffusion of water molecules inside unhydrated cement particles to form what is known as "inner product" (Malhotra, 1994).

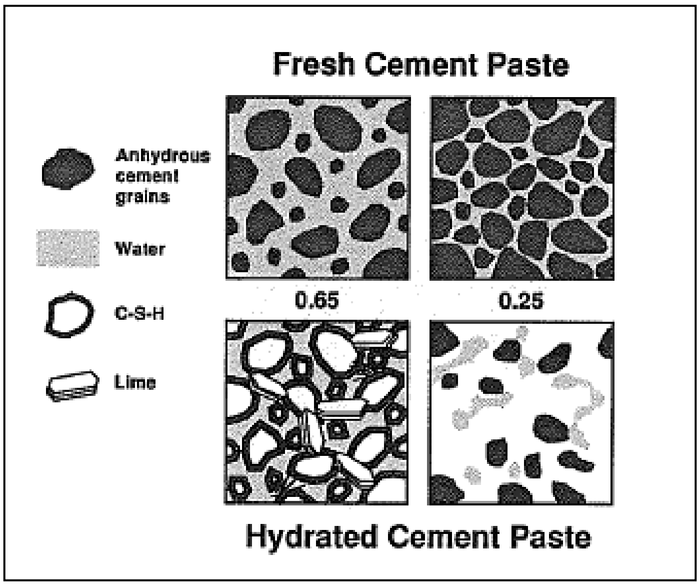


Figure 11: The effect of water/binder ratio on cement paste microstructure (Malhotra, 1994)

On the other hand, in the 0.65 paste, more cement gel will be needed before obtaining some strength as the hydration products need to be developed over a long distance to reach the hydration products formed by other cement particles (Malhotra, 1994). In this case, “outer product” forms through dissolution and precipitation which is not as strong as inner hydration product. Hence in concretes with low w/b ratios, concrete strength is significantly enhanced due to a high densification of the microstructure of the concrete system (Malhotra, 1994). This is not achieved by a lack of an interconnected network of capillaries, but rather due to the extreme fineness of these capillaries, even inhibiting the flow of water through them. These concepts can be explained more clearly by theoretical means with reference to the Powers Model, depicted in Figure 12.

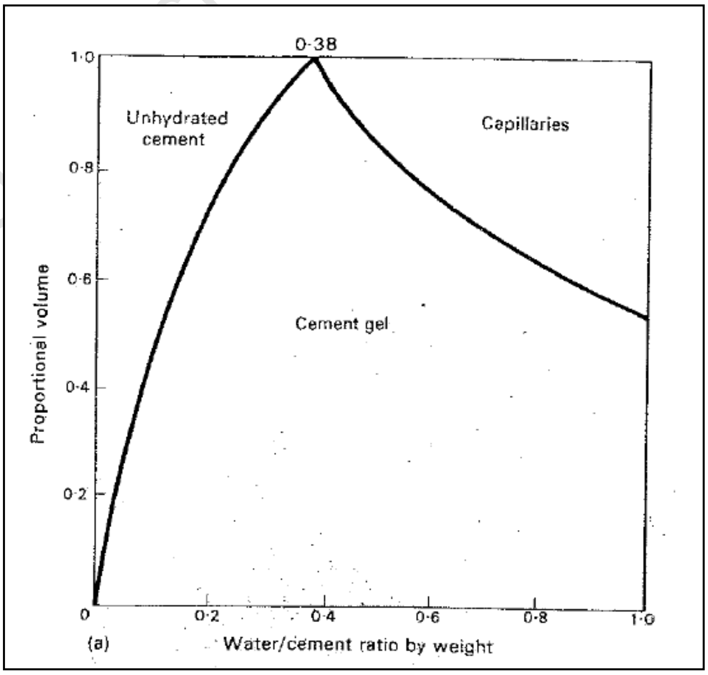


Figure 12: Powers Model: the effect of water/binder ratio on cement paste phases of samples in water (Hansen, 1970)

According to the model, if all the cement in the paste undergoes hydration, it will fill up all the available space in the matrix. Hence there will be no unhydrated cement and capillary porosity is zero (porosity is not actually zero, but the existing capillaries are extremely fine and poorly connected). This is the phase where at any stage of the hydration process the proportion of unhydrated cement is equal to the proportion of capillary porosity. As shown in Figure 12, this occurs at a water/binder ratio of around 0.38 (Grieve, 2009). When the w/b ratio is increased (moving right along the graph), the presence of capillary pores is more prominent as all the cement in the paste hydrates. The excess water present in the matrix later evaporates and leaves larger and well connected capillary pores. Inversely, when the w/b ratio is decreased (moving left along graph), further development of hydration is constrained by a lack of water. A lower w/b ratio will thus increase the solid volume proportion of the paste and in doing so will achieve reductions in pore space and proximity of cement grains (Hover, 1998), as shown in Figure 13. This will result in a denser microstructure and a potentially stronger concrete.

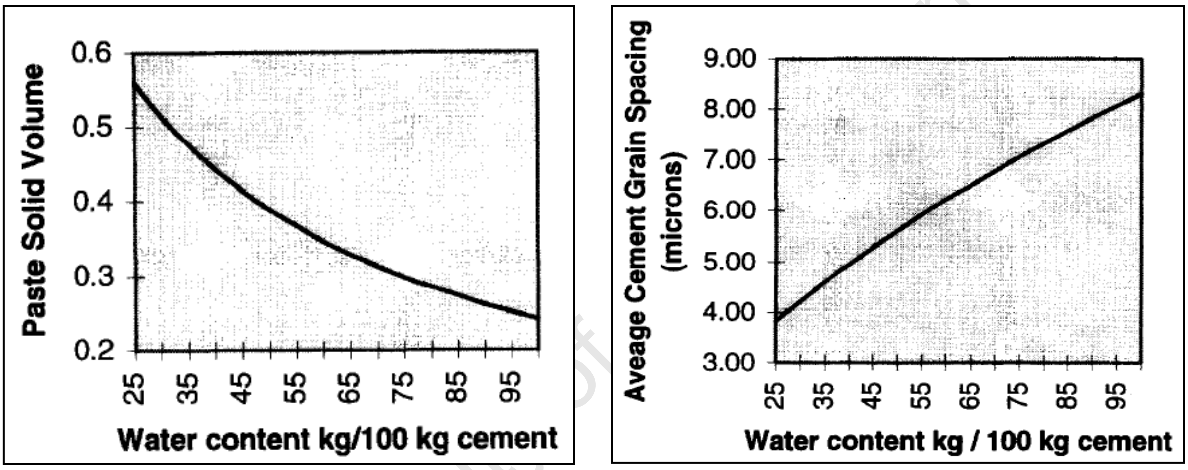


Figure 13: Effect of varying water/binder ratio on solid volume of hardened cement paste and cement particle spacing (Hover, 1998)

Concrete strength will be largely influenced by the porosity of the hardened cement paste, which is significantly affected by the degree to which hydration products have filled the spaces between and among cement grains. The larger the distance between cement grains, the more hydration products required to effectively fill the spaces (Hover, 2011) and the smaller the proportion of solid volume of the paste. W/b ratio is a key factor in mix design as it influences compressive strength to a significant extent through changes in concrete microstructure. The effect of w/b ratio on compressive strength is well documented and has been used over the years in the categorisation of different “types” of concretes classified according to strength. Figure 14 is a depiction of such a classification, displaying common values of w/b ratio for different concretes according to cylinder strength class (NC – normal concrete, HSC/HPC – high strength/performance concrete and UHPC – ultra high performance concrete).

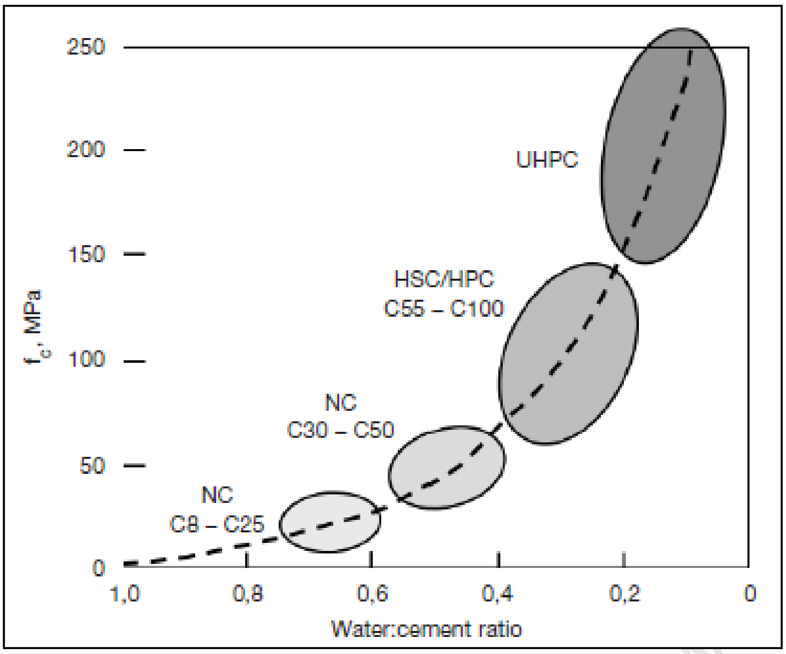


Figure 14: Classification of different concrete strengths with respect to water/binder ratio (Beushausen and Dehn, 2009)

Graphs such as the one portrayed in Figure 14 are commonly used in the initial phases of mix design methodologies, such as in the C&CI Method, where a w/b ratio is selected according to target strength. This reiterates the fact that although concrete performance is ideally defined by various requirements specific to a certain application, strength has become a primary definition criterion (Beushausen & Dehn, 2009).

2.3.2 Binder Content

Binder content is a key parameter to be considered during the mix design process since limiting values of it such as minimum binder contents are also present in prescriptive mix design specifications. However, it cannot be considered in isolation because, together with water content, it determines the water/binder ratio as well as the paste volume. The latter is increasingly being used as an alternative parameter, both quantitatively and descriptively, to better convey the changes in concrete properties such as compressive strength with regard to varying binder contents. In terms of the mix design process, any change in the binder content has a direct impact on the water/binder ratio:

- If the water content is kept constant, increasing the binder content will lead to a decrease in water/binder ratio, which will bring about an increase in strength.
- If the water content is changed in accordance with the binder content to maintain a constant water/binder ratio, what results is a change in the paste volume of the mix.

Previous studies have revealed somewhat contradictory results with regard to the effect of changes in paste volume on compressive strength. Research conducted by Wasserman et al. (2009) was conducted to investigate the issue of minimum cement requirements present in prescriptive specifications. The authors analysed mixtures with four different water/binder ratio values, each represented by three water contents (and thus three different cement contents).

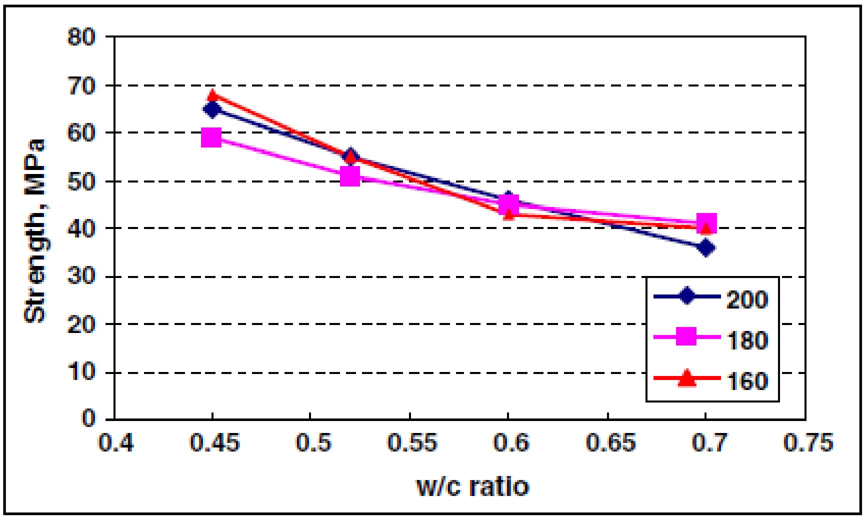


Figure 15: Effect of cement content (different water contents – 160, 180 and 200 kg/m^3) on 28-day compressive strength (Wasserman et al, 2009)

The conclusions drawn by the authors and based on the results displayed on Figure 15 are consistent with the current prevailing trend that strength is primarily a function of water/binder ratio, noting that strength seems to be independent of cement content with all three mixes achieving similar strength values. Different results, however, were obtained in another study.

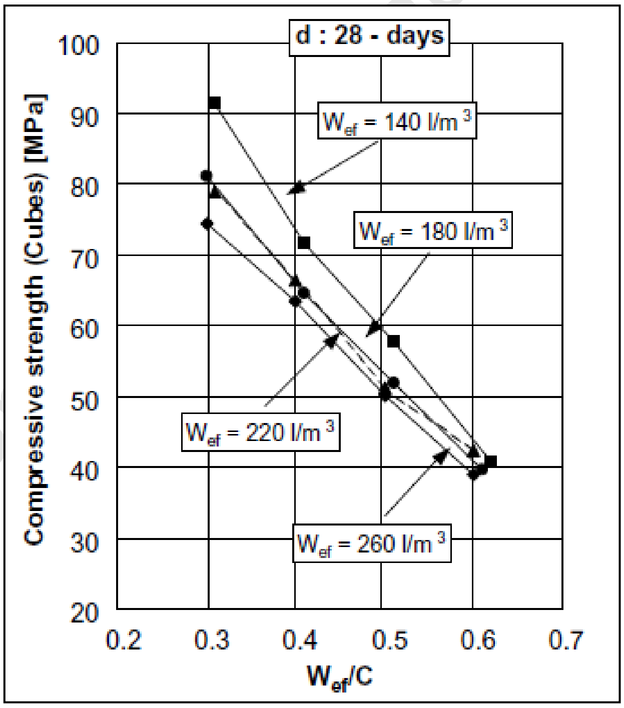


Figure 16: Effect of cement content on 28-day compressive strength (Kolias et al. 2005)

Kolias and other authors (2005) reported in their experiments that when the water content is in the range of conventional concrete mixes, negligible differences in strength can be observed for a fixed w/b ratio with a variation in water (and thus binder) content. This is visible in Figure 16, where an increase in water content from 180 l/m^3 to 220 l/m^3 did not result in a significantly large difference in compressive strength for the selected range of w/b ratios. The differences become quite pronounced, however, for low or high water contents (thus low or high binder contents) at very low w/b ratios. This is also displayed in Figure 16.

At a water/binder ratio of 0.3, the difference between mixes with water contents of 140 l/m^3 (binder content of approximately 420 kg/m^3) and 260 l/m^3 (binder content of approximately 780 kg/m^3) was around 20 MPa in favour of the lower binder content. This can be attributed to the fact that at low w/b ratios and low paste volumes, aggregate proportion is higher and cracks have to follow a longer path around more aggregates. This also makes the absorbed energy higher (Kolias et al. 2005). With a higher paste volume and smaller aggregate proportion for the same w/b ratio, the crack path becomes smaller and thus the absorbed energy is smaller (Kolias et al. 2005). Another possible reason why compressive strength is more susceptible to varying paste volume at low w/b ratios can be due to the refinement of the microstructure that occurs at low w/b ratios. Increases in paste volume are likely to affect compressive strength significantly due to the higher proportion of gel capillaries that disrupts the dense microstructure. At higher w/b ratios, there is a higher proportion of gel capillaries in the paste due to the excess water which later evaporates. Hence increases in paste volume will not have a prominent impact on compressive strength. This effect is further highlighted in Figure 17.

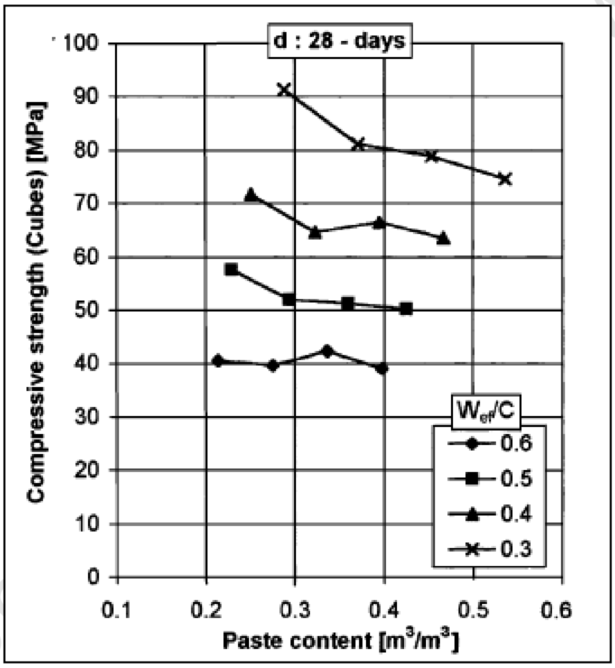


Figure 17: Relationship between compressive strength and paste content by volume (Kolias et al. 2005)

In Figure 17 one sees the influence of increasing paste volume on compressive strength, brought about by an increase in water and binder contents. When paste content is increased as the w/b ratio is kept constant, the negative effect is more pronounced for lower w/b ratios than higher w/b ratios. This observation is of crucial importance when it comes to mixes designed for high-strength applications, where the means of achieving low water/binder ratios need to be thoroughly analysed from many perspectives. Yiğiter et al. (2007) conducted another study that related compressive strength to binder content. Results obtained in the investigation were used to compile the Figure 18.

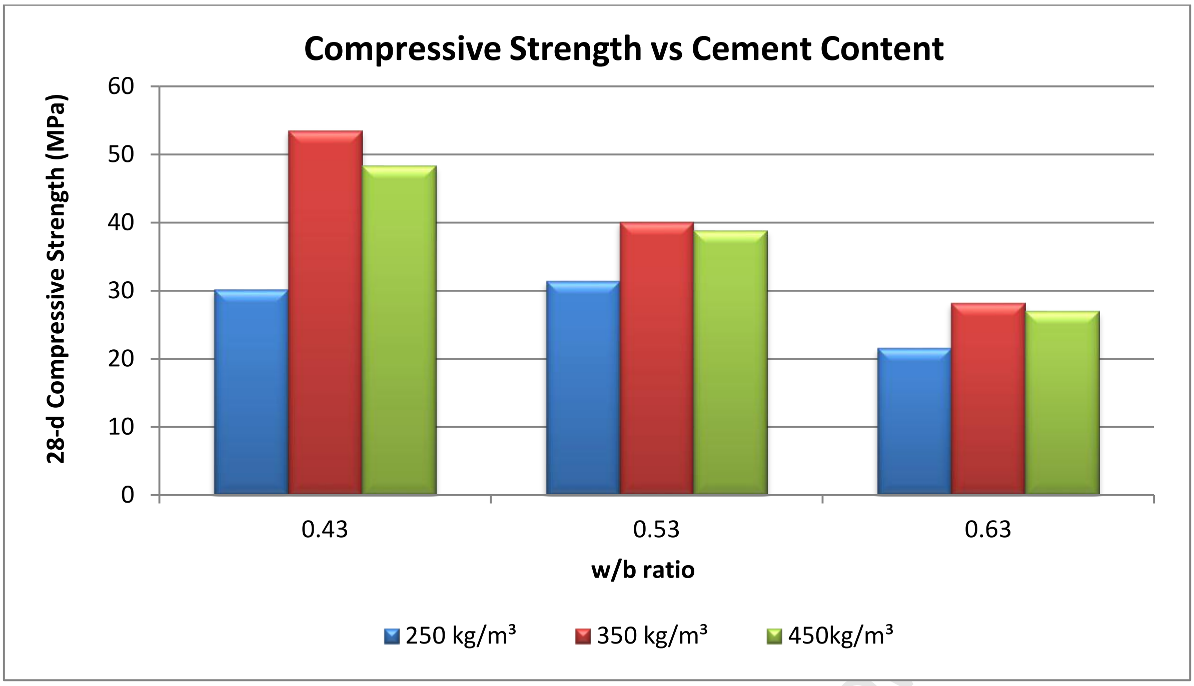


Figure 18: Compressive strength results from Yiğiter's study (Yiğiter et al, 2007)

In the study at hand, three w/b ratios were selected, each with three different cement contents as depicted in Figure 18. The data presented in this study showed that at low w/b ratios, increasing the binder content had a significant positive effect on the strength of the concrete up to a certain point. Thereafter further increases in binder content actually had detrimental effects on compressive strength, although not as pronounced as the positive effects. As the w/b ratio was increased, the effect of increasing binder content on compressive strength was less and less pronounced, but still followed the similar improvement trend up to a specific point, deteriorating thereafter. An attempt can be made to explain the above observations with the following reasoning:

- When w/b ratio and binder content are low, the volume of paste is insufficient to surround and bind the aggregates. This results in numerous discontinuities (pores and voids) between the constituent phases. This most likely occurred in the concrete with w/b = 0.43 and cement content = 250 kg/m^3. The resulting water content of 108 L/m^3 is impractical and while a large amount of super plasticiser may have been required, this concrete most likely also experienced compaction problems due to an insufficient volume of paste.
- If w/b ratio is kept constant but binder content is increased, more paste is generated to better bind the aggregates together, thus improving compressive strength. Together with the filling effect obtained by unhydrated binder particles at low w/b ratios, this explains the drastic improvement in compressive strength experienced by the 0.43 water/binder ratio mix once binder content increased from 250 kg/m^3 to 350 kg/m^3.
- Further increases in binder content at constant w/b ratio resulted in an increase in volume percentage of cement paste. This resulted in a higher inherent proportion of pore spaces, thereby justifying the slight but noticeable reductions in compressive strength.

- Similar observations can be made when starting out at a higher w/b ratio, but in this case the overall effects of increasing binder contents are not so pronounced. This is due to the fact that at higher w/b ratios there is more paste that can bind the aggregates together and thus a higher proportion of pores, regardless of the initially low binder content.

A likely reason why compressive strength development at higher w/b ratios was affected could have been the onset of bleeding, which occurs when excess water migrates upward due to the settlement of the solid materials. This may have occurred in the concretes where the water content was excessively high and impractical, such as those with cement content = 450 kg/m^3 and w/b = 0.53 and 0.63 (water contents of 230 L/m^3 and 280 L/m^3 respectively). It was also noted that in concretes where the range of water contents was somewhat more conventional (150 L/m^3 - 200 L/m^3), compressive strength was not significantly affected by changes in binder content. From the above observations, one can see that varying the binder content can have a significant effect on compressive strength, depending on the initial combination of w/b ratio and binder content selected in the mix design process.

Some methods of mix design use a factor known as aggregate-to-cement mass ratio (m_a/m_c). In another study, Grdić et al. (2010) investigated the influence of such a variable on compressive strength for concretes made at three different w/b ratios (0.46, 0.52 and 0.58) and binder content ranging between 250 kg/m³ and 500 kg/m³ for three different types of aggregate granulometric compositions. Concretes were produced with an aggregate portion that ranged between 1600 kg/m^3 and 1900 kg/m^3 so as to allow values of m_a/m_c to remain in a similar range for all concretes. For each w/b ratio and granulometric composition, it was observed that a characteristic paste volume occurred represented by a specific m_a/m_c value, for which compressive strength was optimum. This can be observed in Figure 19, where results are shown for a specific aggregate type labelled AB in the investigation.

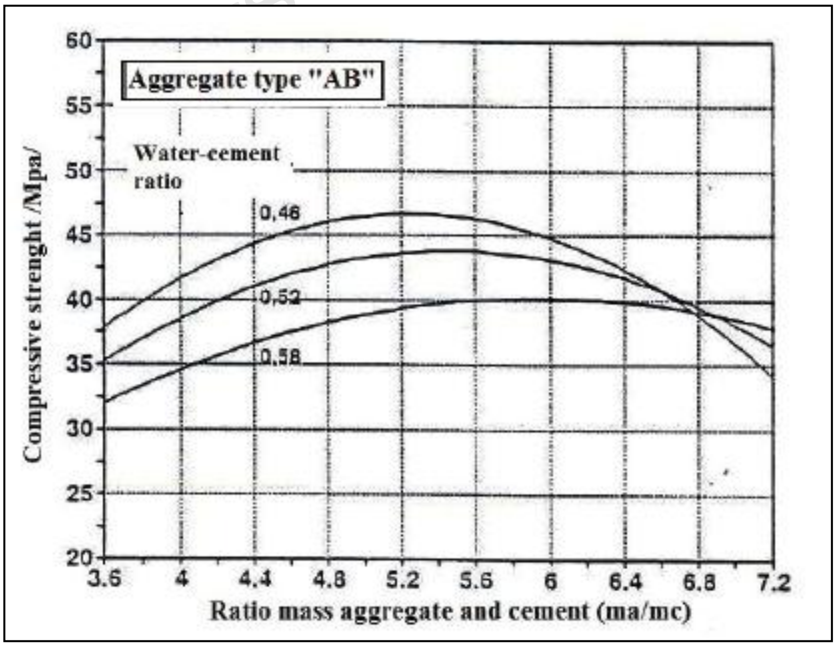


Figure 19: Compressive strength as a function of aggregate mass and cement mass (Grdić et al, 2010)

For all w/b ratios investigated, optimum compressive strength values occurred for m_a/m_c of 5.2 – 5.6. Varying m_a/m_c value from the mentioned range by decreasing or increasing water and cement content resulted in reduction in compressive strengths, a reduction which was less prominent for higher w/b ratios (this is shown by the manner in which the curves become less concave as the w/b ratio is increased). The following observations were made, which coincide with those made in the previous studies discussed in this section:

- When w/b ratio is low, low values of m_a/m_c represent high binder contents and high values of m_a/m_c represent low binder contents.
- At low w/b ratios, depending on the aggregate characteristics, the volume of paste at low m_a/m_c values may be insufficient to effectively bind the aggregates. At high m_a/m_c values there is a higher amount of paste and thus significantly higher porosity (Grdić et al, 2010). Hence compressive strength is affected at the two extremes and an optimum condition occurs.
- At high w/b ratios, similar trends are observed, but to a lesser extent due to the already high degree of porosity inherent in the mixture. At low m_a/m_c values, there is now more paste and therefore a high inherent initial porosity. As the m_a/m_c value increases, the paste volume is reduced and hence a point can be reached where the aggregates are not effectively bound by the paste.

As seen from the results presented in this section, compressive strength seems to be primarily a function of w/b ratio when water contents are of a range between 150 L/m^3 and 200 L/m^3. Paste volume and, consequentially, binder content start being highly influential at very low w/b ratios with excessively low and excessively high water contents. Differences of up to 20 MPa were observed in Kolias's study (2005), while Yiğiter et al (2007) showed that the initial benefit on compressive strength associated with increasing binder content became less and less pronounced as w/b ratio was increased. Furthermore, consideration of factors such as aggregate-to-cement mass ratio may also be a useful tool to determine the influence of binder content on compressive strength for both low and high values of w/b ratio.

2.3.3 Binder Type

In recent times remarkable advances have taken place in the field of concrete technology aiming at the achievement of improved performance of cementitious materials. Among these is a shift in the mix design process towards more environmentally friendly compositions, driven by the use of increasing contents of by-products and mineral admixtures (Bentur et al, 2008). Especially in the last few decades, industry has experienced an increase in the use of industrial by-products, also known as cement extenders, such as fly ash, blastfurnace slag and silica fume as mineral additives in cement and concrete.

Figure 20: Three cement extenders most commonly used in industry are from left: Fly Ash, Slag and Silica Fume (www.southafricacrusher.com, www.slagcement.org & www.asianproducts.com)

The use of these artificial pozzolans does not only allow economical benefits (by-products are less expensive than cement and their re-use promotes sustainability), but also technical benefits, with great performance improvements being achieved through proper selection of admixtures, mix proportioning and curing techniques (Wu et al. 2002).

Ground Granulated Blastfurnace Slag (GGBS) - When iron-ore is reduced in a blastfurnace, the silica and alumina are combined with the limestone flux and rapid cooling must then occur in order to achieve a glassy, reactive state (Grieve, 2009). The final product is then ground to a fine powder. Unlike Portland cement, GGBS is a latent hydraulic binder which requires an activator (commonly Portland cement) to undergo hydration reactions successfully. The lack of an activator results in a rate of reaction that becomes impractical for any use in construction.

Fly Ash - It is obtained in coal-fired power stations as a by product of the burning of coal. It is collected through the use of electrostatic precipitators in the furnaces that are fired by the pulverised coal (Grieve, 2009). Unlike GGBS and Portland cement, the key behind its use as a cement extender lies in the pozzolanic reaction, whereby it reacts with the Portlandite produced from the hydration of Portland cement in the presence of water.

Condensed Silica Fume (CSF) - This extender is obtained in the form of condensed vapour as a by-product of the ferrosilicon smelting process (Grieve, 2009). It is also a pozzolanic material, but it is much more reactive than fly ash due to the extreme fineness of its particles, which significantly enhances the fine-filler effect.

In practice cement replacement levels by weight do not exceed 50% (CSF – 10%; Fly Ash – 30%; GGBS – 50%). Reason for this is not only that more focus is placed on mechanical performance rather than material sustainability (Kuder et al. 2010), but also because the availability of these materials varies for different countries. The technical advantages that replacement of cement by extenders has on physical and mechanical concrete properties are well-established (Thomas et al, 1999; Antiohos et al, 2005; Menendez et al. 2003), with the key difference between the three featured extenders being the chemical reaction with which they contribute to the refinement of the microstructure (Grieve, 2009):

- Fly ash and silica fume are pozzolans; hence they undergo a pozzolanic reaction in the presence of water with cement hydration product Portlandite to produce CSH gel, the main strength contributor of the hardened cement paste.
- GGBS on the other hand undergoes its own hydration reaction when activated by Portland cement, also producing CSH gel and other silica and calcium aluminate products.

The effect of different binder combinations on strength development is well documented. CSF concretes develop high strengths at early ages due to the high rate of pozzolanic reaction and the extreme fineness of its particles. The pozzolanic reaction in fly ash concretes develops at a slower pace as particle fineness is not as high as in CSF. Hence early age strengths in fly ash concretes are generally lower even than those displayed by concretes made with Portland cement, with strength development maturing significantly in the long term. This can be observed from Figure 21.

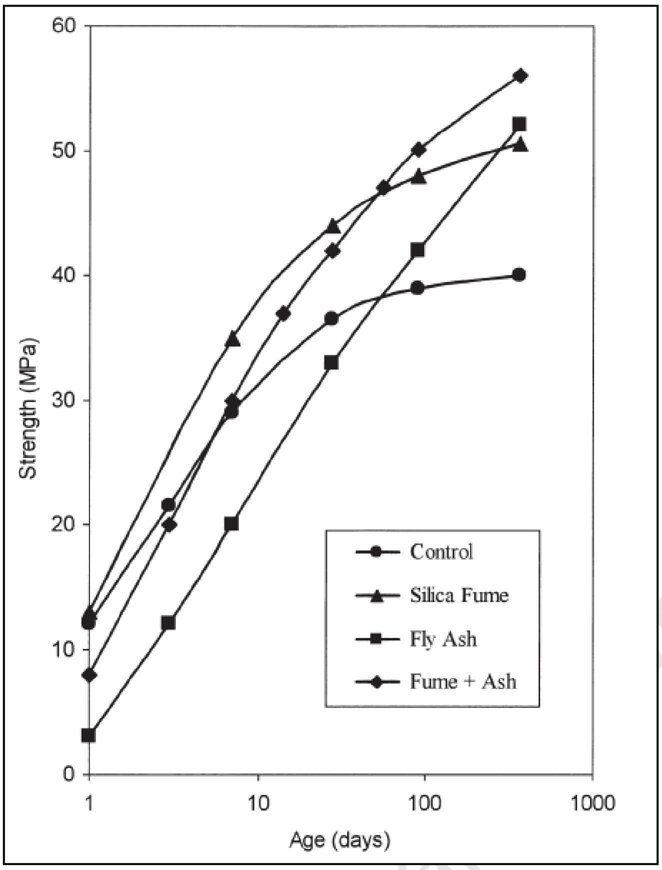


Figure 21: Effect of silica fume and Fly Ash on strength development (Thomas et al. 1999)

Despite the w/b ratio of the trial mixes ranging from 0.26 to 0.35, comparing the shapes of the curves in Figure 21 is especially useful in identifying contributions from each extender in the ternary blend. Silica fume concretes display high strengths for all ages, but the rate of strength development is only high in early ages, gradually decreasing with time as in Portland cement concretes (Thomas et al, 1999). Fly ash has an opposite effect, with strength development starting off slowly but maturing more and more with time. Hence the combination of the two extenders results in a synergy that achieves high strength at both early and long-term ages (Thomas et al, 1999). GGBS contributes to strength by its gradual hydration reaction which refines the pore structure over time. Lower early strength occurs than in Portland cement concretes, but characteristics are enhanced over time. Binary blends made with GGBS are ideal when desired strength levels need to be achieved over an extensive period of time. Alternatively slag can be used in ternary blends along with extenders that contribute to early strength development, such as silica fume or limestone filler, as shown in Figure 22. The strength of GGBS concrete was inferior to the Portland cement concretes for ages up to 28 days, showing improvement thereafter. When combined with limestone filler, however, compressive strength showed improvement at early ages and significantly outperformed the binary blend made with Limestone filler. Contributions from the limestone include better cement packing, which blocks the capillary pores and aids in early strength development (Menendez et al, 2003).

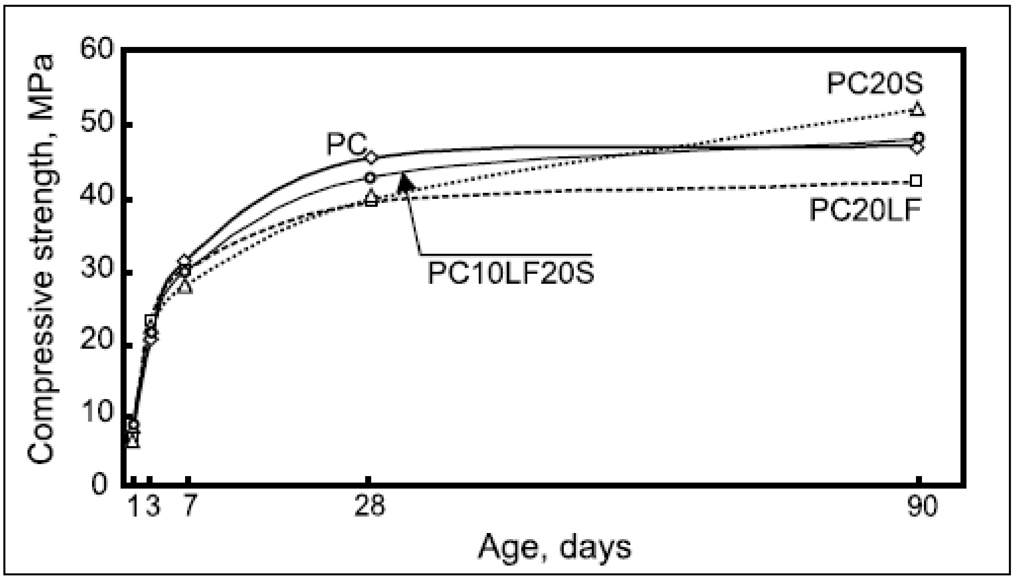
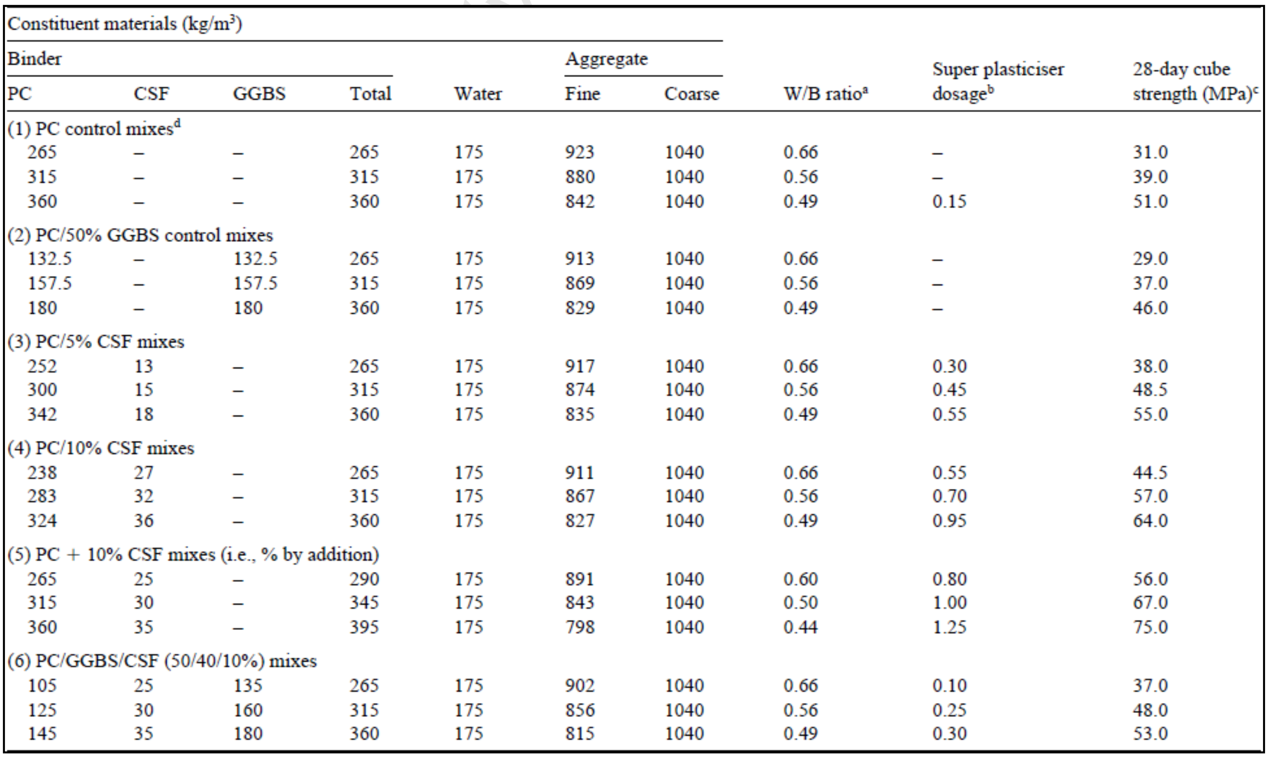


Figure 22: Compressive strength development of binary and ternary blends made with slag and limestone filler. PC – Portland cement; S – Slag; LF – Limestone filler (Menendez et al. 2003)

The early strength contributions from the limestone filler and the long-term strength contributions from the slag due to the gradual development of hydration reactions and pore refinement result in a ternary blend portraying satisfactory mechanical performance at any given age. The summary of the effects of different binders on compressive strength provided in Table 3 was extracted from research conducted on binary and ternary blends of CSF and GGBS by Alexander et al. (1999).

Table 3: Mix proportions and compressive strength results for different binder combinations (Alexander et al. 1999)



Constituent materials (kg/m^3)									
Binder					Aggregate				
PC	CSF	GGBS	Total	Water	Fine	Coarse	W/B ratio[a]	Super plasticiser dosage[b]	28-day cube strength (MPa)[c]
(1) PC control mixes[d]									
265	–	–	265	175	923	1040	0.66	–	31.0
315	–	–	315	175	880	1040	0.56	–	39.0
360	–	–	360	175	842	1040	0.49	0.15	51.0
(2) PC/50% GGBS control mixes									
132.5	–	132.5	265	175	913	1040	0.66	–	29.0
157.5	–	157.5	315	175	869	1040	0.56	–	37.0
180	–	180	360	175	829	1040	0.49	–	46.0
(3) PC/5% CSF mixes									
252	13	–	265	175	917	1040	0.66	0.30	38.0
300	15	–	315	175	874	1040	0.56	0.45	48.5
342	18	–	360	175	835	1040	0.49	0.55	55.0
(4) PC/10% CSF mixes									
238	27	–	265	175	911	1040	0.66	0.55	44.5
283	32	–	315	175	867	1040	0.56	0.70	57.0
324	36	–	360	175	827	1040	0.49	0.95	64.0
(5) PC + 10% CSF mixes (i.e., % by addition)									
265	25	–	290	175	891	1040	0.60	0.80	56.0
315	30	–	345	175	843	1040	0.50	1.00	67.0
360	35	–	395	175	798	1040	0.44	1.25	75.0
(6) PC/GGBS/CSF (50/40/10%) mixes									
105	25	135	265	175	902	1040	0.66	0.10	37.0
125	30	160	315	175	856	1040	0.56	0.25	48.0
145	35	180	360	175	815	1040	0.49	0.30	53.0

Results obtained and discussed herein are in concordance with previously reported findings and provide a quantitative and comparative outlook on the performance of binary and ternary blends made with the two extenders.

- The binary GGBS concrete displayed slightly lower strength values at 28 days than the control concrete, while all three CSF binary blends outperformed the control concrete. The largest improvement was observed in the binary blend where CSF was added, rather than used as cement replacement.
- The ternary blend made from 50% GGBS and 10% CSF approximated the 5% CSF binary blend with regard to compressive strength results. However, the difference in amount of cement used between the two concretes is over 50%.

From the above observations, it is noted that although extremely high strengths can be obtained by the use of cement extenders such as CSF, satisfactory levels of strength development can be achieved by using ternary blends. This can thus lead to significant reductions in the amount of cement used, thus promoting more sustainable concretes.

2.4 Durability of Concrete

Durability in concrete is defined as “the ability to resist weathering action, chemical attack, abrasion or any process of deterioration” (Mehta & Monteiro, 2006). It must be seen as “the interaction between concrete as a system and its environment as both need to be considered in durability assessments” (Ballim et al, 2009). In Figure 23, factors listed under concrete system deal with the concrete’s ability to resist mechanisms of deterioration, while those listed under environment are the factors responsible for the degree of aggressiveness that the concrete will be able to withstand. Durability is usually perceived by many as being largely dependent on constituent materials. While this is true, constituent materials are not the only determining factors of durability, with various other aspects such as environmental conditions, mix design and construction practices also playing a significant role. The microstructure of the concrete system imparts on the concrete an inherent durability before exposure conditions and site practices can have their influence on the concrete. Hence inherent durability can only be as good as the microstructure of the concrete system, which is a function of its constituent materials and proportions thereof. A lack of durability, which subsequently leads to concrete deterioration, is associated with the ingress of aggressive agents through various transport mechanisms. Durability is thus influenced significantly by the quality and ability of the near-surface concrete to limit the ingress of aggressive agents that cause depassivation and corrosion of the reinforcement.

Figure 24 represents a schematic of the concrete cover layer. The quality of this layer determines the extent to which the three main transport mechanisms allow ingress of harmful substances into the concrete. A brief overview of the three main transport mechanisms follows:

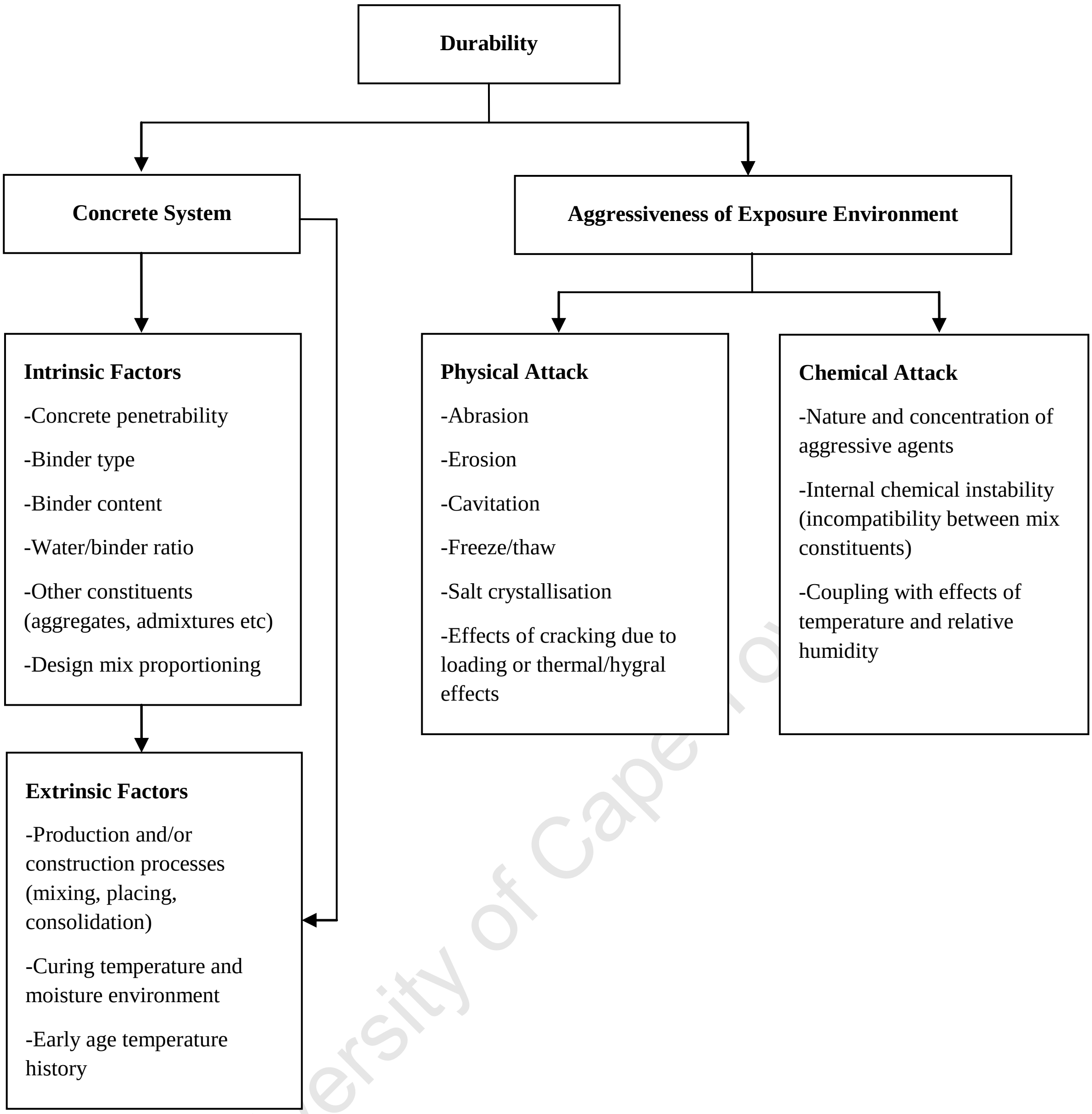


Figure 23: Concrete and environment – factors affecting the durability of concrete (Ballim et al, 2009)

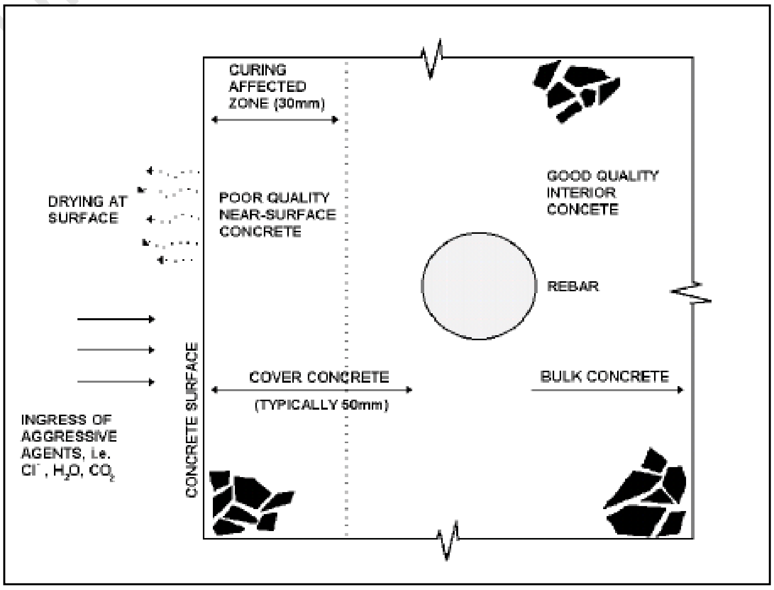


Figure 24: Schematic of concrete cover layer (Alexander, 2004)

Permeation - This is the movement of fluids throughout the pore structure under an externally applied pressure while the pores are filled with the particular fluid (Ballim et al, 2009). Permeation is thus dependent on factors such as concrete microstructure (specifically the structure of the aggregate-paste interface and hardened cement paste), nature of permeating fluid, pressure gradient and moisture conditions of the material. Determining the concrete’s ability to transfer fluids through permeation thus gives a clear and accurate description of the material’s permeability, the characteristics of which may then be used to predict concrete carbonation (Ballim et al, 2009).

Absorption - Fluid is drawn into unsaturated material under the action of capillary forces, which depend significantly on pore geometry (function of the microstructure of the concrete system) and concrete saturation level (Ballim et al, 2009). Absorption caused by wetting and drying of the surface is a crucial transport mechanism, but becomes less significant as concrete depth increases. The rate at which the wetting front moves through a porous material under capillary action is defined as sorptivity (Ballim et al, 2009).

Diffusion - This occurs when gases, liquids or ions move through a porous material via a concentration gradient. It occurs in both partially and fully saturated concrete and its importance as a transport mechanism is significant in concrete structures that are regularly exposed to salts in their design life. Salt concentrations build up at the surface due to absorption and later migrate into the concrete by diffusion down a concentration gradient (Ballim et al, 2009). Transport of ions and fluids through diffusion can be hindered by interaction of ions with cement hydration products e.g. chloride binding, defects such as voids and cracks and electrochemical effects due to reinforcement corrosion.

From the above descriptions, it is clear that concrete durability is largely dependent on porosity, which subsequently becomes a key factor to cater for during the mix design process. Where concrete durability becomes a major concern, the selection of mix design parameters, constituent materials and proportions should be aimed at minimising the porosity and permeability and maximising the chemical resistance of the concrete to aggressive agents in the surrounding environment (Ballim et al, 2009).

2.4.1 Water/Binder Ratio

The capillary pores present in the hardened cement paste make it the main contributor to the penetrability of the concrete system. As reported in Section 2.6.1, in concretes with low w/b ratios paste contents are low and hydration products rapidly fill the gaps between cement particles. When the w/b ratio is increased, hydration products need to grow over larger distances to effectively fill the gaps and the larger proportion of gel required results in a higher capillary pores fraction. Thus at low w/b ratios, the microstructure of the paste is more dense and permeability is reduced to such an extent as to almost yield an impermeable material (Malhotra, 1994). At high w/b ratios the excess water present in the matrix later evaporates and leaves larger, well connected capillary pores, resulting in a higher permeability. This is shown clearly in Figure 25, which depicts the relationship of w/b ratio with both compressive strength and permeability. This figure relays clearly the effects that the changes in microstructure brought about by variations in w/b ratio have on these two properties.

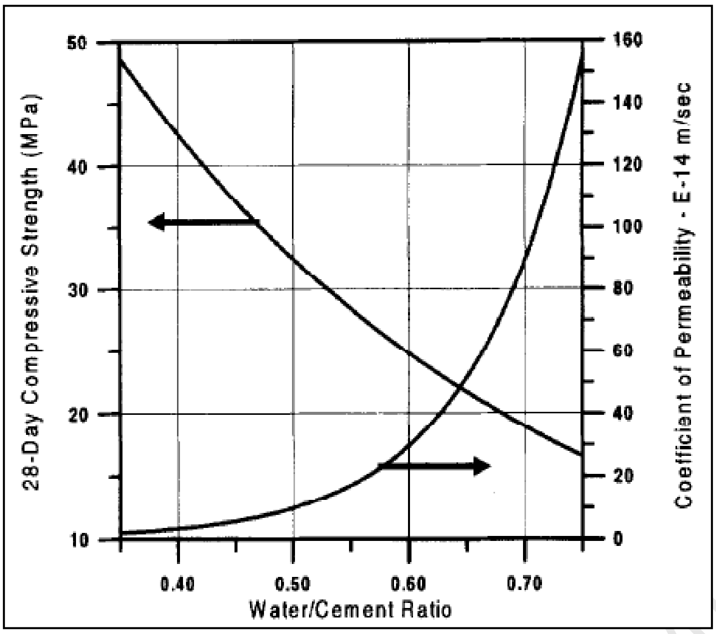


Figure 25: Effect of water/binder ratio on strength and permeability (Hover, 1998)

The exponential increase in permeability seen in Figure 25 as the w/b ratio increases can be explained with the following reasoning. An increase in w/b ratio implies that there are less unhydrated cement particles in the matrix as more paste is produced. Development of the ITZ is more enhanced due to the formation of larger Portlandite crystals, which constitute the weakest and most porous phase of the concrete system (Mehta & Monteiro, 2006). Hence, the capillary pore fraction grows exponentially as the w/b ratio increases, resulting in a higher permeability.

2.4.2 Binder Content

Modern codes focus on minimum binder content requirements for different environmental exposure classes, and associate these with minimum values of concrete compressive strength (as specified in BS EN 206, Table 2). Very little evidence is provided in these codes that identifies a link between binder content and durability properties. In order to discuss changes in microstructure that are brought about by variations in binder content and relate them to durability performance, the concept of paste volume is a useful one. Durability changes occur because paste is the main contributor of porosity to the concrete. Hence if paste volume is increased, the concrete becomes more porous (Kolias et al. 2005). Results obtained in an investigation conducted by Wasserman et al. (2009) with respect to the effect of cement content on capillary absorption are shown in Figure 26. For any fixed value of w/b ratio, capillary absorption increased with an increase in binder content, which caused an increase in paste volume. Since paste is the highest contributor to porosity of the concrete system, as the paste volume increased so did the capillary absorption coefficient. Another study conducted by Kolias et al (2005) obtained similar results which are displayed in Figure 27. Absorption was measured at four different times (after 1, 5, 24 and 48 hours), but it was felt sufficient for the descriptive purpose of this literature review to report on only two of the values, namely 1 hour and 48 hours.

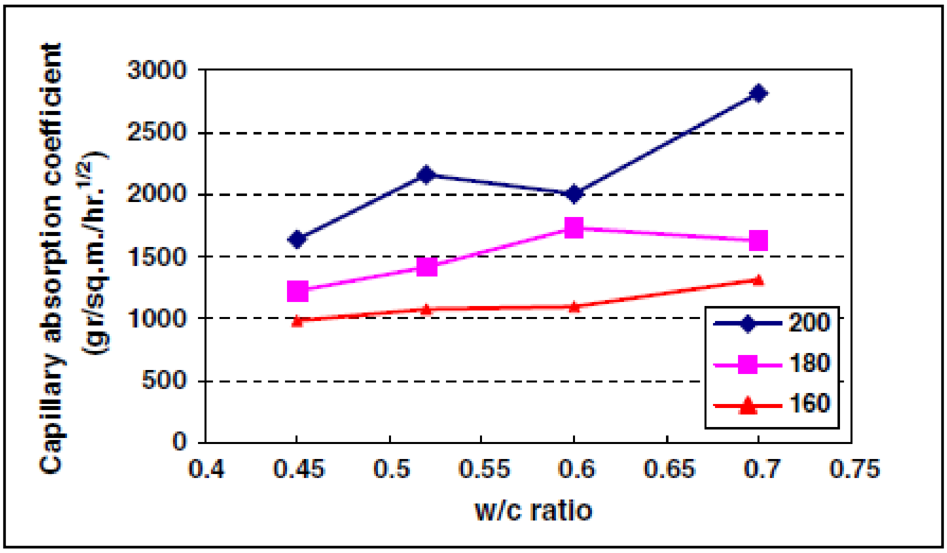


Figure 26: Effect of cement content (different water contents – 160, 180 and 200 kg/m^3) on capillary absorption (Wasserman et al, 2009)

The general trend displayed corresponds to the results obtained in other related findings such as the study by Wasserman et al, which was discussed previously. Absorption increased with an increase in w/b ratio as well as with an increase in paste volume. "The rate of absorption change for a given change in paste volume is lower for lower w/b ratios as a result of the decrease in paste porosity as the w/b ratio decreases." (Kolias et al. 2005:214).

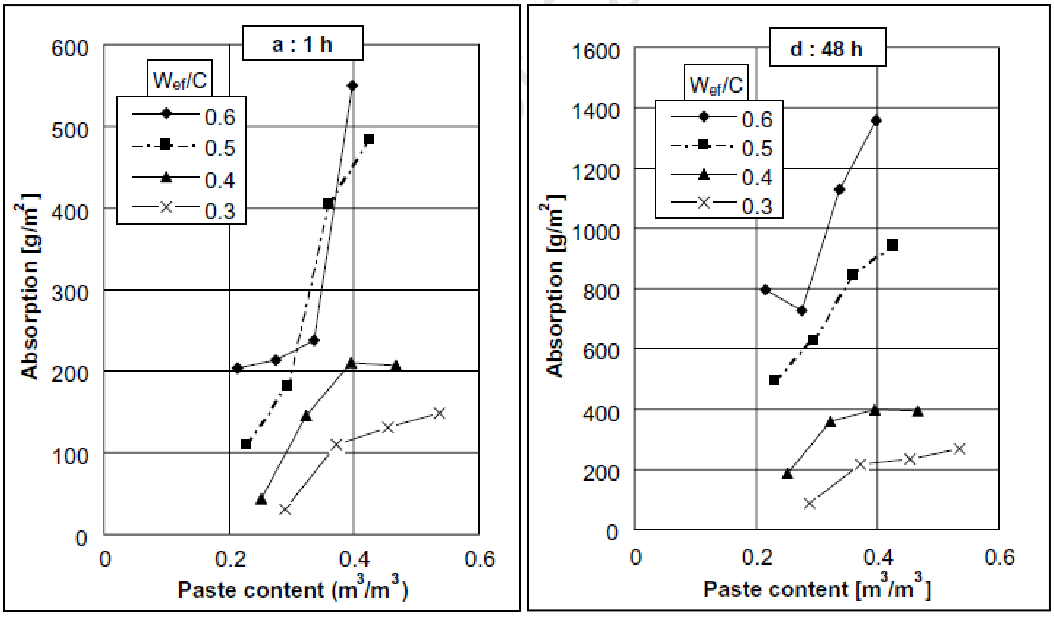


Figure 27: Relationship between absorption potential and paste content (Kolias et al, 2005)

What is important to note here is that, based on these results, if different concretes were to be exposed to environmental actions governed by absorption characteristics, they would behave in a similar way with regards to absorption potential despite the difference in w/b ratio. For example, Kolias et al point out that an absorption value of 100 g/m^2 after 1 hour can be achieved by concretes with w/b ratio of 0.30, 0.40 and 0.50 with respective paste contents of 38%, 29% and 21%. In the study conducted by Wasserman et al. (2009), the influence of different paste volumes as a result of varying cement content on the chloride penetration behaviour of concrete was also investigated.

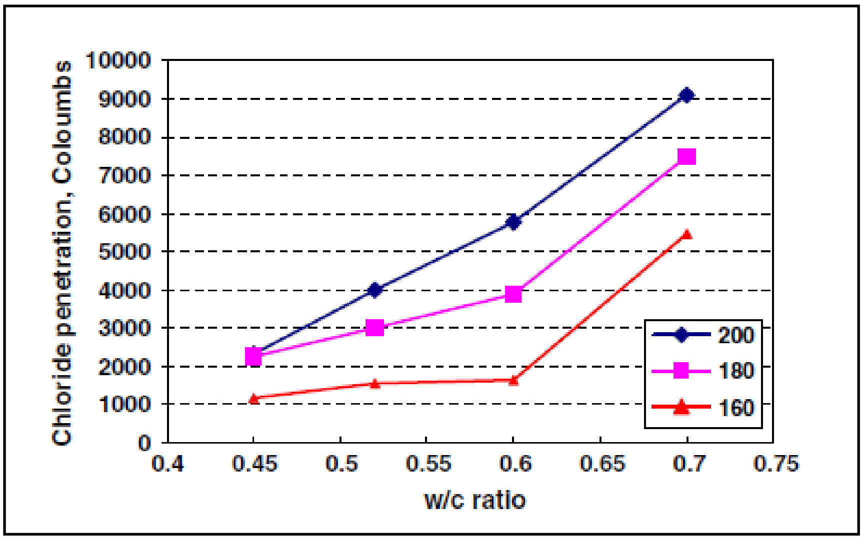


Figure 28: Effect of cement content (different water contents – 160, 180 and 200 kg/m^3) on chloride penetration (Wasserman et al, 2009)

Figure 28 shows the chloride penetration behaviour of concretes with different paste volumes. Since paste is the highest contributor of porosity to the concrete, mixes with a higher paste volume display a higher degree of chloride penetration than those with lower paste volumes. In another investigation, Yiğiter et al (2007) subjected concretes made with Portland Cement (PC) and Slag Cement (SC) to 110 cycles of wetting and drying by seawater exposure. Chloride penetration depth was measured on the concretes with different binder contents and results are displayed in Figure 29.

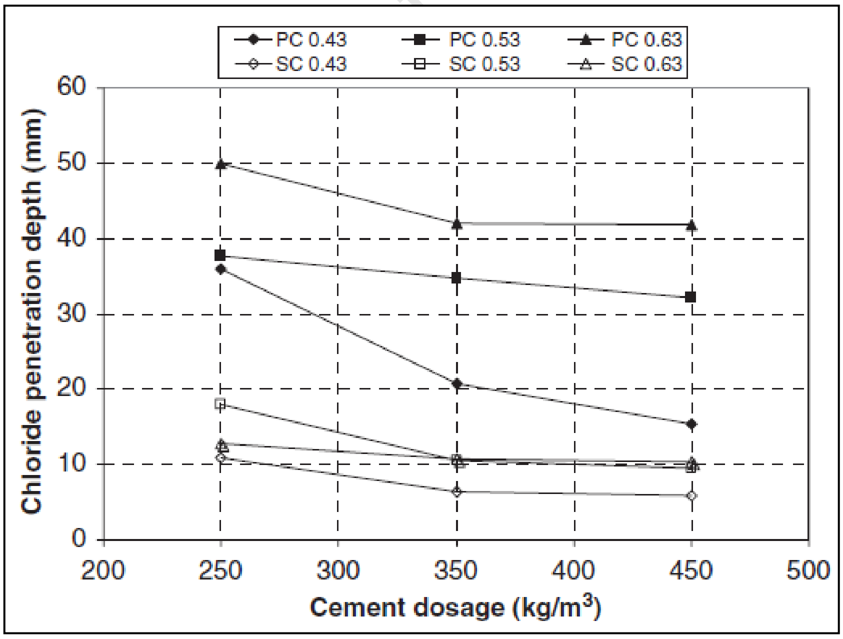


Figure 29: Effect of binder content on chloride penetration depth (Yiğiter et al, 2007)

Note that when comparing results in Figure 28 with those obtained in Figure 29, they may at first seem somewhat contradictory (an increase in binder content in Figure 28 results in higher chloride penetration, while in Figure 29 the opposite occurs). This observation can be explained by referring to the choice of experimental variables in the two experiments. In the investigation by Wasserman et al., the different binder contents were determined based on three fixed water contents for each w/b ratio. This resulted in a range of both binder content and water content conventionally used in industry, implying that initially there is a sufficient amount of paste in the concrete. Thus, any subsequent increase in binder content causes an increase in chloride penetration due to an increase in paste volume. In the experiments conducted by Kolias et al., three different binder contents were chosen for each w/b ratio, at times resulting in unusually low water contents, and thus paste volumes. Hence some improvements were observed with initial increases in binder content (as the binder content increased from 250 kg/m^3 to 350 kg/m^3, chloride penetration depth dropped considerably), but further increases from 350 kg/m^3 to 450 kg/m^3 did not lead to any substantial reduction in chloride penetration depth. Reasoning could be as follows:

- At low w/b ratios, there is insufficient paste volume to surround the aggregates.
- An initial increase in binder content can significantly reduce chloride penetration depths since more paste is produced to better bind the aggregates.
- The initial increase in binder content also improves the chloride binding potential of the concrete, since more binder can now take part in chemically bonding with the chlorides that enter the concrete microstructure.
- Excessive increases, however, can result in a higher volume of permeable paste, as well as more binder being available than chlorides to bind. This balancing effect hence shows no significant improvement in chloride penetration depth. This justifies why chloride penetration depths were not significantly reduced further for both binder types at all w/b rations when binder content increased from 400 kg/m^3 to 450 kg/m^3.

The results presented in this sub-section suggest that improvements in durability cannot be simply associated with increases in binder content, as is often understood by misinterpretation of prescriptive specifications.

2.4.3 Chloride-Induced Corrosion – Binder Content and Chloride Threshold

An interesting question is raised here with regard to the results of increasing binder content on chloride penetration properties presented in literature. Chloride threshold is defined as the chloride quantity above which corrosion to the embedded reinforcement is initiated. Threshold levels are commonly set with respect to binder content in service-life prediction models, implying that a higher binder content results in better resistance against chloride ingress and thus a longer service life. This, however, is not representative of the results presented in literature, especially when adopting a conventional range of water contents (Wasserman et al, 2009). In this section, a brief selective summary of the study on the influence of concrete microstructure around the reinforcement on chloride threshold values is given (Kenny, 2011). The summary identifies that there is a wider range of factors that need to be considered (not only binder content) to accurately correlate chloride threshold values to Service-Life Prediction Models.

A change in chloride threshold value can have a larger impact on the service life of a reinforced concrete structure than the transport properties or cover layer thickness. According to the research conducted by Kenny, there are four ways to represent chloride threshold; chloride concentration in pore solution; chloride-to-hydroxide concentration ratio in pore solution (Cl^-/OH^-); chloride content as a percentage of binder content; and chloride content expressed as a percentage of concrete (usually kg of Cl^-/m^3 concrete). Conversion from one representation method to the other is not simple and many factors need to be taken into account, among which are the following (Kenny, 2011):

- For a constant water content, as the binder content increases and the w/b ratio drops, the porosity tends to decrease. Hence, for a constant chloride concentration, chloride threshold represented by percentage of binder mass is expected to decrease with a reduction in w/b ratio.
- The use of pozzolans and latent hydraulic binders also increases the homogeneity of the microstructure and reduces porosity. Hence for a constant chloride concentration, less binder may be needed when using binary and ternary blends.
- Chloride absorption in the cement paste is dependent on temperature, pH and microstructure. Increases in binder content while w/b ratio remains constant results in an increase in paste volume that increases penetrability. Hence for a constant chloride concentration, a higher degree of penetrability may result in an accelerated time to corrosion initiation.

These are all convenient representation methods for engineering properties, but their relation to corrosion mechanisms is doubtful. Chloride present in the concrete microstructure occurs both as free or as total chloride. The latter incorporates chloride which is immobilised in the concrete solids. The range of chloride threshold values found in literature ranges widely from 0.03% to 4% of free chloride from binder mass and from 0.04% to 2.4% of total chloride from binder mass. The spread of values found in literature is due to the high number of values that may influence the chloride threshold. What is identified in this section is that chloride threshold, which is directly linked to chloride-induced corrosion and hence durability, is not dependent on one isolated parameter of binder content, but rather it is influenced by more interrelated factors which have to be equally taken into account.

2.4.4 Binder Type

The effects of cement extenders on durability properties of concrete are also well established. Much of the consideration behind the use of extenders deals with enhanced characteristics of durability. Numerous studies have been carried out dealing with the durability traits imparted on concrete microstructure by the use of extenders (Thomas et al. 1999; Antiohos et al. 2005 & Menendez et al. 2003):

- The extreme particle fineness of CSF significantly contributes to reduced permeability and chloride diffusion potential of the concrete.
- FA generally tends to reduce the water demand of the concrete mixture. Its slow-maturing pozzolanic reaction contributes to the refinement of the pore structure, which leads to reduced permeability.
- GGBS reduces permeability through the cementing reaction that refines the pore systems. This, however, occurs over a lengthy period of time due to the slow-maturing nature of its hydration reaction. It also reduces chloride diffusion levels in concrete due to its chloride binding potential.

The effects imparted on a concrete's mechanical properties by the use of extenders can also be translated to similar results regarding properties such as chloride diffusion and penetration. Silica fume reduces the chloride diffusion potential at early ages, while fly ash improves long-term characteristics as displayed in Figure 30. The pozzolanic reaction of both silica fume and fly ash, responsible for early and long term strength development respectively, leads to identical effects for diffusion potential, giving the ternary blend enhanced characteristics irrespective of the age of the concrete.

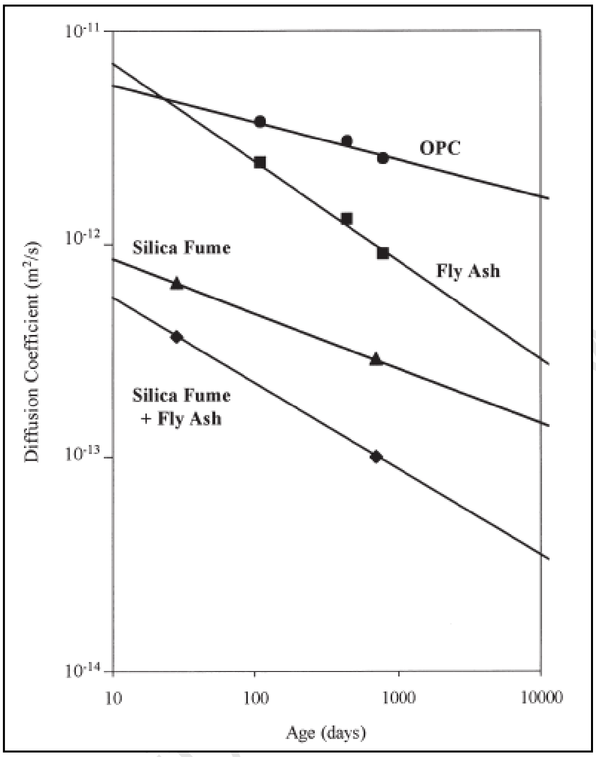


Figure 30: Chloride diffusion coefficient of binary and ternary blends made with silica fume and fly ash (Thomas et al, 1999)

Figure 29 in the previous sub-section also highlights the difference between concrete made with Portland cement as opposed to concrete made with slag with regard to the chloride penetration behaviour of concrete. Results for both cement types (PC and SC) displayed very similar trends, with chloride penetration depths measured in SC concretes being lower than in PC concretes for all w/b ratios and binder contents. Investigations into concrete behaviour with regard to chloride penetration reveal additional effects of extenders on concrete properties when used in binary and ternary blends. In a study conducted by Ahmed et al. (2008), results were obtained from the use of the UCT Chloride Conductivity Test carried out at 28 days on binary and ternary blends of CSF, fly ash and GGBS. The principal aim of this investigation was to compare two different methods of assessment of chloride penetration potential, but only results that are relevant to the development of this literature review are summarised and discussed here. Concretes made from GGBS binary and ternary blends outperformed all other concretes. This is due to two factors, namely refinement of the pore structure due to the latent hydration reactions that characterise GGBS concretes, as well as their chloride binding capacity (Ahmed et al, 2008). The silica fume binary blend displayed slightly improved properties in comparison to the control OPC concrete due to the fast pozzolanic reaction and enhanced micro-filler effect. Fly ash binary and ternary blends did not outperform control concretes as expected. A possible reason could be that since the UCT Chloride Conductivity test is conducted at an age of 28 days by convention, fly ash mixes may not have matured properly by this time due to the slow pozzolanic reaction (Ahmed et al, 2008). Evident in literature is the importance of the use of cement extenders in marine concrete applications. Harmful substances inherent in sea water make their way into the concrete through diffusion in the pore water and adsorption onto the pore walls (Yiğiter et al, 2007). The chloride binding potential and pore-structure refinement that occurs over time in GGBS concretes renders this extender particularly useful.

2.5 Workability

Workability of a mix is defined as the relative ease with which concrete can be placed (Addis, 2008). According to Addis, it is not possible to measure workability, but assessment of various mixture properties can lead to an acceptably accurate qualitative description of the following (Kellerman and Crosswell, 2009):

- Consistence - related to the general wetness or dryness of the mix, it describes the mobility or ease of flow. Wet concrete is usually more workable than dry concrete, but mixes with the same consistence may vary in workability.
- Cohesiveness - the tendency to resist segregation and bleeding.

Workability is regarded as one of the determining factors of mechanical and durability characteristics. Minimum segregation and bleeding, as well as full compaction are required to achieve the desirable mechanical and durability properties (Kellerman and Crosswell, 2009). The workability of a mix should allow the achievement of full compaction with the equipment that is available without segregation occurring.

The proportions in which mix constituents are combined significantly affect workability, and a number of interdependent factors can be categorised according to constituent proportions (Kellerman and Crosswell, 2009):

Water Content – In well proportioned mixes, an increase in water content will make the concrete more mobile and flowable. In mixes with low water content, segregation tends to occur. This can be mitigated by increasing the water content. However further increases leading to high slumps will also cause segregation, as well as excessive bleeding.

Binder Content – Concretes with low binder content are usually quite harsh and have poor finishability. High binder contents, on the other hand, cause a mixture to be sticky and rapidly lose workability.

Paste Content – Within normal mix proportions, workability tends to improve with increasing paste content and increasing paste-aggregate volume ratio. This happens because the amount of paste needed must be higher than that required to fill the voids between packed aggregates. However, excessive increases in paste content may tend to make the mix too flowable and cause segregation.

Binder Type – The use of Fly Ash usually improves workability, while GGBS may also have a beneficial effect despite the sticky nature of its concrete mixes. Silica Fume tends to reduce workability when used in excess of 5% by mass of cement.

One can thus see that even though workability is often just specified on site as a target slump, the achievement of a desired slump through selection of constituent materials, mix design parameters and appropriate site practices can have significant implications on compressive strength and durability properties of concrete. Thus it needs to be considered appropriately in the mix design process.

2.6 The Influence of Curing on Durability and Strength Development

While concrete properties are significantly affected by the choice of constituent materials and design parameters, a major role is also played by the manner in which site practices such as curing are carried out. Curing is a most crucial parameter as it ensures that the engineering properties of the concrete develop to their required potential (Ballim, 1993). For that to happen successfully, curing must be approached as a multi-step process (Hover, 2011). The key lies in keeping the capillary pores full of water for a sufficiently long period of time for the desired properties to develop, making the timing of curing application essential. The interlocking bonds between newly formed hydration products and unhydrated cement grains are virtually non-existent in the first hour after mixing. Application of curing water at this time will thus be detrimental, separating cement particles, increasing porosity and permeability and causing a reduction in strength (Hover, 2011). Allowing the fragile bonds to strengthen as hydration develops enables the application of curing water to be more effective towards achieving the desired concrete properties. The inter-particle voids need to be continuously filled with water for hydration reactions to be properly sustained. Trying to achieve this by alternative methods of curing such as sealing can become problematic when considering low w/b ratio high performance mixtures. In mixes with sufficiently low w/b ratio (less than 0.42), effective sealing of the concrete specimen can lead to drying of the concrete inside as available water is consumed during hydration, a phenomenon known as “self-desiccation” (Hover, 2011). This is why the most effective way to maintain the capillary pores filled with water and sustain hydration is to make liquid water available to the hydrating cement. In order to understand the influence of curing on strength and durability, it is essential to differentiate between two “zones” in the concrete. Figure 31 shows a typical section of a reinforced concrete element divided into two zones:

Covercrete – This is the layer between the outer surface of the member and the reinforcing steel. Its main function is the protection of the reinforcement and underlying concrete from the external exposure environment.

Heartcrete – This is the inner layer of bulk concrete which provides mechanical strength and dimensional stability to the member (Ballim, 1993).

From the definition of the two layers, it is clear to see that the characteristic functions of covercrete and heartcrete are of durability and compressive strength respectively.

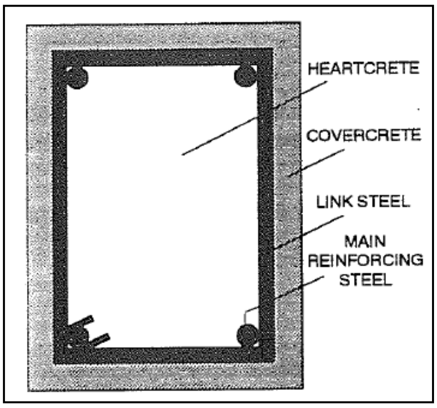


Figure 31: Typical reinforced concrete section with the inner layer – heartcrete – and surface layer – covercrete (Ballim, 1993)

When the member is exposed to drying conditions, detrimental effects on cement hydration due to moisture loss will mostly be felt by the covercrete. Moisture loss is usually not as pronounced in the heartcrete because the drying gradient in that region does not develop to such an extent as to cause migration of all the water to the surface (Ballim, 1993). Thus a lack of curing does not necessarily affect strength development to the same extent as it does durability. The choice of curing regime for a specific project is usually not made using the desired resultant properties as criteria. Instead it is mostly governed by practical problems and economic implications (Alexander et al, 1999). An investigation conducted by Ramezanianpour et al. (1995) aimed to determine the effect of various curing regimes on mechanical and physical properties of concretes incorporating different extenders. The curing regimes chosen are given in the following table.

Table 4: Curing regimes adopted during investigation (Ramezanianpour et al. 1995)

Curing Denotation Number	Description of Curing Regime
1	Standard moist curing following demoulding
2	Curing at room temperature (23 ± 2°C and 50% RH) after demoulding
3	Curing at room temperature (23 ± 2°C and 50% RH) after two days of moist curing
4	Curing at 38°C and 65% RH

Compressive strength and chloride penetration tests were conducted on the concretes at different ages. The idea behind the choice of curing regimes was to encompass as wide a variety of curing methods and environments as practically possible; curing regime (1) represents control (ideal) conditions, where the concrete is continuously supplied with moisture. Curing regime (2) was chosen to simulate a scenario where no curing occurs after stripping of formwork, a common situation especially in developing countries (Ramezanianpour et al, 1995). Curing regime (3) follows a growing trend in the industries of numerous countries where continuous moist curing is carried out initially for a few days before exposing the structure to ambient conditions. Lastly, the choice of curing regime (4) was made to represent the conditions that occur in warm, tropical climates, where the concrete receives little to no curing during the first 24 hours after casting. The conclusions drawn in this study were that an effective moist curing regime is of crucial importance for concrete to achieve its highest strength and chloride penetration resistance (Ramezanianpour et al, 1995), especially with the incorporation of extenders. Blended concretes are more sensitive to the absence of moisture in the curing process but perform significantly better than Portland cement concretes if moist curing is performed effectively.

The insurance of adequate curing techniques is not mentioned in any prescriptive mix design specifications since it is usually specified to the contractor by the concrete supplier. Since prescriptive specifications specify minimum strength values for insurance of durability, and since both strength and durability have been shown to be dependent on curing, the literature reviewed in the following section aims at determining whether a relationship does exist between durability parameters and compressive strength.

2.7 Compressive Strength and Durability Parameters – A Correlation

Since both compressive strength and durability depend on concrete microstructure (porosity and permeability), the existence of a relationship between strength and durability is expected (Al-Amoudi et al, 2009). In their study, Al-Amoudi et al. aimed to investigate such a relationship by analysing test results of both concrete strength and durability indices of plain and blended concretes. The strength, water penetration depth and coefficient of chloride diffusion were evaluated for a range of cementitious materials contents and w/b ratios. Figure 32 and Figure 33 display the results obtained for water penetration and coefficient of chloride diffusion for the different types of concretes.

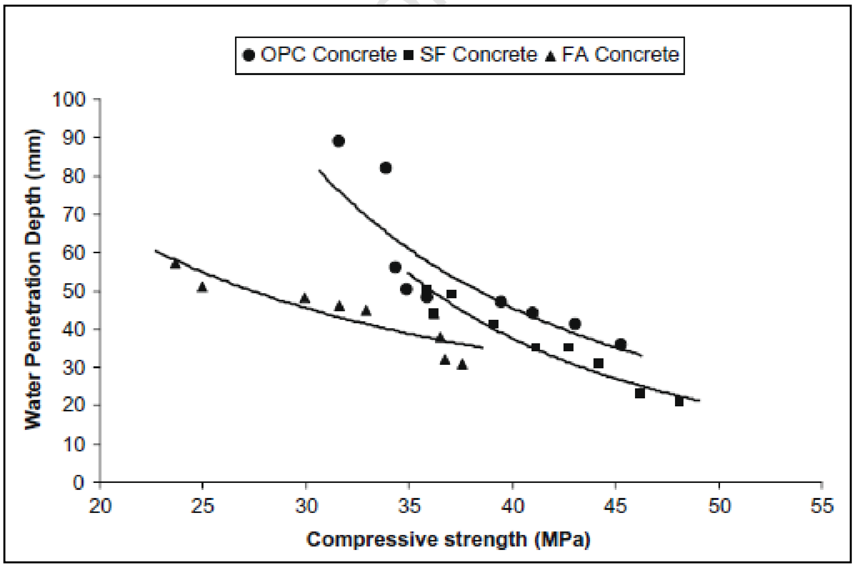


Figure 32: Variation of water penetration depth with concrete compressive strength (Al-Amoudi et al. 2009)

The trends observed were that for all types of concretes, chloride diffusion coefficient and water penetration depth decreased with increasing strength, with blended concretes performing better than plain concretes. The data plotted in Figure 32 and Figure 33 seems to suggest that concretes with higher strengths display improved properties for diffusion and water penetration.

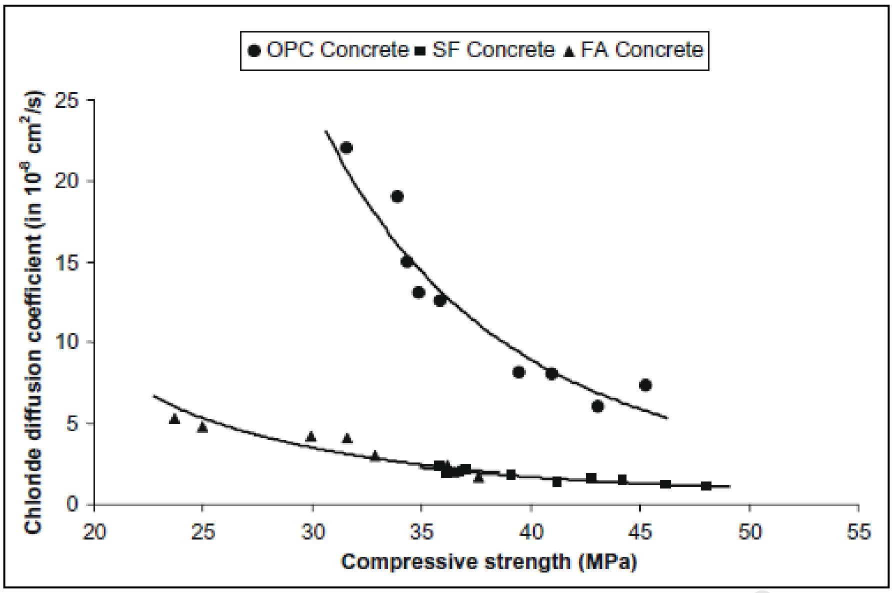


Figure 33: Variation of chloride diffusion coefficient with compressive strength of concrete (Al-Amoudi et al. 2009)

However it is essential to understand that the results obtained in this investigation were for samples that were fully water cured until the tests were carried out. As was noted in Section 2.6, successful development of concrete properties can be significantly influenced by the choice of curing regime, and the influence that curing may have on compressive strength development may be quite different to the influence on durability properties. Since curing is a practice that is not usually carried put perfectly on site, the nature of this relationship could be somewhat different if the concretes were to be exposed to alternative curing regimes aimed at emulating site conditions.

In another study carried out by Ramezanianpour et al. (2011), the relationship between concrete resistivity and compressive strength was investigated. Electrical resistivity represents the movement of ions, such as chloride ions, in pore solution.

- A higher resistivity implies a slower movement of chloride ions in the concrete system and thus a more gradual rate of reinforcement corrosion (Ramezanianpour et al, 2011).
- The slower movement of chloride ions can also be attributed to a well refined microstructure, resulting in the presence of poorly interconnected pores which restrict the movement of ions.

Resistivity is therefore an intrinsic property of the material and can be used to assess concrete permeability. Results obtained by Ramezanianpour et al. dealt with Portland cement concretes and Metakaolin concretes and are displayed in Figures 34 and 35. Results were separated according to the different binder type combinations used due to the fact that concrete systems made with the same cementitious materials displayed similar microstructure (Ramezanianpour et al, 2011).

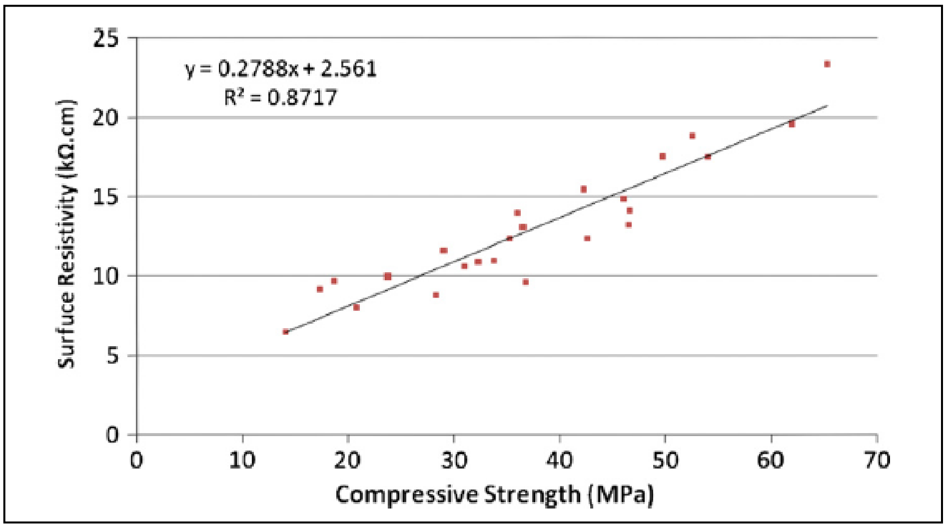


Figure 34: Relationship between compressive strength and surface resistivity for plain cement concretes (Ramezanianpour et al, 2011)

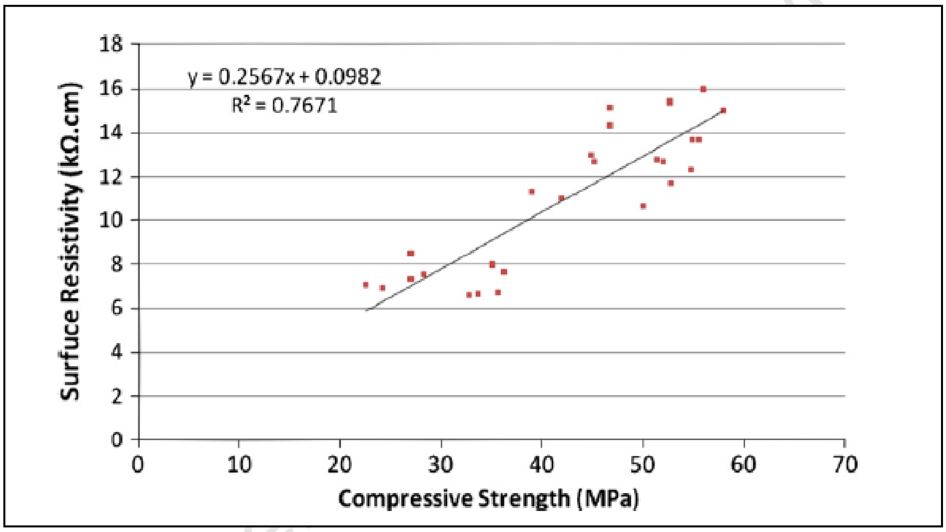


Figure 35: Relationship between compressive strength and surface resistivity for metakaolin concretes (Ramezanianpour et al, 2011)

The trend identified in Figures 33 and 34 was that concretes with higher strengths displayed a higher resistivity. This was most likely attributed to the full water curing regime that was adopted in the experimental plan, hence allowing concrete strength and resistivity to mature effectively in both plain and blended concretes. When interpreting these results, it is important to identify the primary cause behind the improvement of durability characteristics due to an increase in strength. When recalling Figures 27 – 29, the results obtained in those investigations seem to coincide with those displayed in Figures 34 and 35. Durability characteristics deteriorated with increases in w/b ratio, equivalent to decreases in strength. They also deteriorated with increases in paste volume for a fixed w/b ratio, identified in Section 2.3 as detrimental to compressive strength, depending on initial parameters such as water content, binder content and w/b ratio. Hence the interpretation of prescriptive specifications that concretes with higher strength imply a higher durability is not a flawed one per se, but needs to be carefully considered with respect to the primary causes that result in an improvement in compressive strength and subsequent enhancement of durability characteristics.

2.8 Summary

Prescriptive specifications are nowadays predominantly used in mix design. They are based on previous practice and experience and largely focus on specifying limiting parameters such as minimum cement contents, maximum w/b ratios and minimum strength for durability. Durability, however, is related to a material performance concept for a structure in a given environment for the duration of its service-life. As such, it can be effectively catered for in the mix design process by the use of performance-based specifications, which are based on measured material characteristics and exposure conditions. The main difference between the two specification types is that limiting parameters like minimum binder contents present in prescriptive specifications are often interpreted by engineers in industry as being isolated parameters for determining durability. This has often resulted in the specification of excessively high cement contents, leading to various technical, economical and environmental problems with the resultant concrete mixes. As noted in this chapter, all three constituent phases of concrete are associated with a certain degree of porosity inherent in their microstructure which plays a significant role in the development of compressive strength and durability properties. Hence description of the microstructure through parameters of mix design can be used to assess concrete quality.

Compressive Strength – Generally, at low w/b ratios there is a more pronounced detrimental effect on compressive strength brought about by increases in paste content (increases in water and binder content). This effect becomes more and more negligible when w/b ratio is increased, but does not result in an improvement in strength. Thus the general trend is that at high initial binder contents (low w/b ratios), further increases in binder content are more detrimental than at low initial binder contents (higher w/b ratios). This is due to the fact that increases in paste volume result in a larger portion of discontinuities in the cement matrix. Crack propagation will tend to follow the path of least resistance, moving along a path where it will encounter the least amount of aggregates and a larger amount of paste. Hence, when w/b ratio is low, the increase in paste volume brings about more and more alternative paths of least resistance for the crack to propagate in. When w/b ratio is high, there is a higher probability that the path of least resistance is already preset in the microstructure. Hence the detrimental effect is not as prominent. Different binder type combinations are used for achieving target strengths at specific ages and to compensate for the generally higher cost of cement. Blended concretes (binary and ternary blends) are generally made with Fly Ash and GGBS, with Silica Fume used less than these two binders due to its higher cost. The cement replacement levels (by mass of cement) for binary blends with which optimum strength development results have been observed are approximately 30% for Fly Ash, 50% for GGBS and 8% for Silica Fume.

Increases in binder content may result in higher amounts of cement used, thus higher costs, as well as complications associated with high heats of hydration, thermal effects and ASR. Hence the observed trends fails to identify the benefits of increasing binder contents for purposes related to compressive strength.

Durability – A general deterioration in durability is observed when w/b ratio is increased. This is expected as the changes that occur in concrete microstructure result in a poorer concrete quality. Increases in paste volume for a fixed w/b ratio also cause deterioration in durability characteristics. Differently to strength, however, this is more prominent at higher w/b ratios than low w/b ratios. This is because increases in paste volume that occur at high w/b ratios result in a larger and larger increase in the pore fraction present in the cement matrix. At low w/b ratios, there is still a refining effect imparted to the microstructure due to the proportion of unhydrated binder particles acting as pore fillers. Hence, increases in paste volume when w/b ratio is low will still inherently result in a portion of unhydrated binder particles that will effectively fill the increasing pore fraction. Thus the detrimental effect of increasing paste volume on durability characteristics is not as prominent when w/b ratio is low as when it is high. Different binder types may be used to impart specific improvements to concrete microstructure. Pozzolans like Silica Fume and Fly Ash result in a refinement of the microstructure as a result of the products of the pozzolanic reaction. GGBS, with its latent hydraulic binding properties, results in a more gradual development of its cementing properties and also provides excellent chloride binding capabilities, making it useful for aggressive marine environments. The cement replacement levels (by mass of cement) for binary blends with which optimum durability characteristics have been observed are similar to those observed for strength.

With the economical and technical implications associated with increasing binder content, these trends fail to identify the benefits of increasing binder content for durability properties.

Workability – Workability is affected by both intrinsic parameters (nature and proportion of mix constituents) and extrinsic parameters (site practices such as curing and compaction). These need to be carefully considered and carried out with the aim of minimising segregation and bleeding, which affect the maturation of concrete microstructure and thus development of mechanical and durability properties.

Curing – Two concrete zones are identified, each responsible for the development of compressive strength and durability characteristics. Heartcrete (inner layer of bulk concrete – mechanical resistance) and covercrete (layer between outer surface and reinforcing steel – protection of reinforcement). Pores must be continuously filled with water to allow mechanical and durability properties to develop effectively. Blended concretes are more susceptible to curing and usually perform better than Portland cement concretes when curing is carried out effectively.

Link between Compressive Strength and Durability – Review of the literature does show that, for experimental full water-cured concrete, higher strength is associated with higher durability. Development of concrete properties can be significantly influenced by the choice of curing regime, and the influence that curing may have on compressive strength development may be quite different to the influence on durability properties. This relationship could therefore be somewhat different for alternative curing regimes. The trend of high strengths being synonymous with higher durability is therefore not flawed per se, but the following must be duly noted. Improvements in strength and subsequent improvements in durability, as identified in literature, do not depend on one sole determining parameter (minimum binder content, maximum w/b ratio, minimum strength class). Instead they are a function of an integrated framework of mix constituent parameters and their mutual relationships and they need to be considered as such.

Conclusion – It can be seen that concrete durability has to be considered as a function of both material characteristics and performance in a given exposure environment over its design-life, highlighting that the prescription of limiting parameters such as minimum binder contents is not an effective tool to ensure durability in mix design. It is clear to see that a deeper understanding behind the determining factors of concrete durability is needed so as to highlight the malpractice that is associated with misinterpreting the prescriptive specifications in the codes such as minimum binder contents, maximum w/b ratios and minimum target strengths. Hence the study proposed in this thesis will aim at investigating the influence of such parameters, as well as compressive strength, on durability properties. The latter will be investigated since it is the parameter most commonly used nowadays to characterise concrete quality. A relationship between durability and compressive strength, if existent, would be a useful one to aid in the understanding of the behaviour of concrete systems.

3. REVIEW: DURABILITY SPECIFICATION PRACTICE IN SOUTH AFRICA

3.1 Introduction

In this chapter, current trends and practices being followed in industry with respect to concrete mix design were investigated. The aim of this chapter was to determine the manner in which prescriptive specifications of minimum binder content are interpreted and how the result of these interpretations reflects in industry, possibly allowing the identification of inappropriate practices of mix design. Interviews were conducted with ready-mix concrete suppliers, engineers and various professionals in the field of cement and concrete technology.

3.2 Minimum Binder Content - A Brief Background

The design of structural concrete in industry occurs almost solely on the consideration of compressive strength. When performing a structural analysis, compressive strength is the key initial assumption that the engineer uses to assess stress distributions of a structural member. Based on this assumption, engineers will then stipulate a characteristic strength for the concrete. At times the specification for strength is accompanied by durability requirements, for which exceedingly high binder contents are often specified (Crosswell, 2012). The concrete producer will then select mix design parameters based on a target strength that will satisfy the structural and durability requirements, among which specified parameters such as minimum binder content. The history of minimum binder contents dates back to the 60's, when there was a shift in the concrete manufacturing industry from localised i.e. site-batched to more specialised i.e. precast manufacture and ready-mix suppliers. The onset of more specialised suppliers added an edge to the product in that clients could now request more from the product to suit their particular needs (Crosswell, 2012). One such request was the engineering and production of stronger cements. This meant that specific characteristic strengths could be obtained with the use of less cement, but with no accompanying change in water content. What resulted were increased durability concerns due to porous mixes. This was seen as a serious problem, especially in aggressive conditions such as chemical attack. The solution that was adopted back then, and which is still dominant in modern standards, was the specification of minimum binder contents. As a result of these practices, particularly in South Africa, increasing the binder content is widely associated with enhanced compressive strength and durability. While increasing the binder content of a concrete mixture may improve its mechanical characteristics if no alteration is made to the water content, it can also affect concrete performance negatively, resulting in thermal cracking and high heat of hydration to name a few concerns. In today's industry setting, strict adherence to specifications of minimum binder contents has various implications which were not crucial factors to consider during the time when such specifications were first implemented:

- Specification by engineers of minimum contents that are excessively high can result in suppliers (ready-mix concrete or precast manufacturers) using more cement and to thus increase their manufacturing costs, which ultimately reflect on the purchasing prices.

- Numerous technical benefits in both mechanical and physical properties of the concrete can be achieved today thanks to the use of alternative binders, the majority of which are economical and, especially in South Africa, highly accessible (Fields, 2011).
- The specification of "higher-than-necessary" binder contents puts significant strain on the environment due to the intensive levels of energy consumption and harmful emissions associated with the manufacture of cement. Concretes practices that follow such trends are often unsustainable and uneconomical.

Based on the above-mentioned points, one can see that the specification of minimum binder content cannot be associated with a holistic concept of "enhanced concrete performance", which is the association made nowadays by numerous engineers who still adhere strictly to prescriptive specifications (Gouws, 2011). Tendering processes also need to be mentioned as they play a significant role in current industry trends. In one particular case, for the tendering process concerning the Gauteng Freeway Improvement Project, estimates made during the tendering process were based on the use of 400 kg/m^3 of cement. Adjustments for payment to the contractors were made if quantities were exceeded up to about 450 kg/m^3, while any amounts exceeding 450 kg/m^3 were not catered for by additional payments (Evans, 2011). Some incentive was provided in the sense that quantities below 400 kg/m^3 did not result in reduced payment and benefited the contractor directly, provided that all durability requirements would be met. However, this is not a dominant scenario, and while the quantities being discussed are still fairly high, contractors are not likely to reduce cement contents due to financial reasons since cement is generally not the most expensive component of a project for a contractor (Gouws, 2011).

3.3 Binder Content and the Durability Index Approach

In the implementation of the DI Approach by local authorities such as the South African Roads Agency Limited (SANRAL), concrete used for specific structures is also cast into trial panels that are then cored and tested at selected ages for oxygen permeability, water sorptivity and chloride conductivity. Results are then compared to limiting index values such as the ones displayed in Tables 5 and 6.

Table 5: Durability parameters acceptance ranges (Beushausen & Alexander. 2009)

Acceptance Category	Oxygen Permeability (Log Scale)
Concrete made, cured and tested in the laboratory	> 9.80
Full acceptance of in-situ concrete	> 9.70
Conditional acceptance of in-situ concrete (with remedial measures approved by the Engineer)	8.75 – 9.70
Rejection	< 8.75

Table 6: Maximum chloride conductivity values (mS/cm) for different exposure classes and binder types: deemed-to-satisfy approach – common structures, cover = 50 mm (Alexander et al. 2008)

EN 206 Class	Description	70:30 CEM I: Fly Ash	50:50 CEM I: GGBS	50:50 CEM I: GGCS	90:10 CEM I: CSF
XS 1	Exposed to air-borne salt, no direct contact with sea water	3.00	3.50	4.00	1.20
XS 2a	Permanently submerged	2.45	2.60	3.25	0.85
XS 2b	XS 2a + exposed to abrasion	1.35	1.60	1.95	0.45
XS 3a	Tidal, splash and spray zones	1.35	1.60	1.95	0.45
XS 3b	XS 3a + exposed to abrasion	1.10	1.25	1.55	0.35

In order to avoid the financial penalties associated with failure to meet the prescribed durability requirements, some contractors will use concrete mixes with exceedingly high cement contents to overcompensate for specified durability criteria. This is due to the misinterpretation that is dominant in current industry trends that increasing the binder content will cause durability to be enhanced (Gouws, 2011). The shortcoming of this scenario is that each durability index parameter is a quantification of a property that is itself sensitive to both intrinsic factors (among which are mix design parameters such as binder content) and extrinsic factors. Varying the binder content will obviously have effects on the microstructure of the concrete mixture, but these effects cannot be deemed as beneficial or detrimental without analysing other parameters affected by the change in binder content (Dawneerangen, 2011). Furthermore, varying the binder content will have no direct effects whatsoever on the extrinsic factors affecting durability such as curing and compaction, but rather it is these extrinsic factors which might cause a more prominent effect on the concrete due to a change in binder content. Hence one starts to question the association that numerous professionals make between high binder contents and high durability (Evans, 2011).

The main trend identified in the industry research is that despite the growth in use of the Durability Index Approach in South Africa, there is still an insufficient understanding of concrete durability in industry. The Durability Index Approach enables the characterisation of concrete quality through the quantification of parameters obtained from the measurement of transport-related properties. Durability is a concept which captures material potential, construction quality and environmental exposure. The impact of mix design parameters such as binder content can only be categorised under material potential and its minimum content specification cannot simply and solely determine durability. The following sections in this Chapter discuss two case studies, in Cape Town and Johannesburg, South Africa. They were chosen because they represent two of the most crucial exposure environments associated with chloride-induced corrosion (coastal environment in Cape Town) and carbonation-induced corrosion (inland environment in Johannesburg). Each case study is discussed and analysed with the objective of determining the role that prescriptive specifications play in current practices in producing effective, economical and sustainable concretes.

3.4 Case Study 1: Cape Town Harbour Extension

A section of the Industrial harbour in Cape Town was commissioned for an extension by the local Ports Authority. The project involved the enlargement of about 10 m width of numerous quays in the harbour towards the waterline.

Figure 36: Cape Town Harbour Extension – fixing of steel prior to casting of in-situ concrete

All the structural in-situ concrete was provided by the same ready-mix supplier from a temporary on-site concrete plant so as to facilitate the transport of concrete to the site when needed. Given the nature of the exposure conditions, the need for assurance of durability and the selection and proportioning of constituent materials were deemed of paramount importance. The mix design specifications were the following:

- Minimum binder content of 420 kg/m^3, consisting of a 50/50 CEM I 42.5 N: Blastfurnace Slag blend.
- Minimum cementitious materials to water ratio of 2.5, corresponding to a maximum w/b ratio of 0.40.
- Characteristic concrete strength of 45 MPa.
- Slump of approximately 150 mm, with tolerances of ± 30 mm.
- Minimum cover of 40 mm.

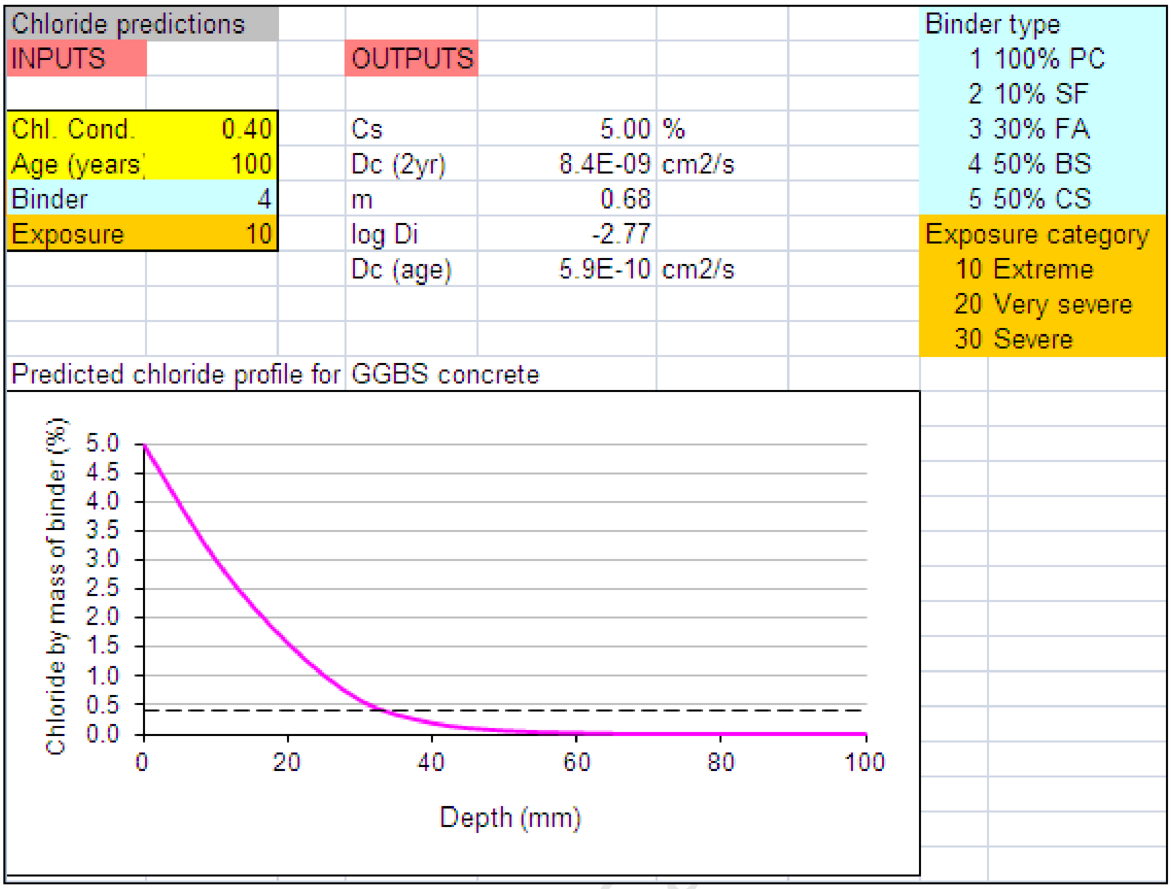
These specifications closely follow the prescriptive-type identified in modern codes and standards. The specified binder type, quantity and combination of binders, as well as the maximum w/b ratio, were justified by “purposes of durability assurance”. Some concerns arose from reviewing these specifications:

- There is a lack of any type of instructions stipulating the investigation of the durability of the structure at any other age (checking during and after project completion through DI testing or cover measurements). When it was confirmed by the ready-mix supplier that no requests dealing with such tests were made by any of the parties involved, this concern was further confirmed.
- The minimum binder content specified exceeds the value recommended for the specific environmental exposure class (360 kg/m^3 - see BS EN 206 Part 1). Since there is no maximum binder content imposed, this could potentially result in the binder content used in other similar projects being in excess of 450 – 500 kg/m^3.
- Strictly adhering to the specified binder content and w/b ratio, the specified slump ranges cannot be met without the use of higher-range water reducing admixtures such as superplasticisers. In this case, the amount of superplasticiser needed to achieve such high workability would also be extremely high, resulting in cost implications.
- The cover used for the project (40 mm) is insufficient for the specific exposure class and should be higher (approximately 50 mm). It is more effective to provide sufficient cover to achieve desired durability rather than solely considering cement contents. This shows a reduced understanding of durability.

Through an interview process with the ready-mix concrete supplier and through the use of current Service Life Prediction Models (SLPM), an analysis of the given case study was carried out. The aim was to investigate the issue of minimum binder content requirements as an effective criterion for durability. Since the project was located in a marine environment, the durability parameter used for the purpose of this analysis was chloride ingress.

- The SLPM estimated the chloride profile (critical chloride concentration depth, expressed as a percentage of binder mass) of the concrete as a function of the cover to the reinforcement.
- To achieve this, the input required consisted of exposure conditions, binder type combination and desired service life. Chloride conductivity index, another required input parameter, was assumed from literature.
- The SLPM thus used various input parameters to relate the chloride conductivity index to the ingress of chlorides into the concrete.

Results for typical South African concretes are displayed in Figure 5 in the Literature Review Chapter, from which the chloride conductivity input parameter was selected for this exercise. A chloride conductivity value of 0.40 was selected for a 50:50 CEM I: GGBS concrete of w/b ratio of 0.40 (BS in Figure 5). This was done because the w/b ratio specified in the case study was identical. Hence it was possible to obtain the relevant input parameters for the SLPM depicted in Figure 37.



Chloride predictions

INPUTS		OUTPUTS			Binder type
					1 100% PC
					2 10% SF
Chl. Cond.	0.40	Cs	5.00	%	3 30% FA
Age (years	100	Dc (2yr)	8.4E-09	cm2/s	4 50% BS
Binder	4	m	0.68		5 50% CS
Exposure	10	log Di	-2.77		Exposure category
		Dc (age)	5.9E-10	cm2/s	10 Extreme
					20 Very severe
					30 Severe

Predicted chloride profile for GGBS concrete

Figure 37: Durability prediction model – chloride ingress (model developed by the Concrete Materials and Structural Integrity Research Unit, UCT)

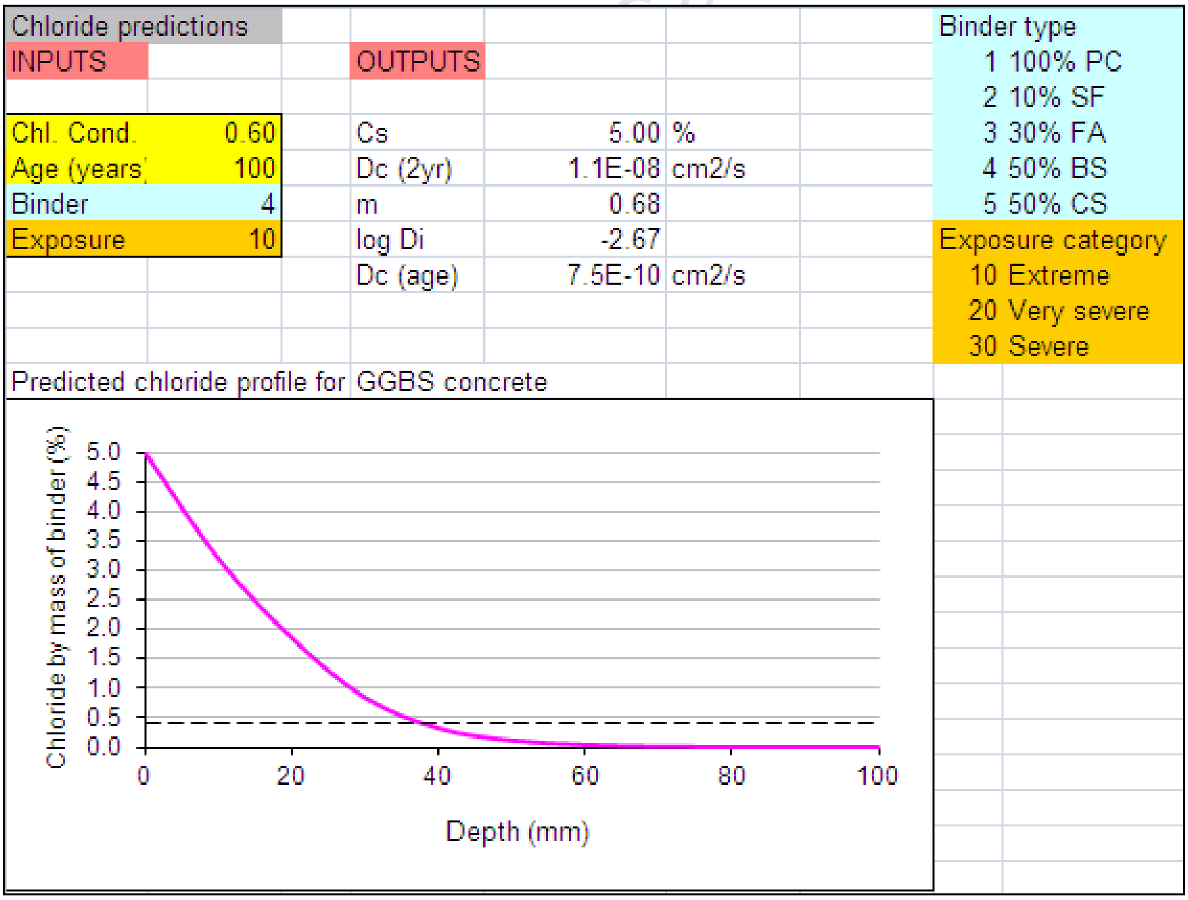
These parameters were the following:

- Chloride Conductivity Index – 0.40 from Figure 37.
- Design Service Life – 100 years (assumed for a marine structure).
- Binder Type Combination – 50:50 CEM I:GGBS.
- Exposure Category – marine structure, extreme.

A comparison was also made between the characteristic concrete strength and the actual strength achieved. With characteristic strength being specified as 45 MPa, the actual obtained strengths were 50 MPa at 7 days and 60 MPa at 28 days. Thus characteristic strength was exceeded by quite a significant margin of 25% at 28 days, clearly showing an overdesign with regard to compressive strength.

The resulting chloride profile showed that for the specified parameters the critical concentration of chlorides was found to be at a depth smaller than the minimum cover of 40 mm. Thus after 100 years of service life, the chlorides in the vicinity of the reinforcement have not yet reached a critical level i.e. there is still a reserve life and the concrete is also overdesigned in this respect. When interviewed about what parameters would have been suitable for the concrete to obtain its characteristic strength, the ready-mix supplier specified that a w/b ratio of about 0.48 would have been sufficient. If a constant water content is assumed (say 170 litres/m^3) for this higher w/b ratio, this results in a lower binder content of 354 kg/m^3. Interpolation between the two w/b ratios of 0.40 and 0.60 revealed a corresponding chloride conductivity value of about 0.60. For the same design life, binder type combination and exposure category, the resulting chloride profile is shown in Figure 38. Despite an increase in w/b ratio and a decrease in binder content, for the same service life the chlorides in the vicinity of the reinforcement have not reached a critical level yet. Thus using a higher binder content and a lower w/b ratio did not lead to any benefits with respect to the level of chloride ingress in the concrete.

It must be noted that the conductivity values used for this exercise (Figure 5 in Literature Review) are based on full water-curing concretes, something which does not commonly occur on site. In the Results Chapter of this thesis, it is later shown that a 50:50 CEM I 52.5 N: GGBS blend that was water cured for 3 days can obtain lower chloride conductivity values than 0.40 mS/cm at higher w/b ratios and lower binder contents. For this, it must be remembered that this exercise is purely aimed at identifying the malpractice of associating higher durability with higher binder content. This highlights the fact that, despite the wide use of the DI Approach in South Africa, durability is still not clearly understood in industry. The result is a continuous misuse of prescriptive specifications by professionals, mistakenly relying on parameters like binder content as sole and isolated determining factors of durability. Concretes produced in this way are potentially overdesigned for strength, leading to implications of high heats of hydration, thermal cracking etc. Furthermore, such concretes can also lead to a waste of materials (cement) and thus be unpractical, expensive, and unsustainable.



Chloride predictions					Binder type
INPUTS		OUTPUTS			1 100% PC
					2 10% SF
Chl. Cond.	0.60	Cs	5.00	%	3 30% FA
Age (years	100	Dc (2yr)	1.1E-08	cm2/s	4 50% BS
Binder	4	m	0.68		5 50% CS
Exposure	10	log Di	-2.67		Exposure category
		Dc (age)	7.5E-10	cm2/s	10 Extreme
					20 Very severe
					30 Severe

Predicted chloride profile for GGBS concrete

Figure 38: Durability prediction model – chloride ingress (model developed by the Concrete Materials and Structural Integrity Research Unit, UCT)

3.5 Case Study 2: The Gauteng Freeway Improvement Project

The Gauteng Freeway Improvement Project (GFIP) was initiated in 2007 by SANRAL and involved the improvement of 560 km of roads, with the first phase consisting of 185 km of road network. The project consisted in the expansion of the current road network by adding lanes in each direction, construction of interchanges and construction of precast median barriers. The purpose of this case study was to identify what type of specifications were used for the design of the concrete mixes used in the project and the resulting effects on strength and durability properties of the concretes.

In the project, SANRAL implemented durability index-based performance methods for quality control by using measures of strength, durability indices and concrete cover. The durability indices that are reported here consist of OPI only because the project was located inland and as such is much more susceptible to carbonation-induced corrosion, to which OPI values can be linked. Tables 9 and 10 summarise the mix design parameters for the concretes used in the project.

Table 7: Summary of the range of concrete mix properties from four plants of concrete ready-mix producer (Nganga. 2011)

Binder Content (kg/m^3)				Water Content (L/m^3)	w/b ratio
PC	Fly Ash	GGBS	Total		
383 - 403	68 - 71		451 - 474	184 - 208	0.41 – 0.44
360 - 373		90 - 93	450 - 466		0.44 – 0.45

Table 8: Summary of mix proportions of concrete used in production of precast elements (Nganga. 2011)

Mix Constituents	Proportion (kg/m^3)
Portland Cement	410
Fly Ash	176
Total Binder	586
Water (L/m^3)	220
w/b ratio	0.38

From Table 7 and 8 the following observations were made (Nganga. 2011):

- Low w/b ratios were used for both in-situ elements and precast elements. Reasons for this were that at low w/b ratios there is a reduction of voids in the cement paste, leading to lower penetrability of the concrete.
- SANRAL Project specifications assumed binder contents of up to 400 kg/m^3 to meet durability criteria. Adjustments in payment to the contractors were to be made when binder content ranged between 400 kg/m^3 and 450 kg/m^3, but when binder content exceeded 450 kg/m^3 no adjustments were to be made. Based on this, the binder

content used in both in-situ and precast elements was high, reaching as much as 474 kg/m^3 in in-situ elements and 586 kg/m^3 in precast elements.

Oxygen permeability index test results obtained from Nganga's work for different phases of the GFIP are summarised in Table 9.

Table 9: Summary of ranges of DI values of concrete mixes used in GFIP (Nganga. 2011)

Project Phase ID	Mean OPI (log scale)	Max OPI (log scale)	Min OPI (log scale)
1 (in-situ)	9.75	10.41	9.07
2 (in-situ)	9.91	10.42	9.37
4 (in-situ)	9.87	10.40	9.39
6 (in-situ)	10.06	11.10	8.83
9 (Precast)	10.25	10.70	9.85

Project specifications used by SANRAL for this project are extracted from Beushausen and Alexander (2009) and given as Table 5 in Section 3.3 of this chapter. It can be seen by comparing values given in Table 9 to those provided in project specifications (Table 5) that many of concretes achieved OPI values in the range of conditional acceptance (8.75 – 9.70). However it is also noted that most of the in-situ OPI results were much higher than the full acceptance value of 9.70, with OPI values reaching as much as 11.10. Since OPI is a log scale value of the permeability coefficient, this is a significant difference.

Table 10: Summary statistics of strength values (Nganga. 2011)

Project Phase ID	Sample Size	Strength (MPa)			
		Specified	Mean	Max	Min
4	79	30	37.9	48.8	25.0
	23	40	43.5	49.2	39.9
6	22	30	48.2	61.4	37.3
	45	40	56.1	71.5	42.8
	19	60	79.0	84.6	69.2
9	136	30	49.4	77.0	30.0

Strength results are also summarised for different project phases in Table 10. It can be seen that for the majority of concretes, the mean strength value exceeded the specified value, resulting in higher achieved strengths than actually needed. Of course this is what is actually needed, since the characteristic strength of a concrete implies that only 5% of the obtained values fall below the specified value. What is interesting to note is the margin by which the specified values and the obtained values differ. At times the maximum strength achieved on selected samples highly exceeded the specified value, with as much as 77 MPa having been achieved for a 30 MPa concrete. The minimum values were not as significantly different to the specified characteristic values.

The mix design data presented in Table 7 and 8 showed that concretes were designed for this project with high binder contents, both for the in-situ and precast components. Based on the tendering process used by SANRAL, the range of high binder contents used resulted in the contractors and precast manufacturers being directly responsible for a portion of the costs of cement (from 24 kg/m^3 to136 kg/m^3) all for fear of “failing durability requirements”. What resulted is that most of the concretes achieved extremely high values of both strength and OPI. Despite some of the concretes having failed to meet full acceptance requirements for OPI and achieving lower strengths than specified, what is identified in this case study is a trend of overdesign. High binder contents and low w/b ratios resulted in unnecessary levels of strength and OPI values. These in turn may have jeopardised durability due to the higher possibility of high heat of hydration and thermal effects associated with low w/b ratios and high binder contents.

3.6 Brief Discussion of Case Studies

A comparison of both case studies further emphasises that the roles that prescriptive parameters like minimum binder content and maximum w/b ratio play are not isolated, but rather that they need to be considered with other factors as well as the effect that such factors have on concrete microstructure. In both case studies, binder contents much higher than the minimum recommended values in BS EN 206 were specified. This, it was believed, was done for purposes of enhancing durability. Results were however indicative of overdesigns with respect to both strength and durability for both. In Case Study 1, chloride ingress levels were obtained which could have equally been achieved by increasing the w/b ratio through a reduction in binder content (this was shown by the exercise conducted with the Service Life Prediction Model, as well as later, in the chapter which discusses the results). In Case Study 2, the use of high binder contents and low w/b ratios resulted in overdesign with respect to both OPI values and compressive strength, all hailing from an inappropriate implementation of the DI Approach. This emphasises the importance of conducting a thorough study that investigates durability as a function of a framework of mix design parameters (w/b ratio, binder type and binder content), mechanical properties (compressive strength) and extrinsic factors (site practices). This would ideally lead to a more thorough and formalised use of the DI Approach that reflects a deeper appreciation of the crucial factors involved.

4. EXPERIMENTAL METHODOLOGY

4.1 Identifying Key Research Questions

The literature review compiled in this document identifies durability as being dependent on more than just binder content, with various intrinsic and extrinsic factors related to mix design parameters having a significant influence. Despite this, the evidence from industry suggests that binder content is regarded as the dominant determining parameter for durability properties of concrete, while other intrinsic mix design parameters (w/b ratio, binder type) and extrinsic factors (curing, compaction) are not given the consideration that literature has proven the need for. The principal aim of this research will therefore be to conduct a thorough study into the influence of mix design parameters and compressive strength on durability indices, incorporating a wide variety of parameters relevant to industry. In the second and third chapters it has been shown that there are a variety of parameters that influence durability indices and that there are certain trends in the selection of such parameters in industry for the mix design process. The choice of experimental parameters will thus be a key aspect for the relevance of the study to industry.

Binder content, w/b ratio and binder type are mix design parameters whose selection and combined functioning affect durability. Extrinsic factors such as compaction and curing regimes also play a significant role. The quantification of these parameters must be carried out in such a way so as to yield practical and feasible measures in industry. For example, fixing the range of binder contents as a control parameter can result in mixtures with impractical water contents, depending on w/b ratio (see Yiğiter et al. 2007). Selecting to limit water contents can result in a more practical range of binder contents for each w/b ratio and a scenario that more closely resembles industry. Also, the selection of binder types should be made in consideration of what is readily available in industry, keeping in mind factors such as cost, availability and optimum proportioning of materials. The choice of extrinsic parameters, such as curing and compaction, should also be aimed at resembling site practices and conditions as much as possible for relevance of the study to industry.

4.2 Selection of Experimental Parameters

The choice of experimental parameters was carried out once a thorough analysis of both literature and industry findings had been made. Three w/b ratios (0.40, 0.50 and 0.60) were selected to include mixes suitable for a variety of structural applications. For each w/b ratio, mixes with four different water contents were generated in order to vary the binder content in the mix. The objective was to encompass a range of water contents practical for industry use. Ranges of water contents as the identified in the investigations by Kolias et al. (2005), with values differing between 140 l/m^3 and 260 l/m^3 were not deemed feasible. Instead the range of water contents was limited to between 155 l/m^3 and 195 l/m^3 to reflect a currently more common industrial scenario while also allowing for some extreme cases at both ends, allowing trends to be more easily identified. Workability was catered for by the use of water-reducing admixtures where needed. Each experimental mix was then designed with three different binder combinations; namely a 100% CEM I 52.5 N control concrete, a binary blend of 70% CEM I and 30% Fly Ash and a binary blend of 50% CEM I and 50% GGBS. The current study represents the first time in which CEM I 52.5 N was used extensively, as the previously used CEM I 42.5 N was no longer available in the Western Cape. These extenders and replacement levels were also chosen in order to reflect as close a trend to industry as possible. CSF was not selected as its use in industry is restricted due to its high relative cost. Table 11 summarises the experimental mix design parameters that were adopted in the investigation.

Table 11: Summary of experimental mix design parameters

Water/Binder Ratio	Binder Content (kg/m^3)	Water Content (L/m^3)
0.40	388	155
	420	168
	455	182
	488	195
0.50	310	155
	336	168
	364	182
	390	195
0.60	258	155
	280	168
	303	182
	325	195

Specimens from each experimental mixture were exposed to two different curing regimes. The first was moist curing, which involved the placing of the specimens in water at approximately 20°C one day after casting, immediately after stripping. The second was laboratory curing, where the specimens were stripped the day after casting, placed in the same moist conditions as described above for 3 days, then removed from the curing tanks and exposed to controlled exposure conditions of approximately 20°C and 50% Relative Humidity. The 3-day moist curing period (labelled as lab curing in the results chapter) was selected to closely resemble curing practices commonly adopted in typical site conditions (Ballim et al, 1993).

The properties tested consisted of compressive strength at three ages, namely 7, 28 and 90 days. Durability Index Tests were also carried out at different ages. Water sorptivity tests were conducted on the samples at 28 days, while oxygen permeability and chloride conductivity tests were carried out at 56 days. The two latter indices were tested at a later age so as to allow the concrete properties to develop sufficiently to emphasise to a larger extent the differences in results owing to paste volumes, binder types and curing regimes.

This was done for permeability and conductivity only as these indices are of particular importance in existing prediction and assessment models.

4.3 Mix Designs

Experimental mixes were designed in accordance with the C&CI Method (Addis et al, 2009) with the exception that target strength was not used as a criterion for selection of constituent materials and proportions. Rather w/b ratio and water content were used to obtain a practical range of binder contents. Quantities were determined on the basis of volume calculations in m^3 using relative densities of the constituent materials. The following procedure was used:

- The three w/b ratios were each assigned four water contents, and thus four binder contents.
- Binder masses were then converted to volumes using their relative densities.
- The stone content was calculated based on the Compacted Bulk Density (CBD) of the coarse aggregate and the Fineness Modulus (FM) of the sand, as specified in the C&CI Method.
- Having obtained the required volume of stone, binder and water, the sand content was determined by subtracting the total of the said constituents from a fixed volume of 1000 litres (one cubic metre), thus obtaining the constituent proportions for a 1000 litre mix.

Properties of the aggregates and binders used in the experimental phase, as well as the mix design quantities for all experimental mixes, are provided in Figures 39 – 41 and Tables 12 – 15.

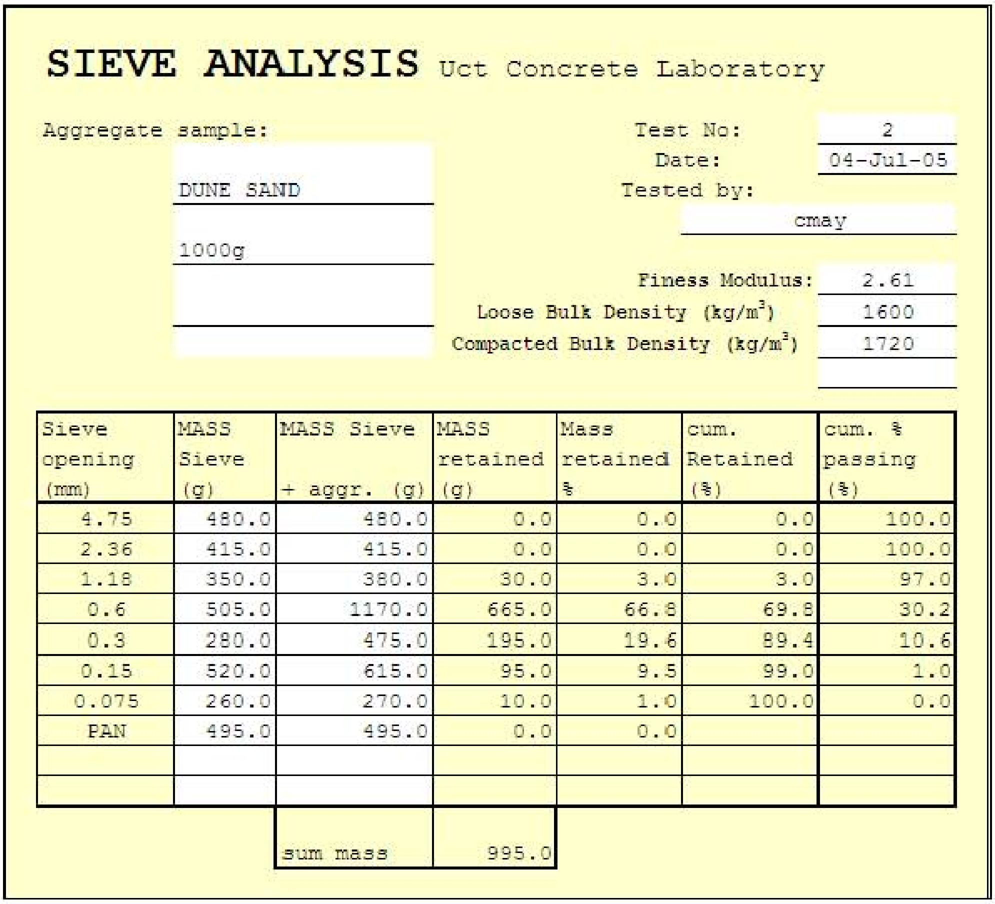
4.3.1 Aggregate Properties

The aggregates used were 19 mm greywacke stone and a 50/50 blend of unwashed crusher sand and Philippi Dune Sand so as to provide a combination of aggregates that result in a mixture with adequate particle grading. Testing of aggregate properties was discussed prior to experimental procedure but not deemed necessary, hence properties were not tested. Data for the aggregates used is presented in Figures 39-41. A few comments were made:

- Dune sand was analysed in July 2005 and is unlikely to have a Fineness Modulus of 2.61. The high value could be due to excess sand sample used in sieve test.
- No information regarding loose bulk density of unwashed crusher sand was obtained, which could have been useful in terms of packing properties.
- Only 19mm Greywacke was used, in compliance with standard laboratory practices of CoMSIRU.
- Testing of the extenders was also deemed to be outside of the scope of works and typical chemical compositions were therefore provided.

4.3.2 Binder Properties

The binders used were CEM I 52.5 N, supplied by PPC Cement; Fly Ash, supplied by Ash Resources as Durapozz; and Ground Granulated Blastfurnace Slag, supplied by Afrisam as Slagment. A breakdown of chemical properties of each binder is given in Tables 12 – 14, while Table 15 provides a summary of typical Blaine Surface Area or Specific Surface Area (SSA) values for the different binders used in the experimental study. The SSA value provided by PPC for CEM I 52.5 N was 346 m^2/kg. This coincides with the range presented in the table, which was compiled for CEM I 42.5 N. It must be noted, however, that sieve analysis for the CEM I 52.5 N cement resulted in 60% of particles passing through the 25 micron sieve, making this cement quite fine.



SIEVE ANALYSIS Uct Concrete Laboratory

Aggregate sample: DUNE SAND

1000g

Test No: 2

Date: 04-Jul-05

Tested by: cmay

Finess Modulus: 2.61

Loose Bulk Density (kg/m^3) 1600

Compacted Bulk Density (kg/m^3) 1720

Sieve opening (mm)	MASS Sieve (g)	MASS Sieve + aggr. (g)	MASS retained (g)	Mass retained %	cum. Retained (%)	cum. % passing (%)
4.75	480.0	480.0	0.0	0.0	0.0	100.0
2.36	415.0	415.0	0.0	0.0	0.0	100.0
1.18	350.0	380.0	30.0	3.0	3.0	97.0
0.6	505.0	1170.0	665.0	66.8	69.8	30.2
0.3	280.0	475.0	195.0	19.6	89.4	10.6
0.15	520.0	615.0	95.0	9.5	99.0	1.0
0.075	260.0	270.0	10.0	1.0	100.0	0.0
PAN	495.0	495.0	0.0	0.0		
		sum mass	995.0			

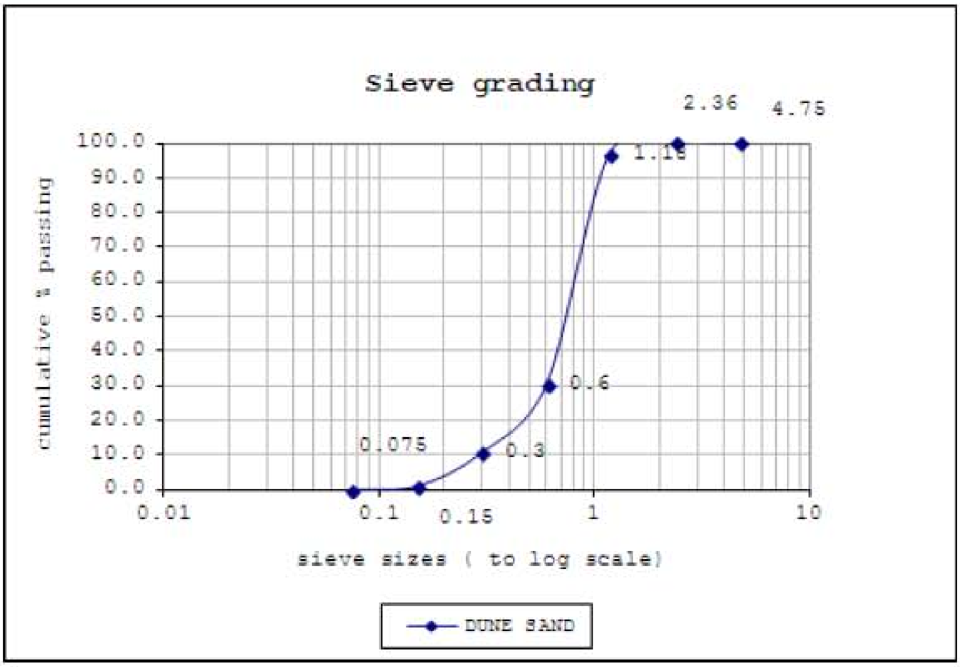
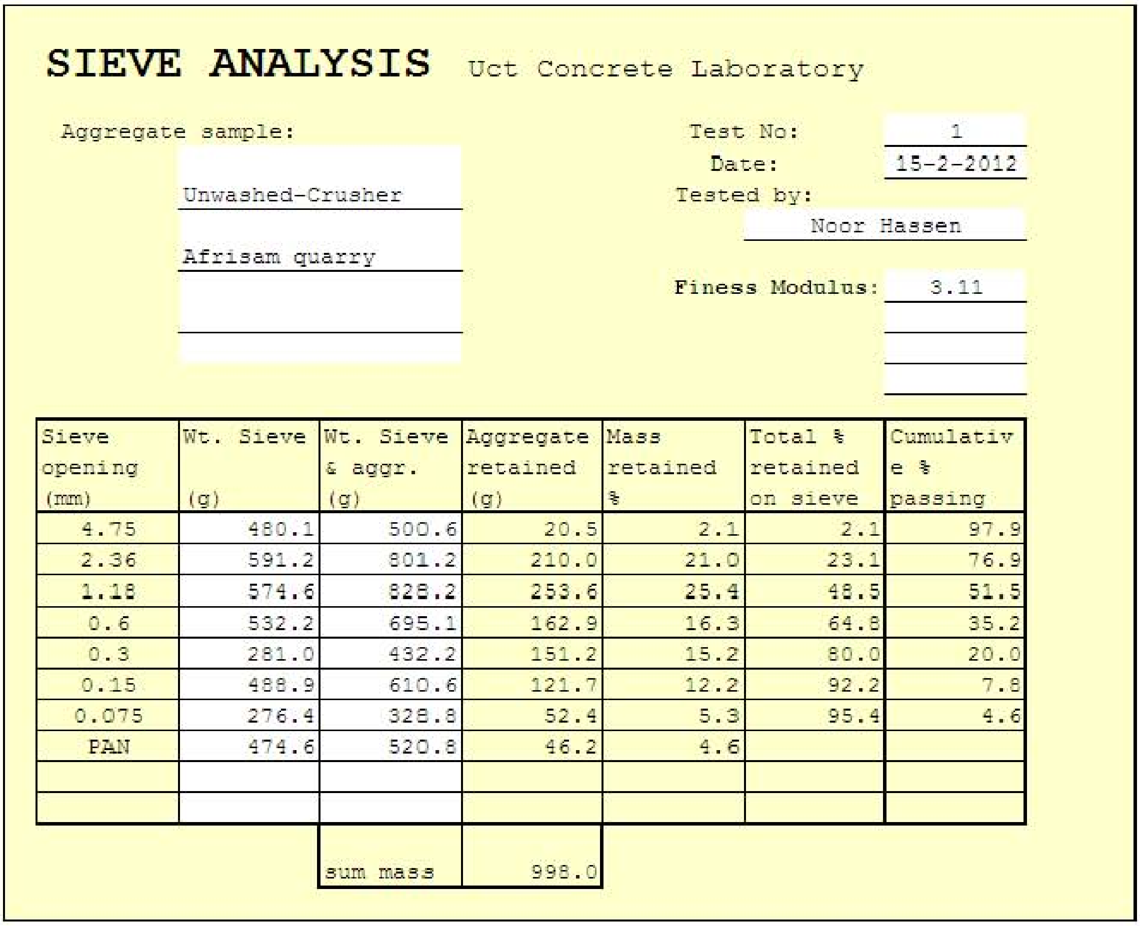


Figure 39: Sieve analysis and grading curve for dune sand



SIEVE ANALYSIS Uct Concrete Laboratory

Aggregate sample:
Unwashed-Crusher
Afrisam quarry

Test No: 1
Date: 15-2-2012
Tested by: Noor Hassen

Finess Modulus: 3.11

Sieve opening (mm)	Wt. Sieve (g)	Wt. Sieve & aggr. (g)	Aggregate retained (g)	Mass retained %	Total % retained on sieve	Cumulative % passing
4.75	480.1	500.6	20.5	2.1	2.1	97.9
2.36	591.2	801.2	210.0	21.0	23.1	76.9
1.18	574.6	828.2	253.6	25.4	48.5	51.5
0.6	532.2	695.1	162.9	16.3	64.8	35.2
0.3	281.0	432.2	151.2	15.2	80.0	20.0
0.15	488.9	610.6	121.7	12.2	92.2	7.8
0.075	276.4	328.8	52.4	5.3	95.4	4.6
PAN	474.6	520.8	46.2	4.6		
		sum mass	998.0			

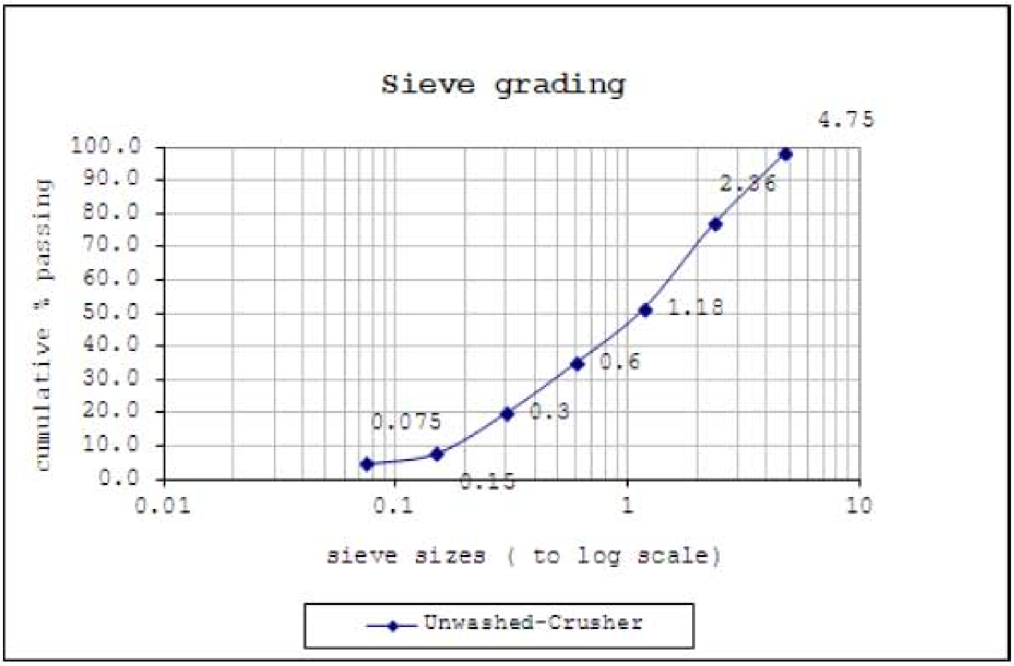
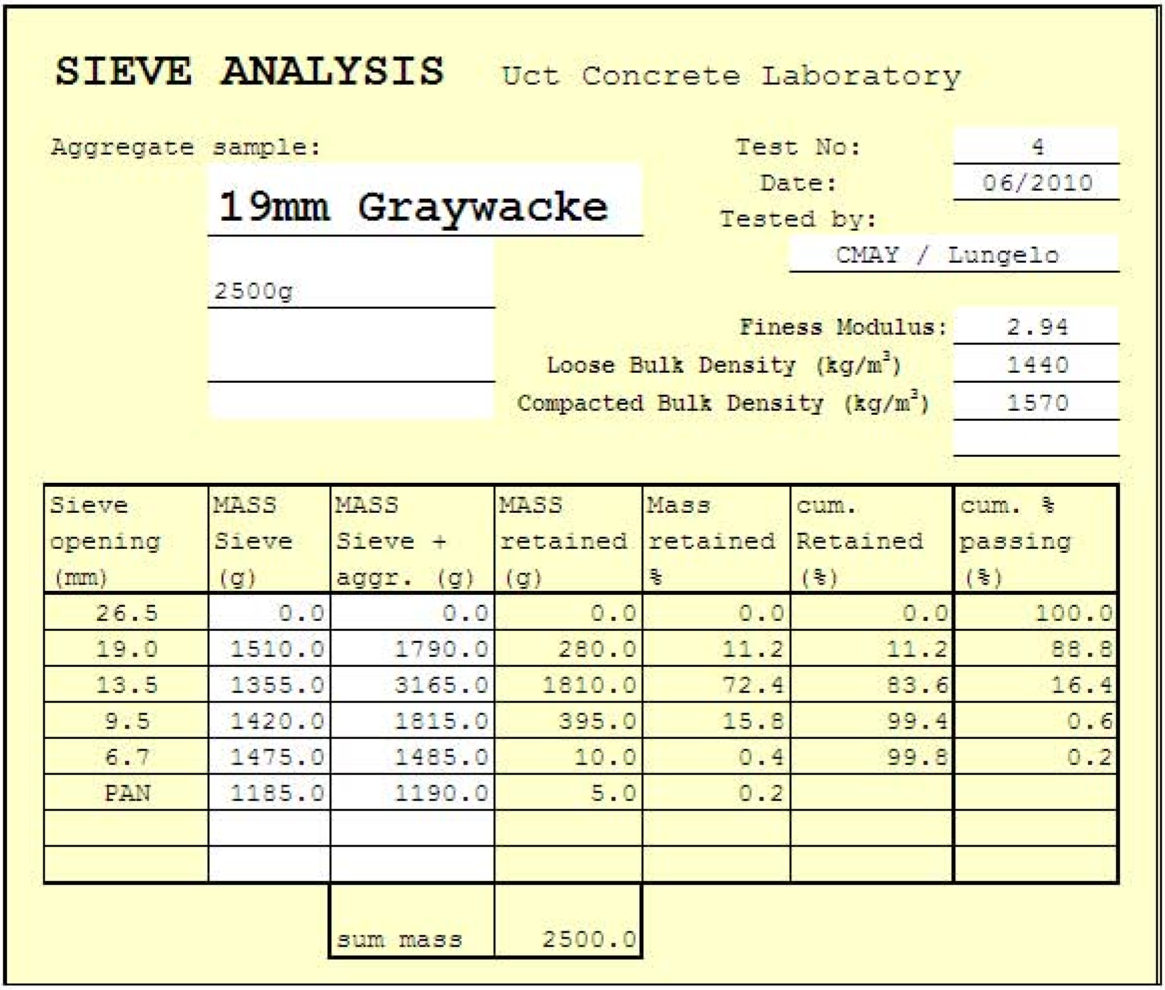


Figure 40: Sieve analysis and grading curve for unwashed crusher sand



SIEVE ANALYSIS Uct Concrete Laboratory

Aggregate sample:

19mm Graywacke

2500g

Test No: 4

Date: 06/2010

Tested by: CMAY / Lungelo

Finess Modulus: 2.94

Loose Bulk Density (kg/m^3) 1440

Compacted Bulk Density (kg/m^3) 1570

Sieve opening (mm)	MASS Sieve (g)	MASS Sieve + aggr. (g)	MASS retained (g)	Mass retained %	cum. Retained (%)	cum. % passing (%)
26.5	0.0	0.0	0.0	0.0	0.0	100.0
19.0	1510.0	1790.0	280.0	11.2	11.2	88.8
13.5	1355.0	3165.0	1810.0	72.4	83.6	16.4
9.5	1420.0	1815.0	395.0	15.8	99.4	0.6
6.7	1475.0	1485.0	10.0	0.4	99.8	0.2
PAN	1185.0	1190.0	5.0	0.2		
		sum mass	2500.0			

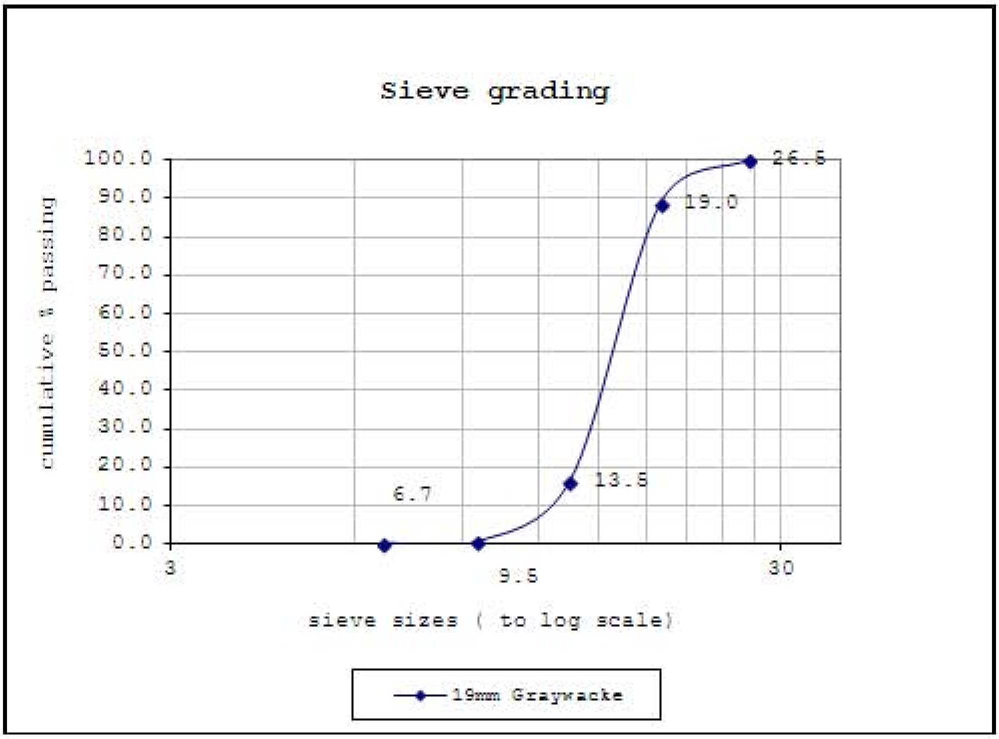


Figure 41: Sieve analysis and grading curve for 19 mm Greywacke stone

Table 12: Chemical composition of CEM I 52.5 N (courtesy of PPC)

Oxide	**% by mass of cement**
SiO_2	21.1
Al_2O_3	4.0
Fe_2O_3	3.35
CaO	65.8
MgO	0.87
SO_3	2.3
K_2O	0.7
Na_2O	0.1
Limestone	4.4 (86.9 % $CaCO_3$)
Bogue Analysis	**% by mass of clinker**
Free Lime (CaO)	1.33
C_3S	61.61
C_2S	17.22
C_3A	6.77
C_4AF	10.63

Table 13: Typical chemical composition of South African Fly Ash (Grieve, 2009)

Oxide	**% by mass of Fly Ash**
SiO_2	48 - 55
Al_2O_3	28 - 34
CaO	4 - 7
Fe_2O_3	2 - 4
MgO	1 - 2
$Na_2O + 0.658\ K_2O$	1 - 2

Table 14: Typical chemical composition of South African GGBS (Grieve, 2009)

Oxide	% by mass in GGBS
SiO_2	34 - 40
Al_2O_3	11 - 16
CaO	32 - 37
FeO	0.3 – 0.6
MgO	10 - 13
K_2O	0.8 – 1.3
MnO	0.7 – 1.2
S	1.0 – 1.7
TiO_2	0.7 – 1.4

Table 15: Specific surface area of cementitious materials (Grieve, 2009; Newman & Choo, 2003; Megat Johari et al, 2011)

Binder Type	SSA (m^2/kg)
OPC Portland Cement (CEM I 52.5 N)	0.346
Fly Ash (FA)	0.25-0.38
Ground Granulated Blastfurnace Slag (GGBS)	0.42-0.45

4.3.3 Mix Proportioning

Mix proportioning was used in accordance with the C & CI method. Target strength values were, however, not selected initially, but w/b ratios were fixed and water contents were limited to obtain a practical range of binder contents. Mix proportions are summarised in Tables 16 – 18.

Slump was not identified as a primary parameter for the investigation, hence slump results were not reported in the Results and Discussion Chapter. It is understood that the experimental mixes of different compositions would have had a significant effect on concrete microstructure. However for the purposes of this work it was deemed sufficient prior to commencement of experimental work that the experimental concretes all lie within a target range of 100 mm +/- 15 mm, a range which was satisfied for all experimental mixes.

4.4 Experimental Plan

Three w/b ratios of four water contents each resulted in 12 mixes per binder type, thus a total of 36 experimental mixes. The samples tested consisted solely of 100 mm x 100 mm x 100 mm concrete cube specimens (1 litre concrete cubes). The range of parameters selected for the study required a specific number of samples per mixture. The samples were left in their respective exposure environments until needed for the various testing procedures. All the testing procedures were carried out in accordance with their relevant SANS standard. A brief breakdown of each testing procedure is given in the following sub-sections.

Table 16: Mix proportioning for Portland cement mixes

100% CEM I 52.5 N					
Relative Densities	3.14		1	2.7	2.6
w/b ratio	CEM (kg/m^3)	Alternative Binder	WATER (L/m^3)	Stone (kg/m^3)	Sand (kg/m^3)
0.4	388	N/A	155	1100	817
	420		168	1100	756
	455		182	1100	691
	488		195	1100	630
0.5	310		155	1100	881
	336		168	1100	825
	364		182	1100	766
	390		195	1100	711
0.6	258		155	1100	924
	280		168	1100	872
	303		182	1100	816
	325		195	1100	764

Table 17: Mix proportioning for Fly Ash mixes

30% Fly Ash					
Relative Densities	3.14	2.3	1	2.7	2.6
w/b ratio	CEM (kg/m^3)	Fly Ash (kg/m^3)	WATER (L/m^3)	Stone (kg/m^3)	Sand (kg/m^3)
0.4	271	116	155	1100	781
	294	126	168	1100	718
	319	137	182	1100	649
	341	146	195	1100	586
0.5	217	93	155	1100	853
	235	101	168	1100	795
	255	109	182	1100	733
	273	117	195	1100	675
0.6	181	78	155	1100	900
	196	84	168	1100	846
	212	91	182	1100	789
	228	98	195	1100	735

Table 18: Mix proportioning for GGBS mixes

50% GGBS					
Relative Densities	3.14	2.9	1	2.7	2.6
w/b ratio	CEM (kg/m^3)	GGBS (kg/m^3)	WATER (L/m^3)	Stone (kg/m^3)	Sand (kg/m^3)
0.4	194	194	155	1100	803
	210	210	168	1100	742
	228	228	182	1100	675
	244	244	195	1100	613
0.5	155	155	155	1100	870
	168	168	168	1100	814
	182	182	182	1100	753
	195	195	195	1100	697
0.6	129	129	155	1100	915
	140	140	168	1100	862
	152	152	182	1100	806
	163	163	195	1100	753

4.4.1 Compressive Strength Tests

At the ages of 7 days, 28 days and 90 days, three samples per mix were removed from their exposure environment. The cubes were weighed to check whether the density of the concrete was within an acceptable range and then crushed until failure using an Amsler Compression Machine. The loading rate used for this test was manually maintained at 0.4 MPa per second (15 MPa per minute). Three samples per mixture were tested and the mean of the three results was taken as the strength of that particular concrete at a given age.

4.4.2 Durability Index Tests

At 28 and 56 days, two samples from each mix were removed from the two curing regimes and cored to obtain cylinders of about 70 mm diameter. Figure 42 shows the coring procedure.

Figure 42: Concrete cube specimen ready to be core-drilled

The first 5 mm of both sides of each cylinder were then discarded before each cylinder was cut into two circular disc-shaped specimen of thickness 30 mm ca. This is depicted in Figure 43. The samples were then placed in an oven at 50° C for a period of 7 days ± 4 hours for conditioning before conducting the durability index tests. Preparation, conditioning and testing procedures were carried out in accordance with the Durability Index Testing Manual (Alexander et al, 2010) and are described in Appendix A.

Figure 43: Each core obtained from the cube samples is cut into two disc-shaped specimens

5. RESULTS AND DISCUSSION

5.1 Introduction and Summary of Results

Table 19: Summary of experimental results for CEM I concretes

w/b ratio	Binder content (kg/m^3)	Oxygen Permeability Index (log)		Water Sorptivity (mm/√hr)		Chloride Conductivity (mS/cm)		Compressive Strength (MPa)		
		water cured	lab cured	water cured	lab cured	water cured	lab cured	7 d	28 d	90 d
0.40	388	10.71	10.16	5.3	6.7	0.63	0.79	56	61	69
	420	10.41	10.04	5.7	8.9	0.70	0.87	56	60	69
	455	10.49	10.02	7.3	9.3	0.81	0.89	57	63	67
	488	10.25	9.82	8.8	9.9	0.95	0.92	49	57	67
0.50	310	10.67	10.41	6.2	8.1	0.74	0.92	44	50	52
	336	10.52	10.13	7.0	9.1	0.90	1.07	46	52	58
	364	10.26	9.99	7.9	10.4	0.97	1.06	44	51	56
	390	10.44	9.89	9.8	10.5	1.07	1.07	44	50	55
0.60	258	10.83	10.47	10.2	12.7	0.94	1.05	42	45	51
	280	10.51	10.04	12.8	11.4	1.19	1.09	37	42	44
	303	10.49	9.96	13.9	9.1	1.40	1.33	39	42	45
	325	10.25	9.77	12.3	12.2	1.43	1.51	35	42	45

In this chapter, relationships between durability indices and binder content, w/b ratio, curing regimes and compressive strength are investigated and discussed. The objective is to identify whether increases in binder content bring about improvements in both strength and durability properties. Experimental results are summarised in Tables 19 – 21.

Since strength is the parameter that is most commonly used in industry to describe concrete quality, the chapter begins by investigating the influence of binder content on compressive strength. Thereafter, it investigates the influence of compressive strength on durability indices to identify whether a meaningful relationship between the two exists. The chapter then investigates the influence of binder content on durability index parameters. This is done by analysing binder content as a primary variable for selected w/b ratios and binder types for all experimental concretes. The aim of this analysis is to identify the trends of durability index parameters with respect to changes in such parameters.

Table 20: Summary of experimental results for Fly Ash concretes

w/b ratio	**Binder content (kg/m^3)**	**Oxygen Permeability Index (log)**		**Water Sorptivity (mm/√hr)**		**Chloride Conductivity (mS/cm)**		**Compressive Strength (MPa)**		
		water cured	**lab cured**	**water cured**	**lab cured**	**water cured**	**lab cured**	**7 d**	**28 d**	**90 d**
0.40	388	10.77	10.46	7.4	7.4	0.23	0.63	47	63	74
	420	10.79	10.22	6.5	8.7	0.24	0.61	46	62	72
	455	10.64	10.18	7.4	9.0	0.26	0.62	43	62	68
	488	10.84	10.38	9.6	11.6	0.26	0.72	41	60	67
0.50	310	10.94	10.32	7.5	8.2	0.28	0.78	36	53	63
	336	10.70	10.13	7.3	8.5	0.35	0.84	34	51	62
	364	10.71	10.03	7.6	10.1	0.45	1.08	33	47	59
	390	10.67	9.90	10.0	11.2	0.44	1.08	32	47	57
0.60	258	10.82	10.26	8.0	9.5	0.45	1.07	27	42	50
	280	10.50	10.05	7.2	8.3	0.52	1.11	28	42	51
	303	10.33	9.80	8.6	9.4	0.61	1.25	25	39	50
	325	10.15	9.45	9.7	10.4	0.72	1.41	21	37	48

A summary of the results obtained in the chapter provides a breakdown of the observed trends in tabular form. Trends are simplified and categorised into different degrees of positive, negative or negligible influence on DI values due to changes in mix design parameters. The aim of this section is to provide somewhat practical guidelines that can be used in real-life mix design scenarios. A section on the practical implications in mix design describes the trends observed in the discussions in a practically suitable way with reference to mix design choices for actual projects. The chapter then concludes by emphasising the malpractice of increasing binder content to enhance strength and durability with a comparative analysis between the experimental concretes and concretes designed by adhering to prescriptive specifications.

Table 21: Summary of experimental results for GGBS concretes

w/b ratio	**Binder content (kg/m^3)**	**Oxygen Permeability Index (log)**		**Water Sorptivity (mm/√hr)**		**Chloride Conductivity (mS/cm)**		**Compressive Strength (MPa)**		
		water cured	**lab cured**	**water cured**	**lab cured**	**water cured**	**lab cured**	**7 d**	**28 d**	**90 d**
0.40	388	10.23	10.21	8.4	6.7	0.17	0.21	53	63	68
	420	10.19	10.06	7.6	7.4	0.17	0.20	52	62	63
	455	10.11	9.96	8.8	8.5	0.19	0.25	48	59	62
	488	9.98	9.80	8.7	9.3	0.21	0.24	43	61	62
0.50	310	10.07	9.97	7.5	7.6	0.17	0.21	38	54	58
	336	10.01	10.01	7.5	7.9	0.19	0.27	36	50	54
	364	9.93	9.84	8.6	8.5	0.19	0.27	33	48	54
	390	9.87	9.61	7.7	9.1	0.22	0.36	31	46	52
0.60	258	9.99	9.94	7.9	8.5	0.23	0.37	30	44	51
	280	9.81	9.44	10.7	9.5	0.28	0.48	26	40	47
	303	9.78	9.35	10.5	11.3	0.23	0.44	23	36	44
	325	9.75	9.30	12.3	12.7	0.33	0.60	23	36	41

5.2 The Influence of Binder Content on Compressive Strength

The property that is most widely used in industry to characterise concrete quality is compressive strength, with the common procedure being to specify a characteristic value and to design a mix based on a specific target value. Interpretation of prescriptive specifications by numerous engineers leads to specification of higher binder contents than needed to seemingly enhance strength and, consequently, durability. Therefore in this section, the influence of binder content on compressive strength is investigated to try and identify whether a beneficial relationship between the two parameters exists.

Figure 44 displays compressive strength results obtained for Portland cement concrete with four different water contents shown on the legend corresponding to four different binder contents. Strength values were approximately close to each other and no identifiable trend was observed with respect to an increase in paste volume for a given w/b ratio. A clear trend was that w/b ratio had a much more prominent influence on strength development.

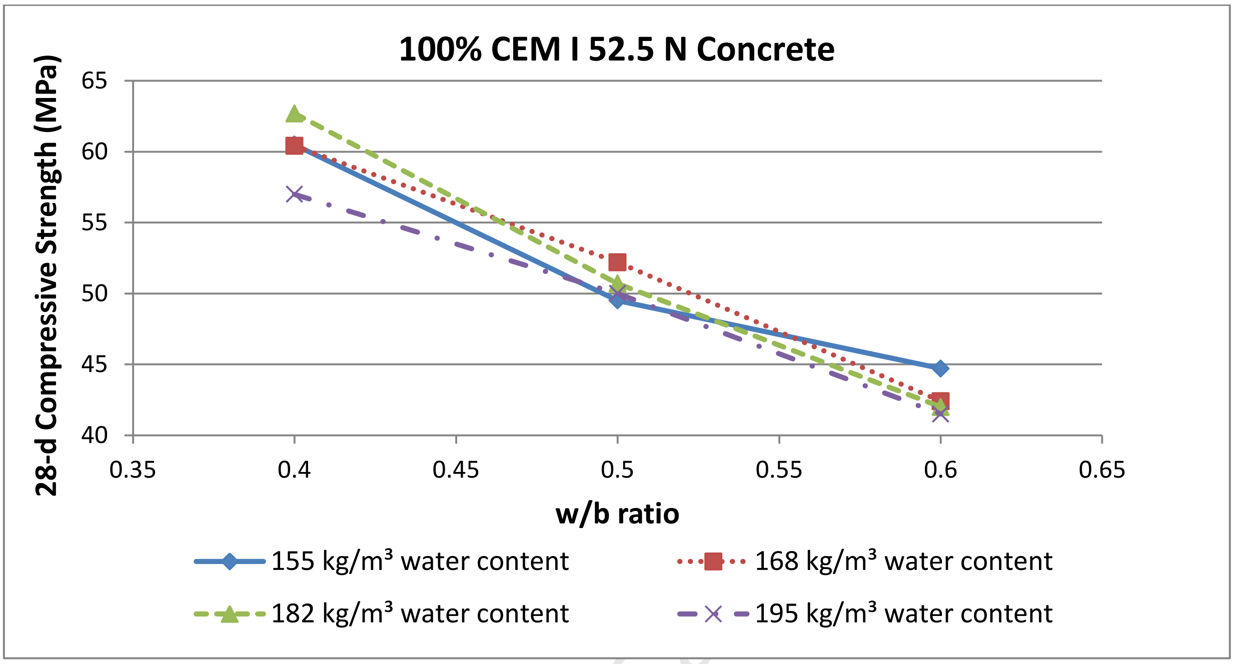


Figure 44: Influence of binder content on compressive strength of water cured CEM I 52.5 N samples

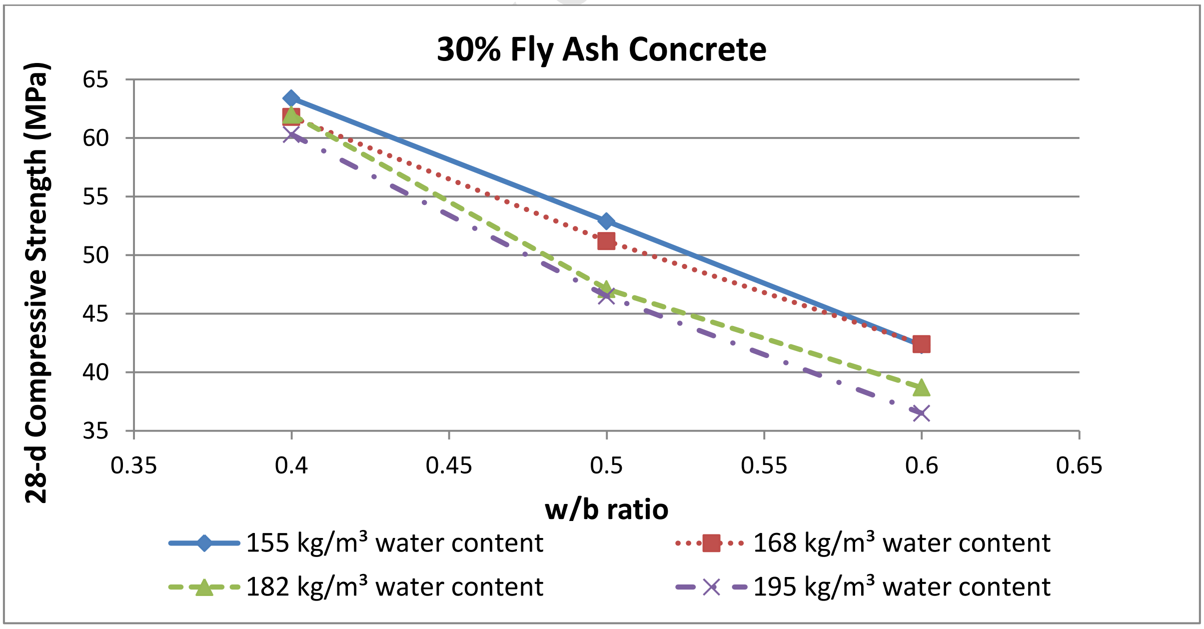


Figure 45: Influence of binder content on compressive strength of water cured Fly Ash samples

Results displayed in Figures 45 for blended fly ash concretes showed a more prominent influence of binder content on compressive strength. As the paste volume increased for a given w/b ratio, a clearer reduction in strength was observed. Furthermore, the difference in strength between different paste volumes became more noticeable as the w/b ratio increased. Similar observations were made for the blended slag concretes (Figure 46), where an increase in paste volume resulted in a strength reduction that was more significant at higher w/b ratios.

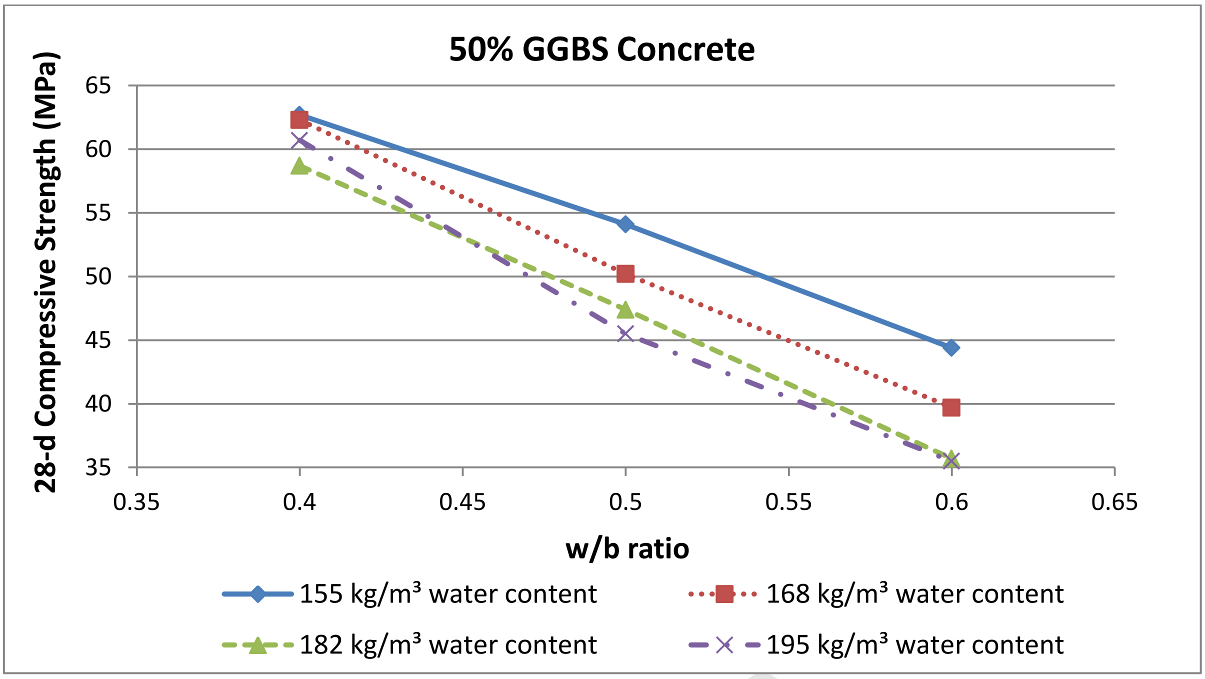


Figure 46: Influence of binder content on compressive strength of water cured GGBS concretes

An explanation behind the observed trends may be the following. For a fixed w/b ratio, as the water and binder contents are increased, more paste is produced. Thus the pore fraction in the microstructure increases. This essentially implies that crack development is facilitated along its propagation path. Figure 47 shows this concept. As the paste volume is increased (from left to right), there are more options for the crack to choose a path of least resistance along which to propagate. Hence at higher paste volumes, compressive strength was decreased.

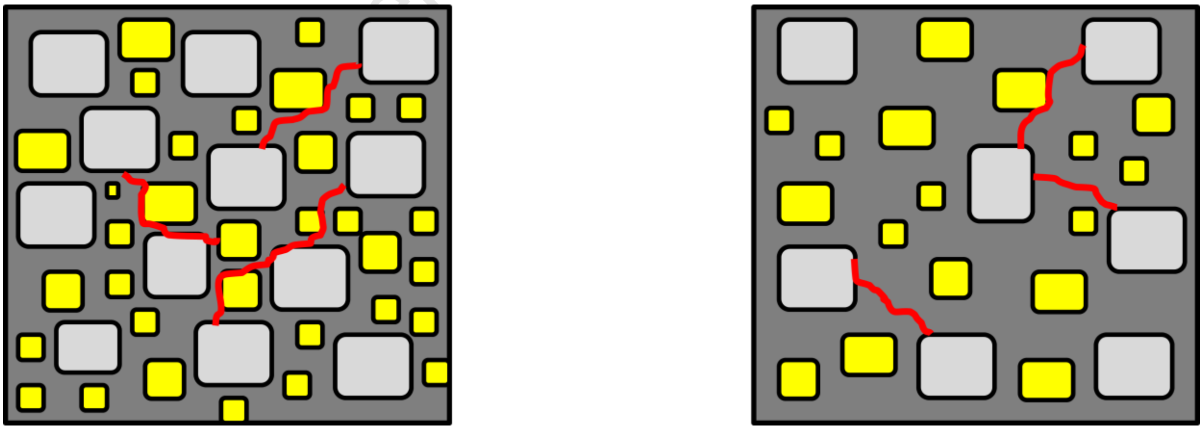


Figure 47: Representation of the effect of paste volume on crack propagation. At higher paste volumes, cracks develop along a larger portion of paste and are less hindered by aggregates.

This effect was more prominent in the higher w/b ratio concretes (0.60). This is because in concretes with low w/b ratio, a refining effect is imparted onto the microstructure due to the presence of unhydrated binder particles. These act as pore fillers and essentially refine the pore structure. As the paste volume increases for the low w/b ratios, voids are still filled by unhydrated binder particles and the reduction in strength is not a significant one. As w/b ratio is increased, the proportion of paste increases as all the binder is hydrated. Further increases in paste volume at high w/b ratios hence result in a larger fraction of discontinuities and a much more accentuated reduction in strength. These results coincide with previously published literature (Kolias et al, 2005 and Yiğiter et al, 2007), where it was found that when the initial paste volume is sufficient to bind the aggregates, increasing paste volume can be detrimental to compressive strength.

The above explanations are well suited to describe the results obtained for the blended concretes. However, results obtained for the Portland cement concretes more closely resembled those obtained by Wasserman et al. (2009). Here the effect of paste volume was not found to be a prominent one at all. Reasons for this are not yet clear, but experimental results seem to suggest that for Portland cement concretes, the primary factor affecting compressive strength is w/b ratio, while for blended concretes paste volume plays a role as well. This may have something to do with the finer nature of the CEM I 52.5 N particles. More hydration could be occurring per unit time, resulting in a denser, stronger microstructure. Also, it must be noted that in other paste-rich concretes (self-compacting concrete), the microstructure would not be adversely affected or particularly prone to crack propagation. Another possible explanation behind the experimental observation made above and depicted in Figure 47 could be the poor grading in higher paste concrete mixes. This could result in discontinuity in the microstructure and thus reduced strength and higher susceptibility to cracking.

Further trends were identified by introducing the variable of aggregate mass/cementitious mass ratio (M_a/M_c), also mentioned in the research conducted by Grdić et al. (2010). Compressive strength was plotted for all binder types as a function of the M_a/M_c ratio. Data used for the compilation of Figures 48 - 50 is tabulated in Appendix B.

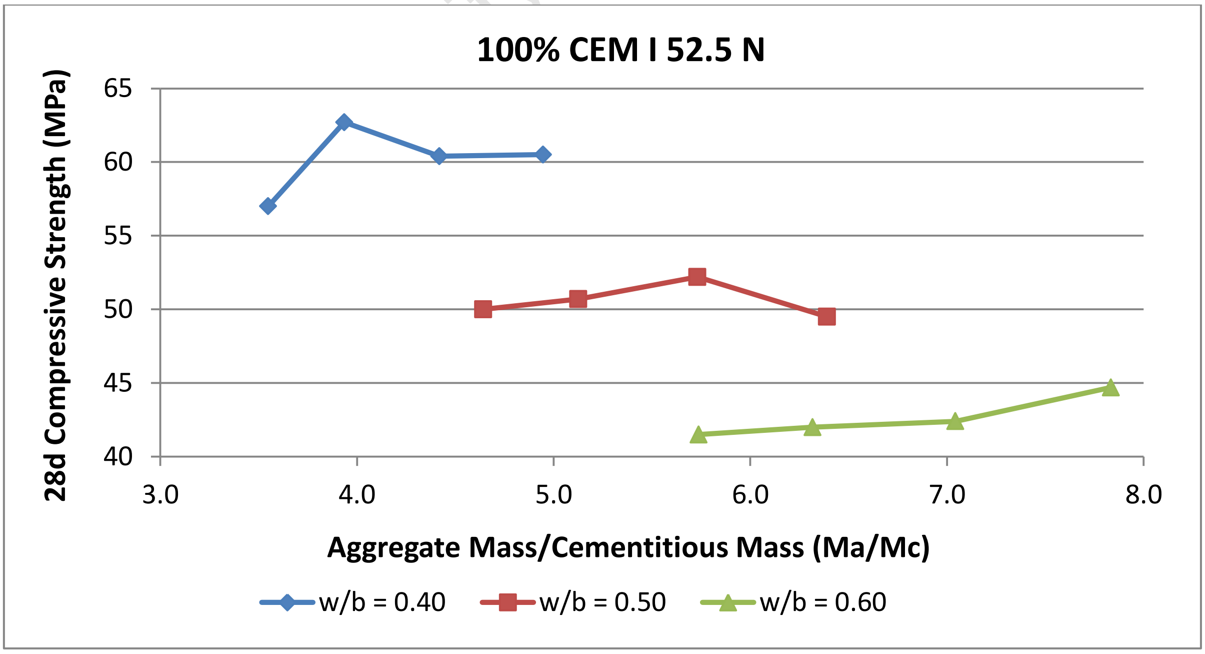


Figure 48: 28 day Compressive strength of CEM I water cured concretes as a function of Ma/Mc ratio

Figure 48 shows the results obtained for CEM I water cured concretes. For the higher w/b ratio, an increase in M_a/M_c ratio (a decrease in binder content) resulted in a slight increase in strength. For the lower w/b ratio concretes, however, no specific trends could be identified.

In the fly ash blended concretes (Figure 49), an increase in strength was observed for increasing M_a/M_c ratio for all w/b ratios. The smaller increase experienced at w/b ratio of 0.40 is also due to the pore-refining effect that occurs at low w/b ratios.

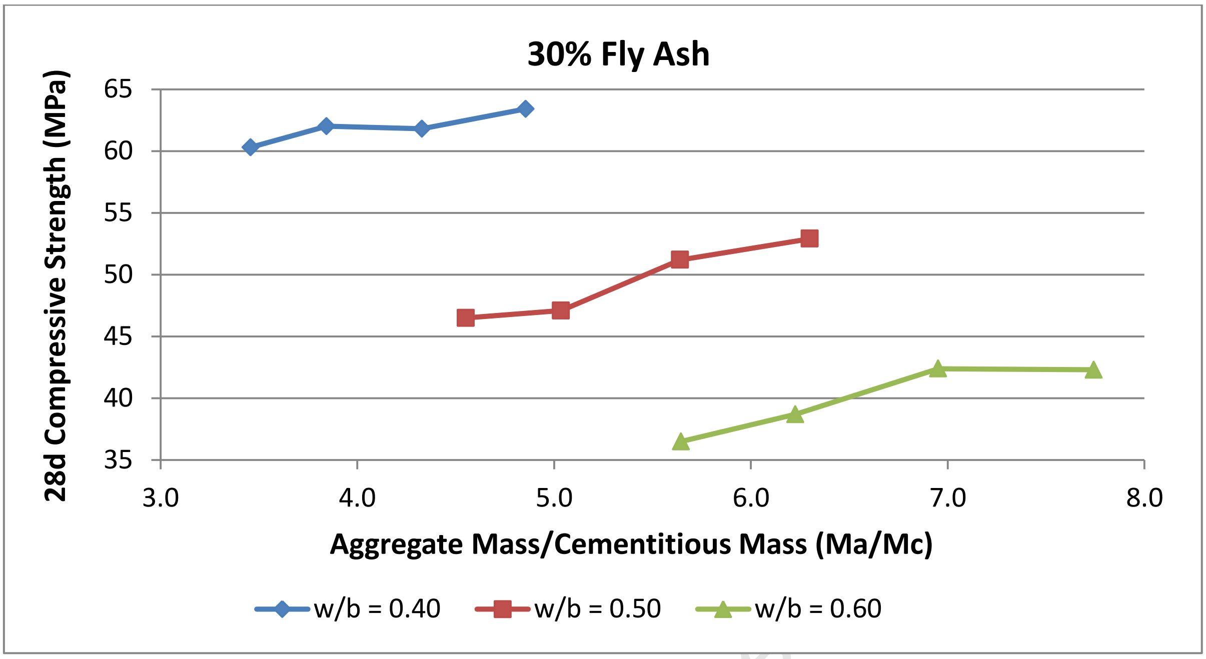


Figure 49: 28 day Compressive strength of Fly Ash water cured concretes as a function of Ma/Mc ratio

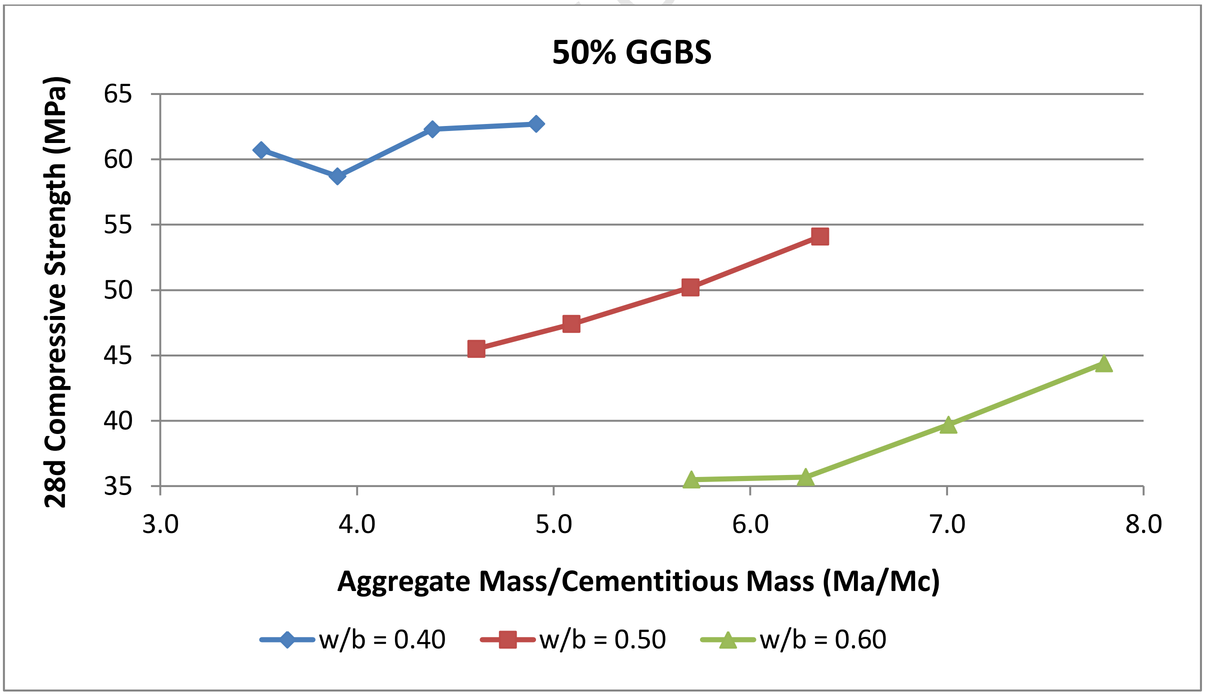


Figure 50: 28 day Compressive strength of Fly Ash water cured concretes as a function of Ma/Mc ratio

Results for the blended slag concretes are displayed in Figure 50. Compressive strength also showed a general increase with increasing M_a/M_c ratio, or decreasing binder content. Also more so at higher w/b ratios than low, due to the pore-refinement that occurs at low w/b ratios.

From the results presented in this section, it seems that compressive strength is more sensitive to binder content in blended concretes than in Portland cement concretes. Clear increasing trends in strength were observed in the blended concretes when M_a/M_c ratio values increased. In Portland cement concrete, however, this was not always the case. This is attributed to the differences in microstructure as explained previously in this section. Similar trends were observed for 7 day and 90 day strengths as well. These figures, as well as summary figures, can be found in Appendix B.

5.2.1 Summary

The results presented in this section suggest that compressive strength seems to be both a function of w/b ratio as well as paste volume. Increasing binder content while maintaining water content constant causes a reduction in w/b ratio, which brings about favourable changes in microstructure to enhance mechanical characteristics. Increasing binder content and water content to maintain a constant w/b ratio causes an increase in paste volume. Based on the results obtained, this has detrimental effects on the mechanical characteristics of blended concretes and brings no significant improvements to mechanical characteristics of Portland cement concretes. Crack development in concretes with higher paste volumes occurs along more paste and travels around less aggregates, essentially minimising the energy needed to propagate. This phenomenon occurs more prominently in concretes with high w/b ratio due to the pore-refining effect imparted to low w/b ratio concretes by the unhydrated binder particles. Investigation into the aggregate mass/cementitious mass ratio revealed that at low paste contents in blended concretes, with higher paste homogeneity, there is possibly an improvement in the microstructure of the ITZ which results in better interaction between aggregates and cement paste. Increases in paste volume were thus detrimental as they resulted in excessive amounts of paste to bind the aggregates. Based on the observations made, it is evident to see that increases in binder content causing increases in paste volumes are not beneficial to strength development, and that minimum binder content specifications are not effective tools for purposes of strength development.

5.3 The Influence of Compressive Strength on DI Parameters

Prescriptive specifications stipulate minimum binder contents and minimum compressive strength values for durability requirements of concrete in different exposure environments. Hence this section investigated the relationship between durability and compressive strength for different concretes. The aim was to identify whether a meaningful relationship between the two does exist. Where trends and relationships were identified, observations were made and results discussed by referring purely to these two parameters, and not to the changes occurring in other parameters which may have resulted in higher strength and better durability. This was done in the next section, where the influence of binder content on durability index parameters was investigated. Reference was then be made to parameters such as paste volumes with respect to their influence on durability indices, thus also enabling a comparison of the trends observed in this section.

Samples were cored and prepared for durability testing at the following ages for both full water curing and lab curing:

- Water Sorptivity tests were carried out at 28 days

- Oxygen Permeability and Chloride Conductivity tests were carried out at 56 days.
- Compressive Strength tests were carried out at 7 days, 28 days and 90 days for full water curing only. This was done since compressive strength is defined as the strength measured on a fully water cured sample.

Strength values for 56 days were interpolated linearly between 28 days and 90 days to compare relevant compressive strength results with 56 day permeability and conductivity values. For water sorptivity, results obtained at 28 days were compared to 28 day strengths. It is also important to note that in this section, permeability results are discussed in terms of permeability coefficient values and not OPI values.

Results are discussed for each durability index and binder type and a summary is provided at the end of the section to emphasise the most important findings and relate them to previously published literature.

5.3.1 Permeability

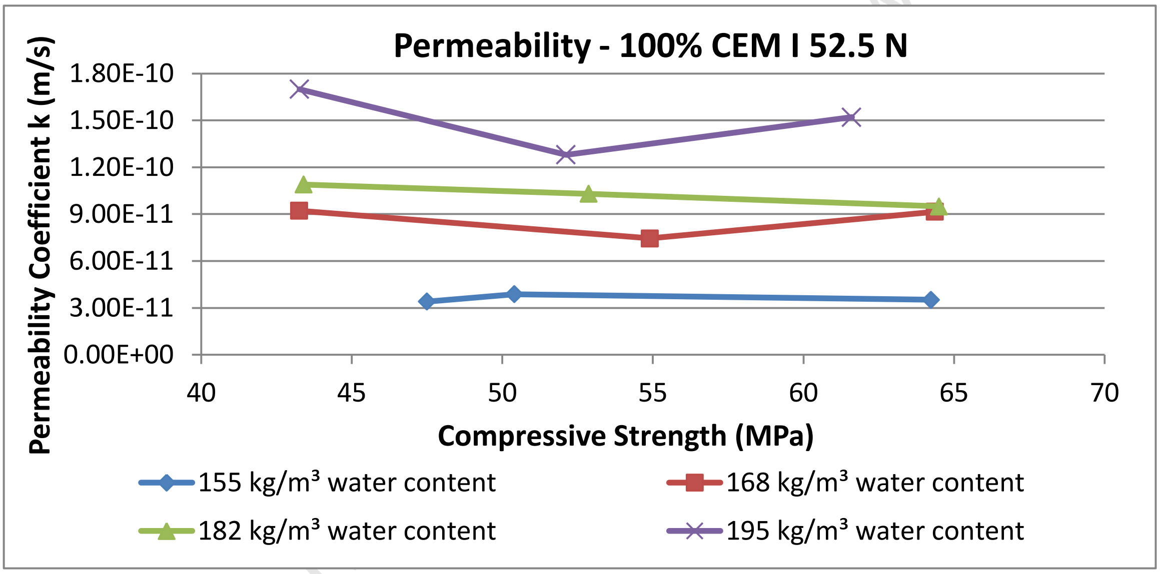


Figure 51: Permeability vs strength of CEM I lab cured concretes for different paste volumes

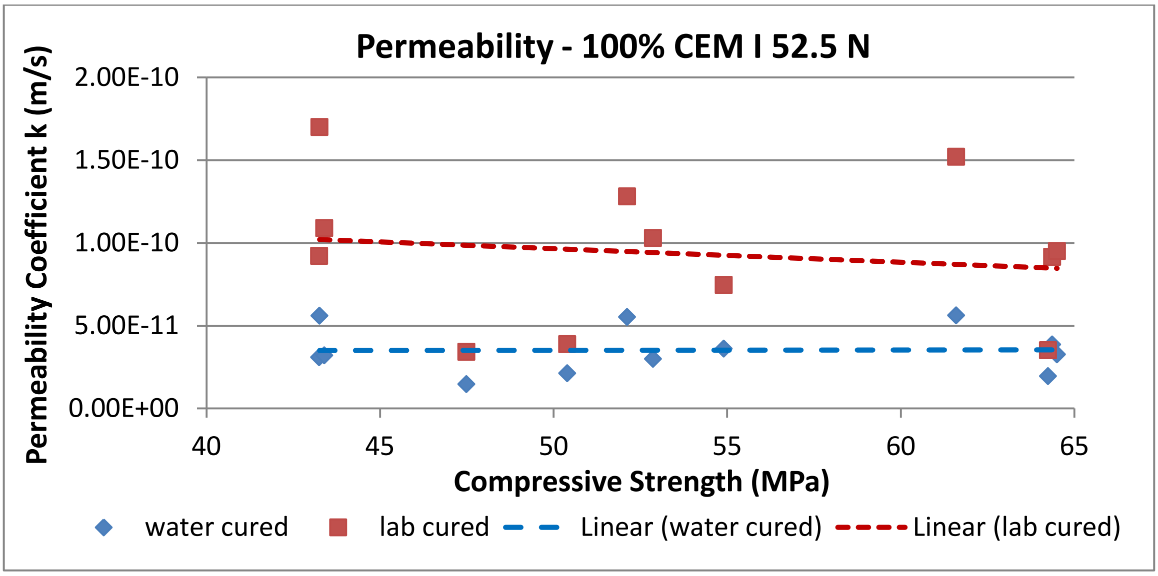


Figure 52: Compressive strength and permeability – 100% CEM I 52.5 N

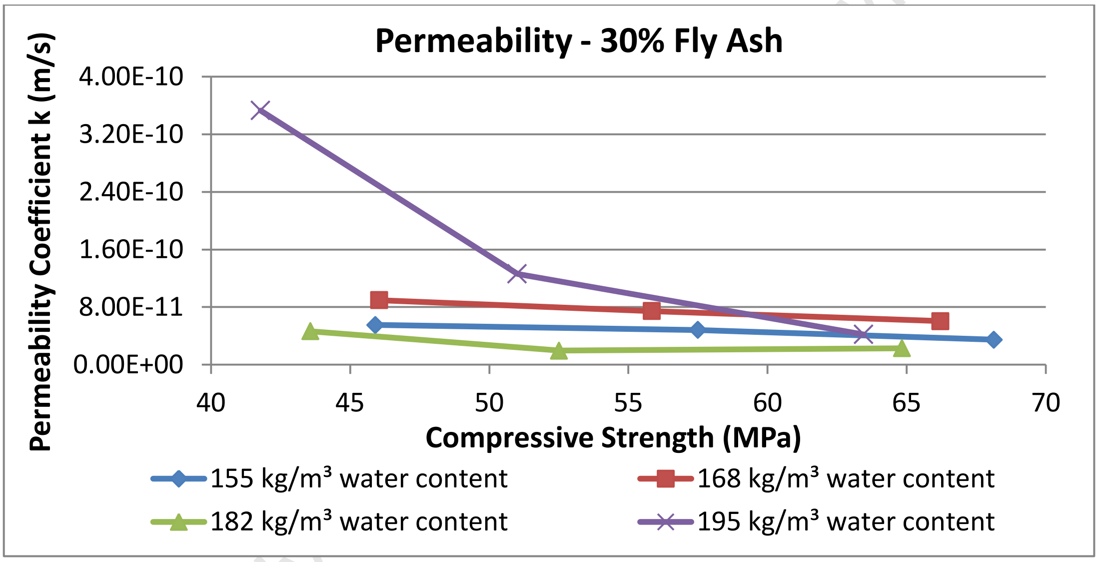


Figure 53: Permeability vs strength of Fly Ash lab cured concretes for different paste volumes

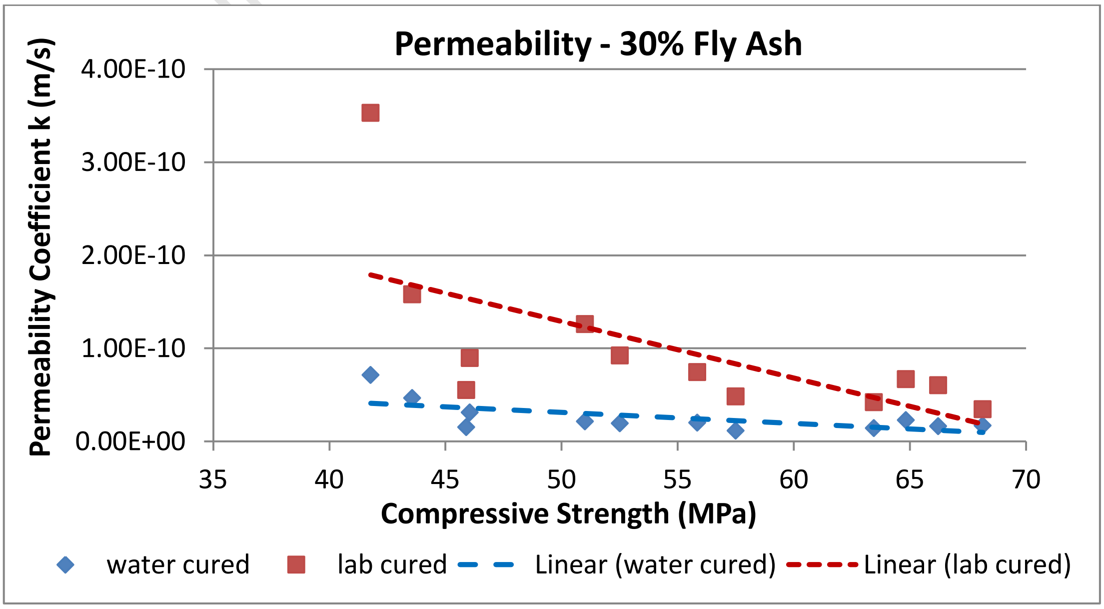


Figure 54: Compressive strength and permeability – 30% Fly Ash

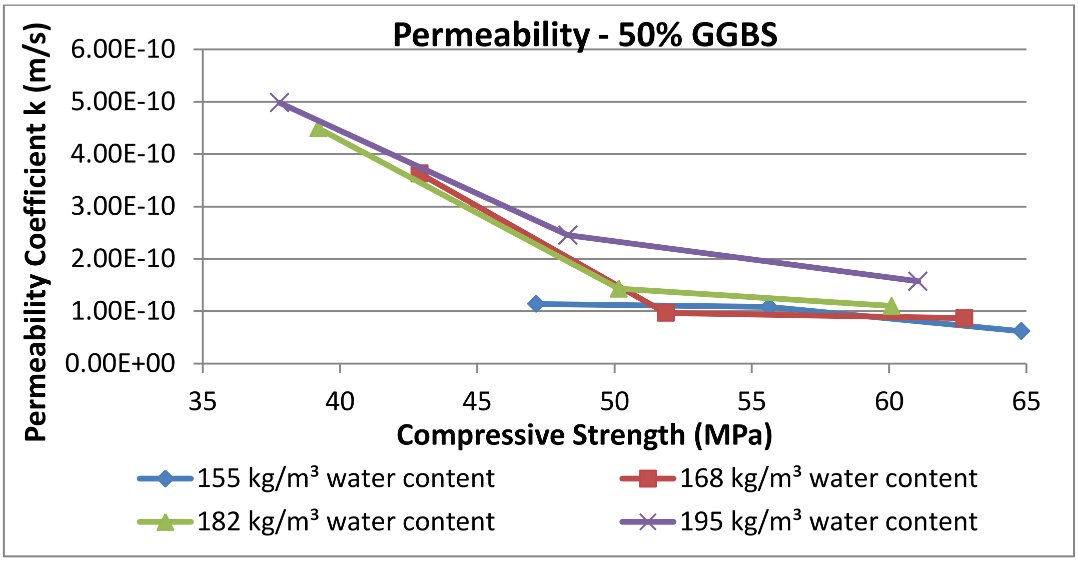


Figure 55: Permeability vs strength of GGBS lab cured concretes for different paste volumes

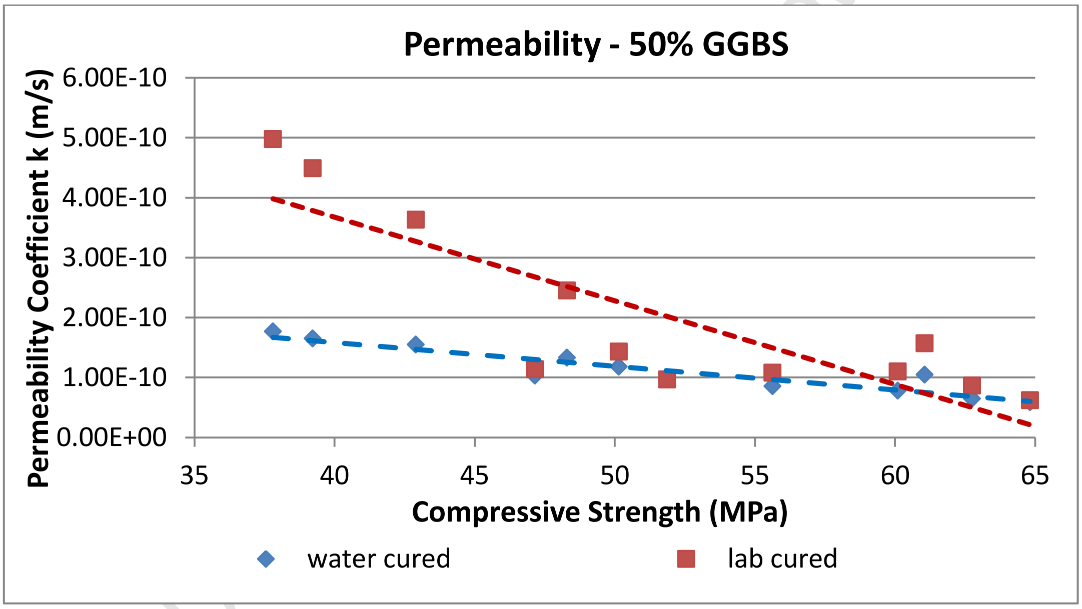


Figure 56: Compressive strength and permeability – 50% GGBS

Results obtained for CEM I 52.5 N concretes at different water contents are displayed in Figure 51. Results clearly show that for a constant value of compressive strength, concretes with higher paste volumes displayed higher permeability values. This may be due to the fact that paste is the most significant contributor to porosity and permeability of the concrete system. However, as compressive strength increased, no significant change was identified in the permeability of CEM I concretes, with values remaining relatively constant. This is also shown in Figure 52, which grouped all w/b ratios and binder contents together. Although the difference in water cured and lab cured results was quite clear, based on the results, it seemed that permeability characteristics of the CEM I concretes was fairly insensitive to changes in compressive strength, with no identifiable trend between the two parameters.

Results for fly ash blended concretes shown in Figure 53 displayed similar trends to CEM I concretes for all paste volumes as compressive strength was increased. An exception was observed for the water content of 195 kg/m^3 and cannot be explained. Another similar trend to CEM I concretes was that for a constant strength value, higher paste volumes displayed higher permeability values. This makes sense for similar reasons as those observed for CEM I concretes. The results displayed in Figure 54 show the water cured and lab cured permeability for the fly ash blended concretes in relation to compressive strength. Both curves show a rather prominent decreasing trend in permeability values as compressive strength decreases, with the trend being more pronounced in lab cured samples. This highlights the need for effective curing practices to ensure successful development of the pozzolanic reaction.

Results obtained for GGBS concretes are displayed in Figures 55 and 56. Permeability values obtained for GGBS were generally higher than the fly ash blended concretes and Portland cement concretes. Reasons for this are unclear, although this coincides with previous findings (Alexander & Mackechnie, 2001a). Permeability in GGBS concretes showed a higher sensitivity to changes in strength than the other two binders only at lower strength values (between 35 – 45 MPa), but not at higher strengths. This can be attributed to the pore-refining effect that occurs at low w/b ratios due to unhydrated material present in the cementitious matrix. Figure 56 shows results grouped together for all w/b ratios and binder content. The decreasing trend in permeability with increasing strength is clearly seen here. The influence of curing on microstructure development of GGBS concrete is also evident, with lab cured concretes showing a higher decreasing trend than water cured concretes.

A possible explanation for the insensitivity of permeability of CEM I concretes to changes in strength (Figures 51 and 52) could be due to the finer nature of the CEM I 52.5 N particles. This can result in more hydration per unit time, possibly leading to a denser and more impermeable microstructure. Even for concretes with different w/b ratios, and thus different strengths, the permeability of the concrete was not affected significantly by changes in strength. Hence higher paste volumes seemed to have an effect on the permeability characteristics of CEM I concretes. This trend is worth noting since it differs from the trend observed in Section 5.2, where for the same concretes no identifiable influence was observed with respect to compressive strength at higher paste volumes. The influence of binder content (paste volume) on durability indices is investigated in more detail in Section 5.4.

5.3.2 Water Sorptivity

Figures 57 – 62 display the water sorptivity results obtained for the experimental concretes. Since the trends observed here were explained with reasoning similar to that of permeability for each binder, the figures have been grouped together and are followed by combined discussions with reference to paste volume and curing regime respectively.

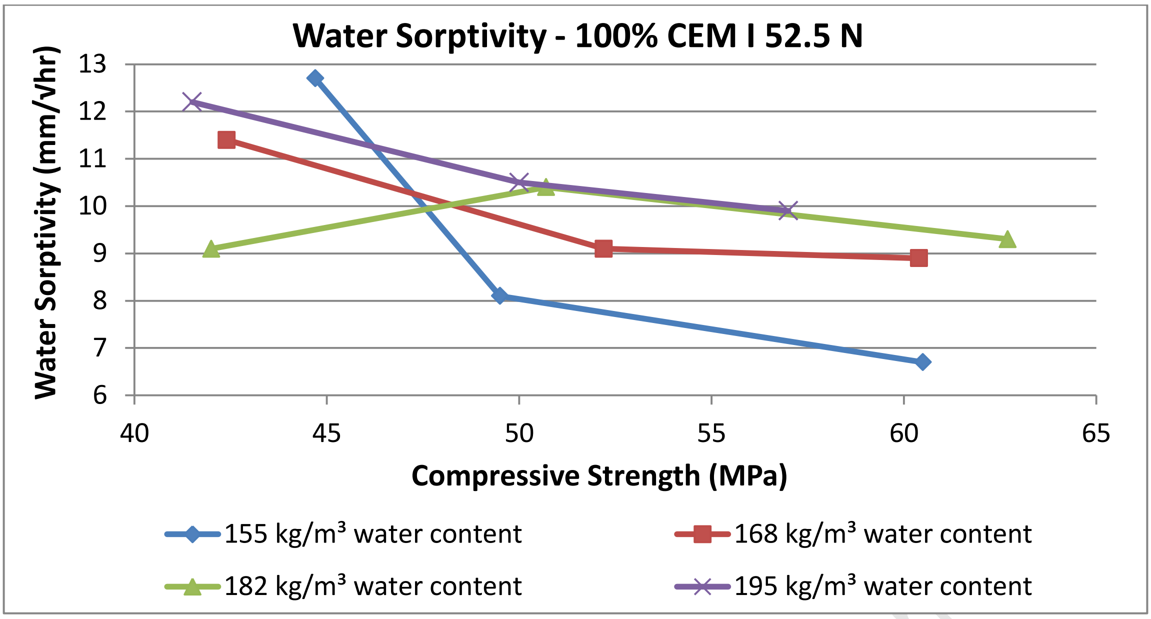


Figure 57: Water sorptivity vs strength of CEM I lab cured concretes for different paste volumes

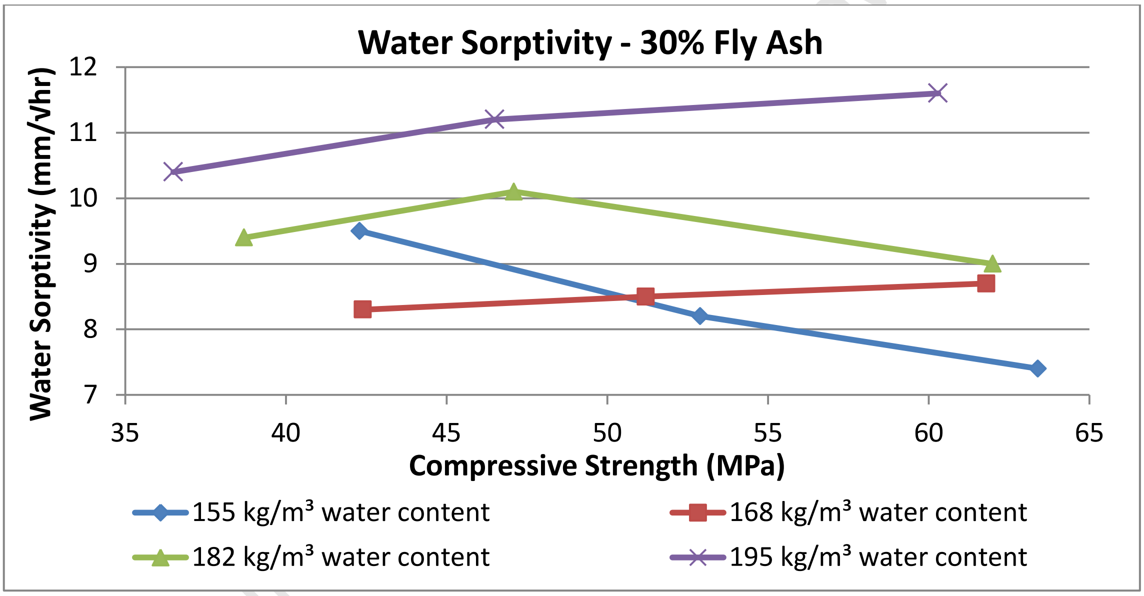


Figure 58: Water sorptivity vs strength of Fly Ash lab cured concretes for different paste volumes

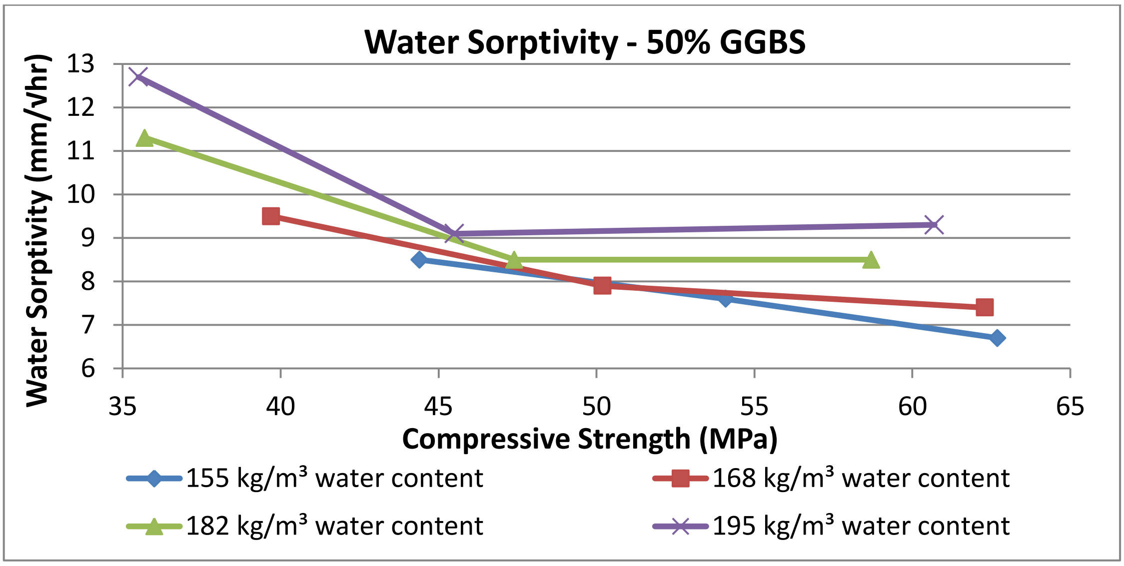


Figure 59: Water sorptivity vs strength of GGBS lab cured concretes for different paste volumes

Sorptivity values showed a general decrease as compressive strength increased for both CEM I and GGBS, as observed in Figures 57 and 59. Results for fly ash blended concretes for the different water contents (Figure 58) did not display such trends. With increase in strength, some fly ash concretes experienced an increase in sorptivity values, others a reduction. What is however identified for all binder types is that at high strengths, an increase in paste volume led to a higher sorptivity value for a given strength. A similar observation was made for lower strengths, although the 155 kg/m^3 water content concretes for CEM I and fly ash inexplicably showed higher values than the 168 kg/m^3 at low strengths. Another observation made for both CEM I and GGBS was that as the strength values increased, decreases in sorptivity values became more gradual. This is again due to the pore-refining effect that occurs at low w/b ratios. It is unclear why the same was not observed for fly ash concretes. However what can be said based on these results is that the recurring trend seems to be that an increase in strength causes a decrease in water sorptivity.

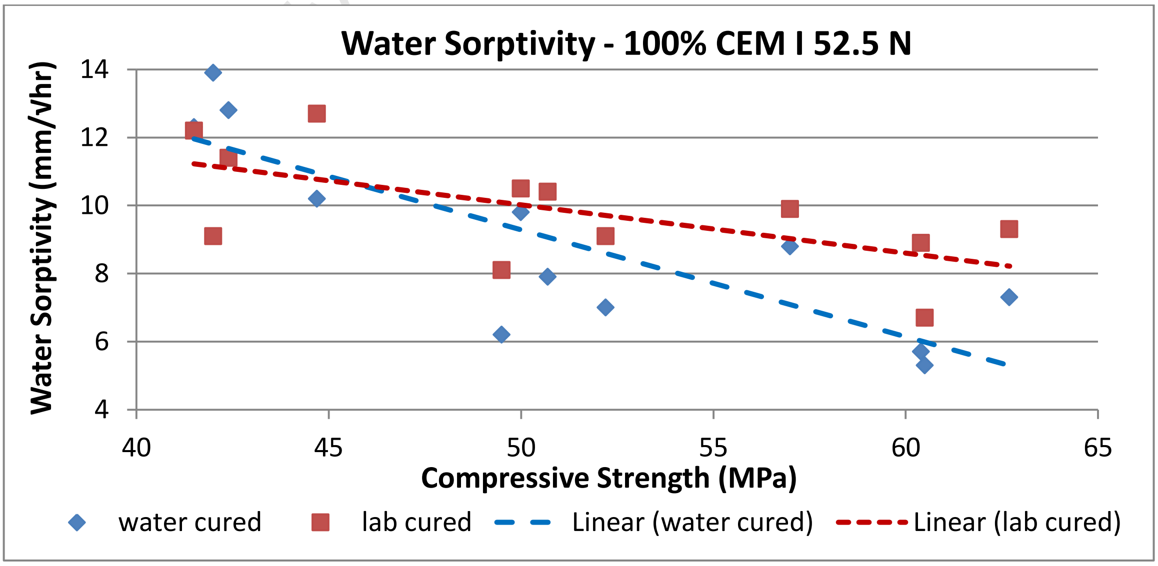


Figure 60: Compressive strength and water sorptivity – 100% CEM I 52.5 N

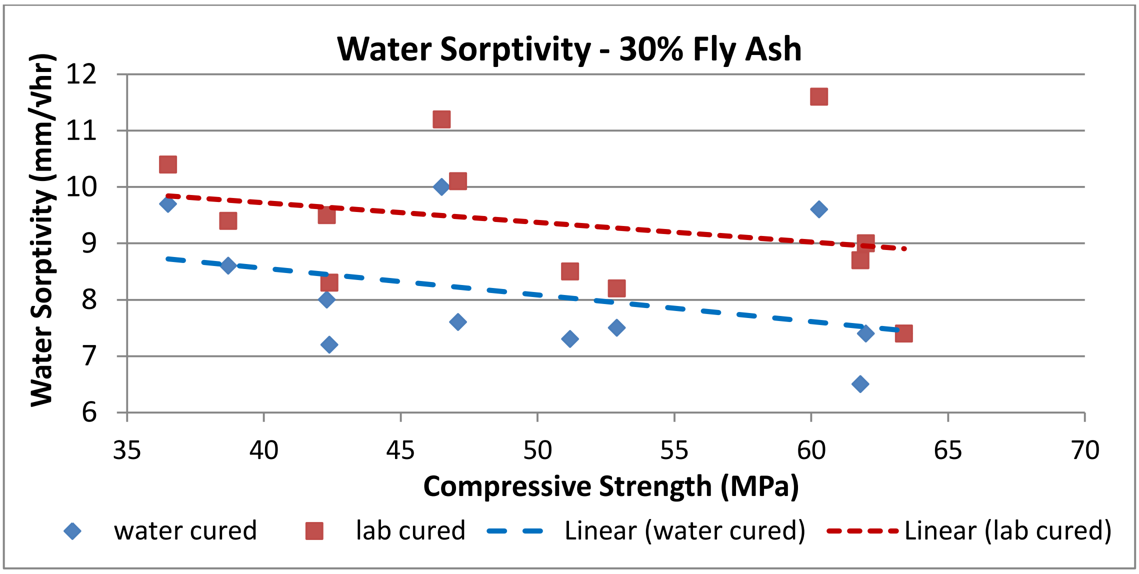


Figure 61: Compressive strength and water sorptivity – 30% Fly Ash

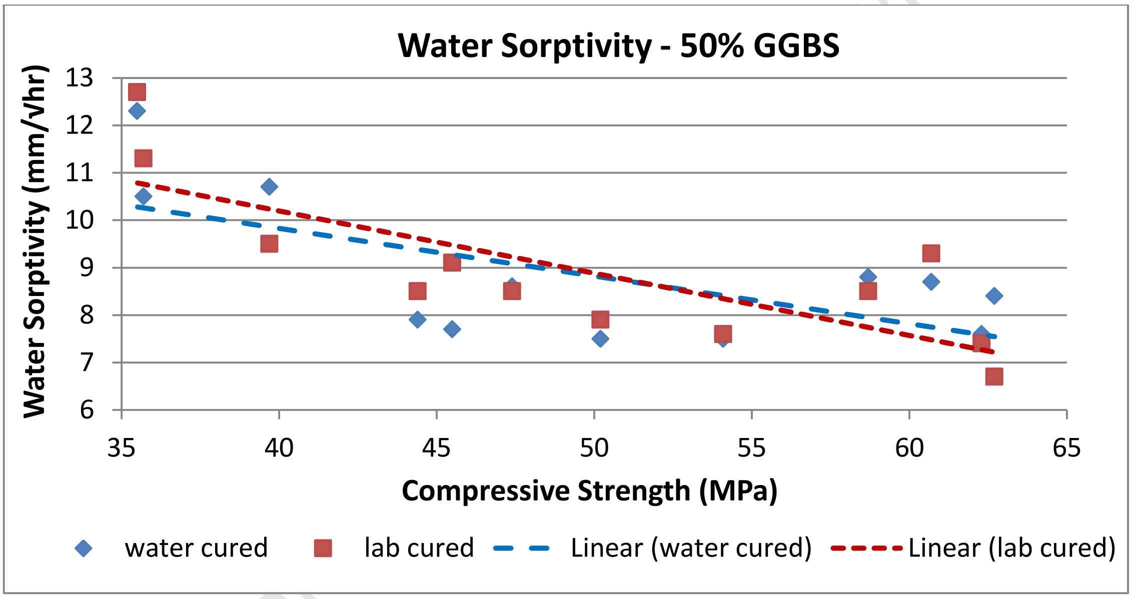


Figure 62: Compressive strength and water sorptivity – 50% GGBS

Sorptivity for both curing regimes showed to be sensitive to changes in strength, with higher strengths displaying lower values. This can again be attributed to a denser microstructure that occurs at lower w/b ratios and higher strengths. Results generally suggest show that lab cured samples were either less sensitive to changes in strength than water cured samples or relatively equal. This is seen from the steeper gradient of water cured samples in CEM I concretes (Figure 60), as well as from the negligible difference in gradient of the two curves in the blended concretes (Figures 61 and 62). It is not clear as to why this is so, since curing has always been important in the successful development of the hydration reaction. The influence of curing was more prominent in CEM I and fly ash concretes than in GGBS concretes. The reduction in sorptivity values as compressive strength increased was relatively similar, but in fly ash concretes the lab cured samples displayed generally higher values for the same strength. This again highlights the importance of curing for the development of the pozzolanic reaction. In CEM I concretes, the higher sorptivity values of lab cured samples occurred at high strengths only, while in GGBS concretes there was a negligible difference in performance at different curing regimes. Hence the physical effect of curing on water sorptivity characteristics of GGBS concrete does not seem to be a prominent one. It is not clear as to why.

5.3.3 Chloride Conductivity

Results in this sub-section have also been grouped to form combined discussions as in the previous sub-section on water sorptivity. Discussions are carried out in terms of compressive strength with reference to paste volume and curing regime respectively.

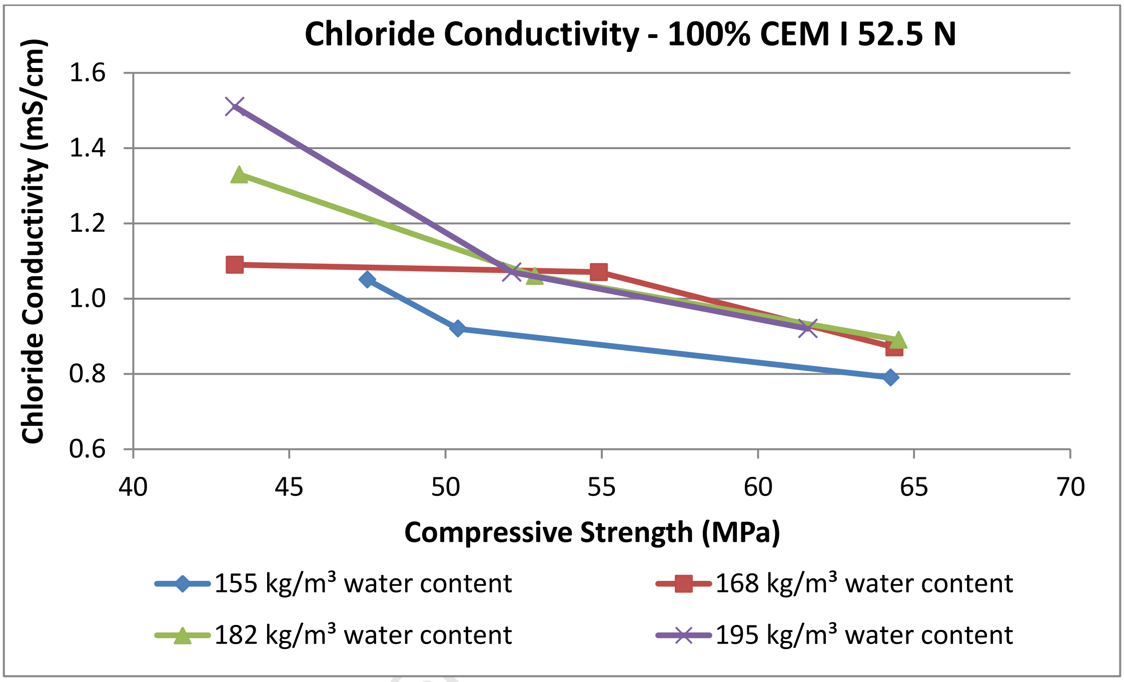


Figure 63: Chloride conductivity vs strength of CEM I lab cured concretes for different paste volumes

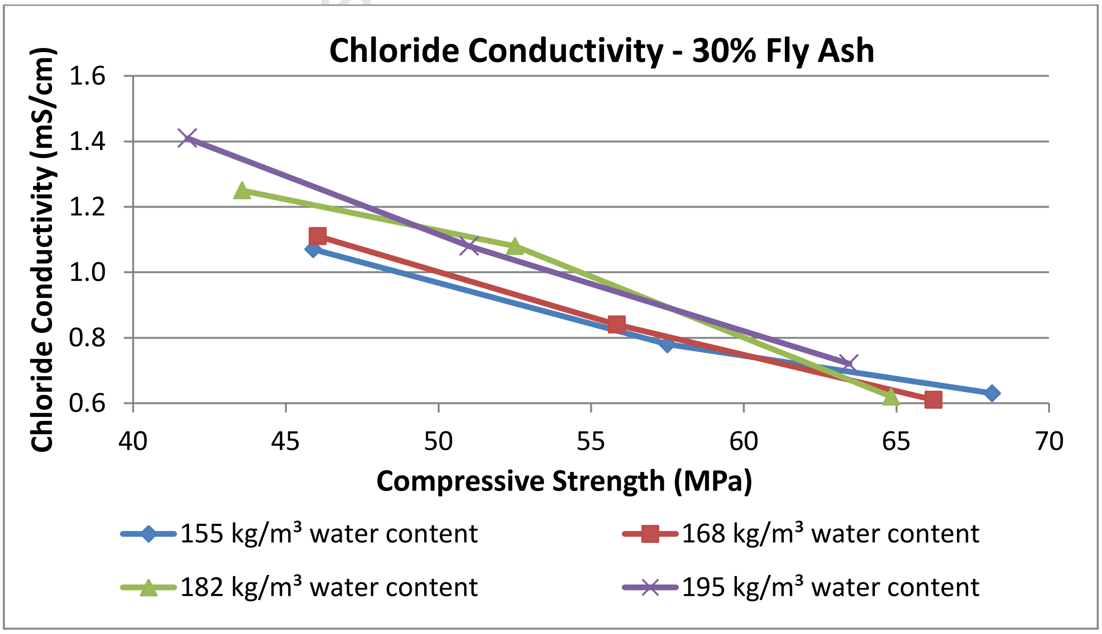


Figure 64: Chloride conductivity vs strength of Fly Ash lab cured concretes for different paste volumes

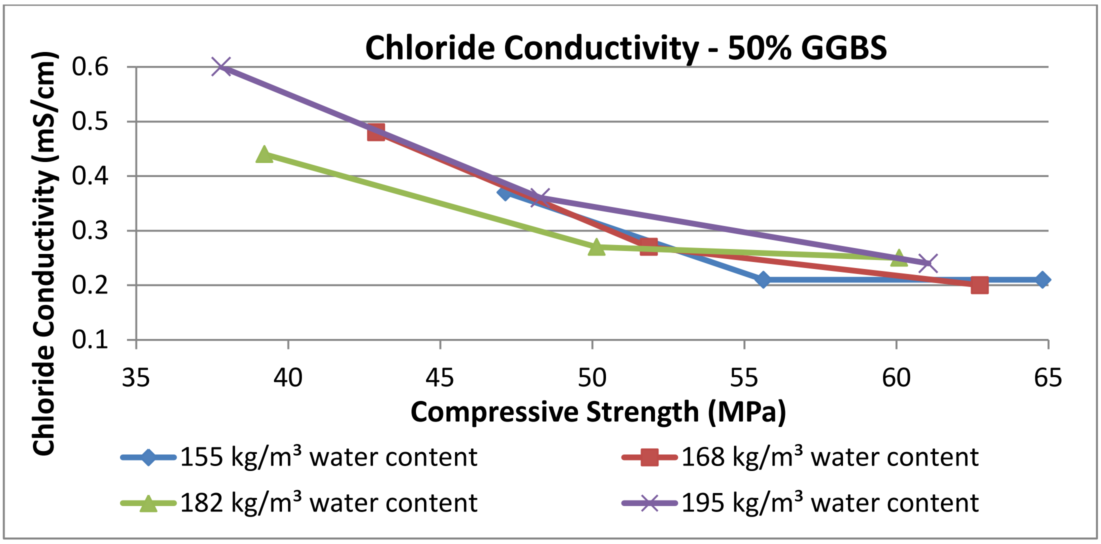


Figure 65: Chloride conductivity vs strength of Fly Ash lab cured concretes for different paste volumes

In determining the relationship between compressive strength and chloride conductivity for CEM I concretes, one can see that as compressive strength increased, a decreasing trend in conductivity values was observed. What can also be observed for all binder types from Figure 63 - 65 is that for a given strength, concretes with higher paste volumes generally displayed higher values of conductivity. This coincides with previously made observations with respect to paste content and penetrability. Smaller differences in conductivity at higher strengths also coincided with previous observations made with respect to the refining effect of low w/b ratio concretes.

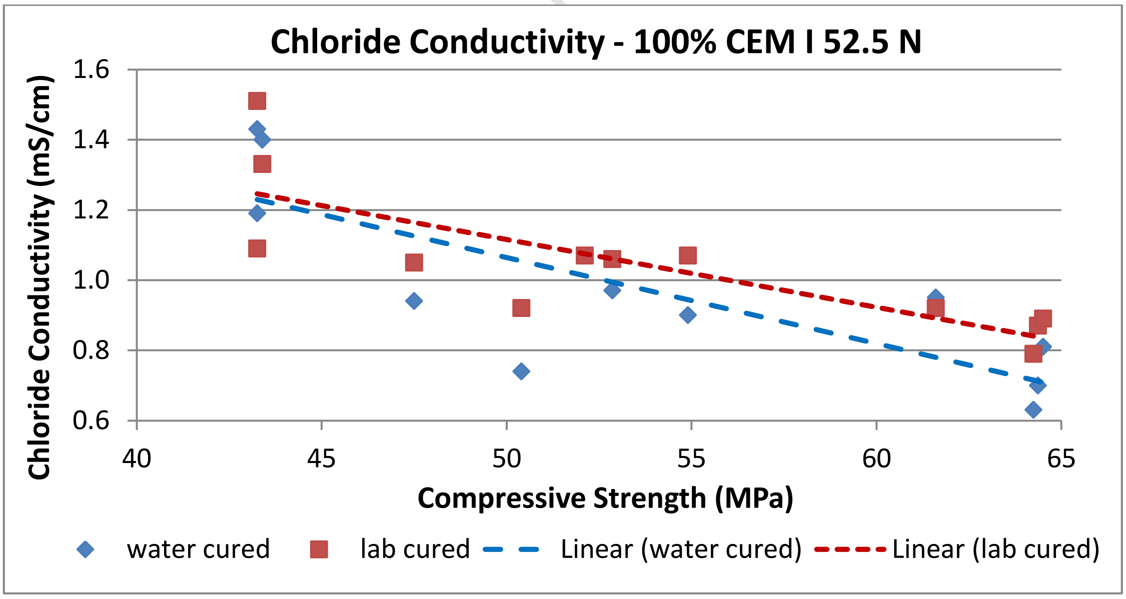


Figure 66: Compressive strength and chloride conductivity – 100% CEM I 52.5 N

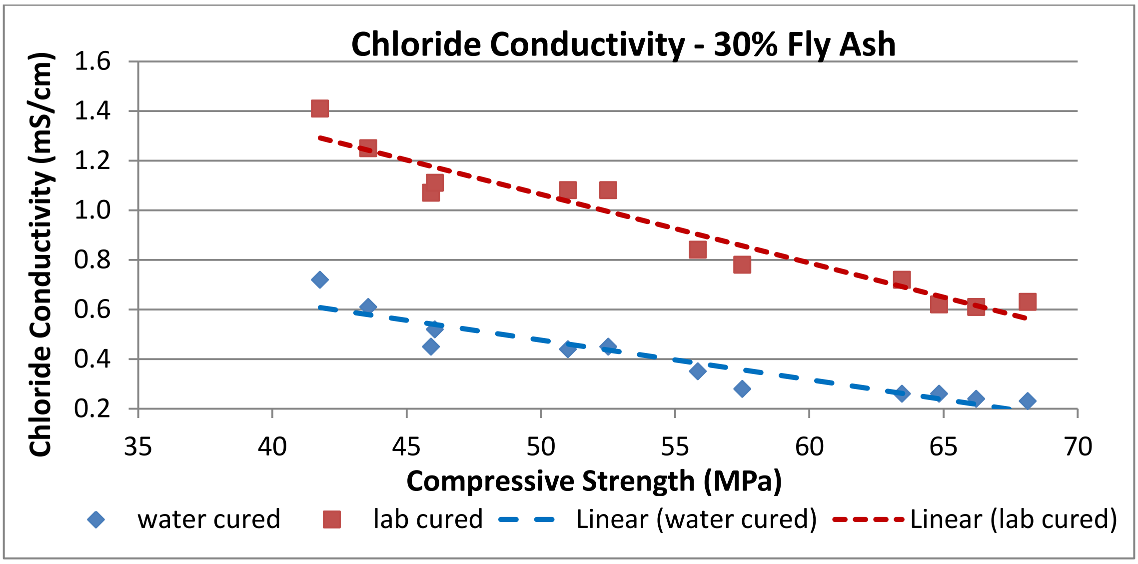


Figure 67: Compressive strength and chloride conductivity – 30% Fly Ash

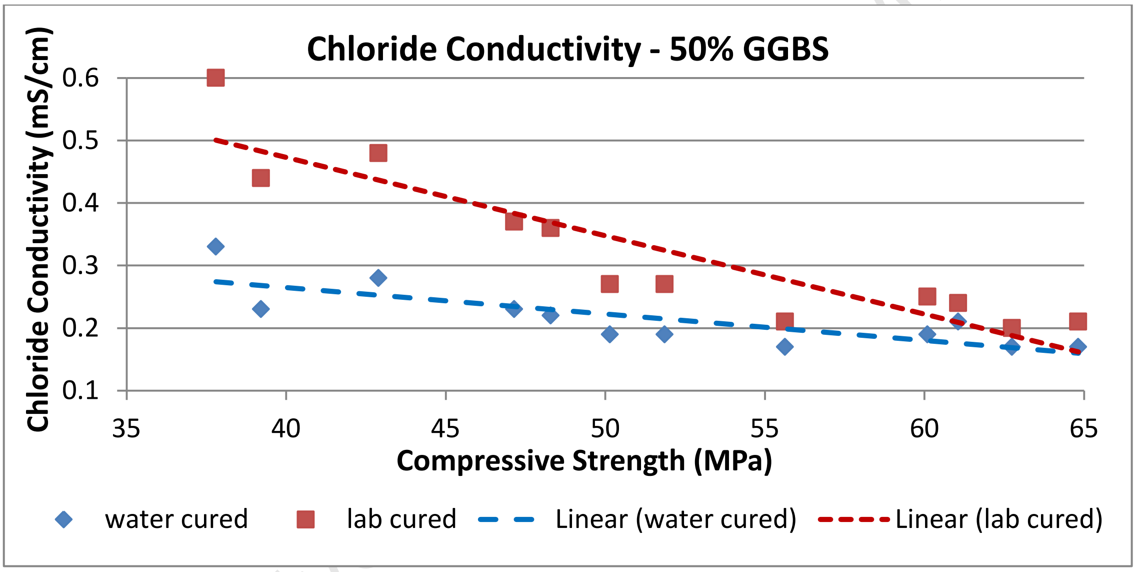


Figure 68: Compressive strength and chloride conductivity – 50% GGBS

The differences in results between water cured and lab cured concretes for CEM I was not prominent, as can be seen in Figure 66. A different trend was observed for the blended concretes, where for both fly ash and GGBS there was a significant difference between results for water cured and lab cured concretes. This again highlights the importance of curing in for successful development of both the pozzolanic reaction in fly ash concrete and the hydration reaction in GGBS concrete.

5.4 The Influence of Binder Content on DI Parameters

The analysis proposed for this section involved consideration of one main parameter, namely binder content, and its influence on durability indices. Since increases in binder content for the same w/b ratio were generally not beneficial to strength, and since beneficial trends between strength and durability indices could be observed, the anticipated outcome of this analysis was that increases in binder content would not result in improved durability index values. This is contrary to how many professionals in industry presently interpret prescriptive specifications such as those stipulated in BS EN 206. Analysis in this section was carried out with binder content as the main parameter under discussion. This was done largely by examining trends in lab cured concretes with respect to binder content (paste volume) and w/b ratio since these two parameters appear in EN 206 along with minimum compressive strength. Lab curing was only discussed since it represents much more closely how concretes are likely to behave in a site exposure environment. It is displayed on the charts as “LC”.

5.4.1 Binder Content and Water/Binder Ratio

Results in this sub-section have also been grouped to form combined discussions as in the previous section on the influence of binder content on compressive strength. Discussions are carried out in terms of compressive strength with reference to paste volume and curing regime respectively.

Permeability

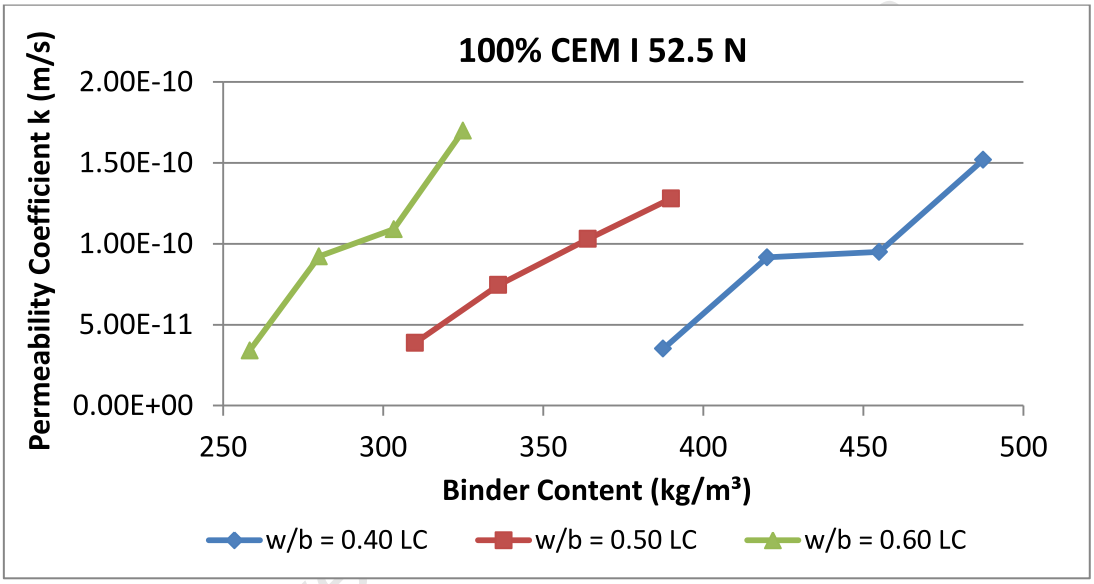


Figure 69: Influence of binder content and paste volume on permeability of CEM I concretes

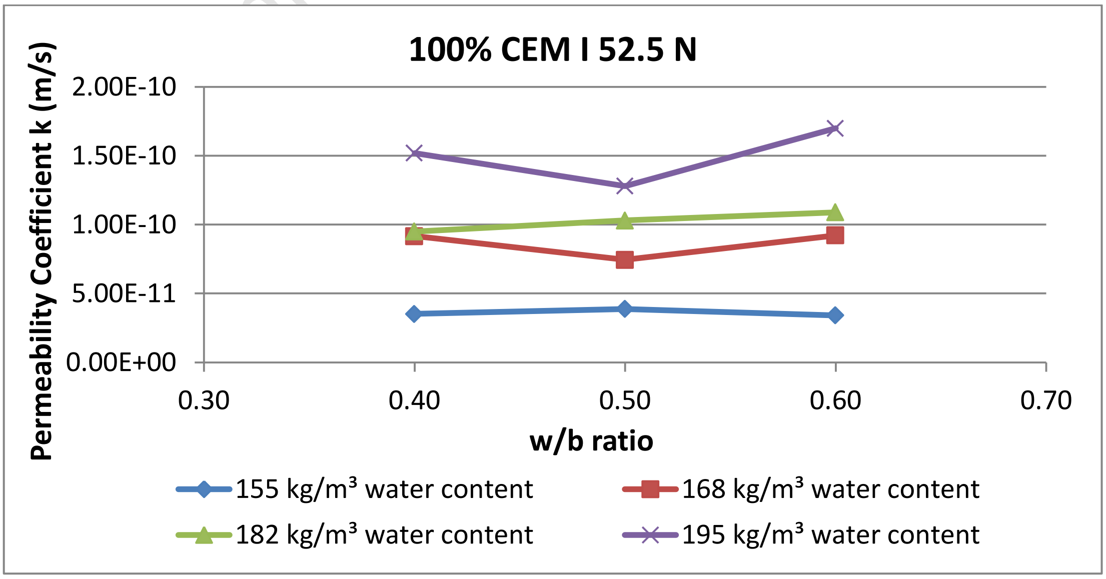


Figure 70: Influence of w/b ratio and paste volume on permeability of CEM I concretes

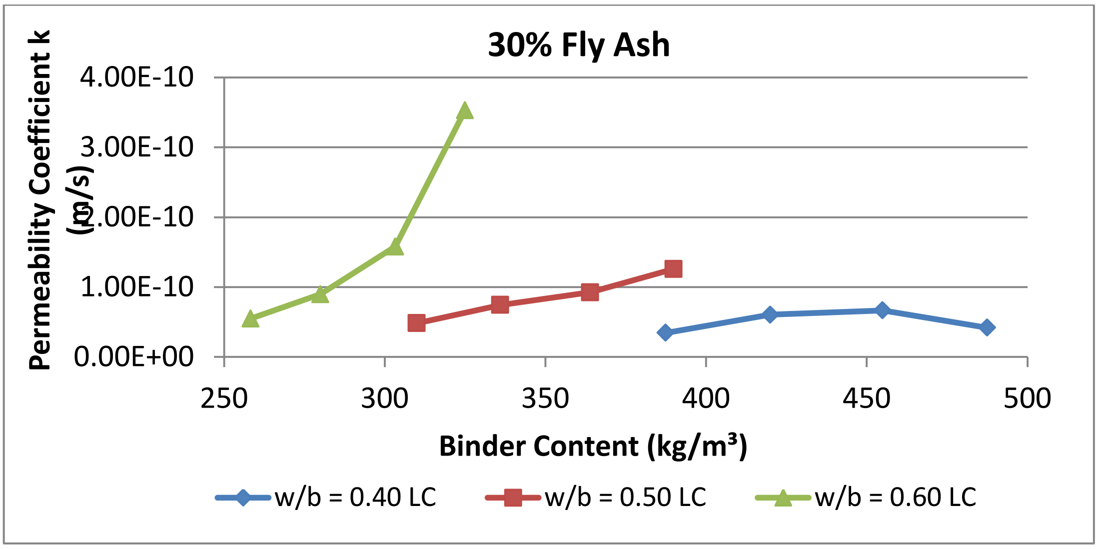


Figure 71: Influence of binder content and paste volume on permeability of Fly Ash concretes

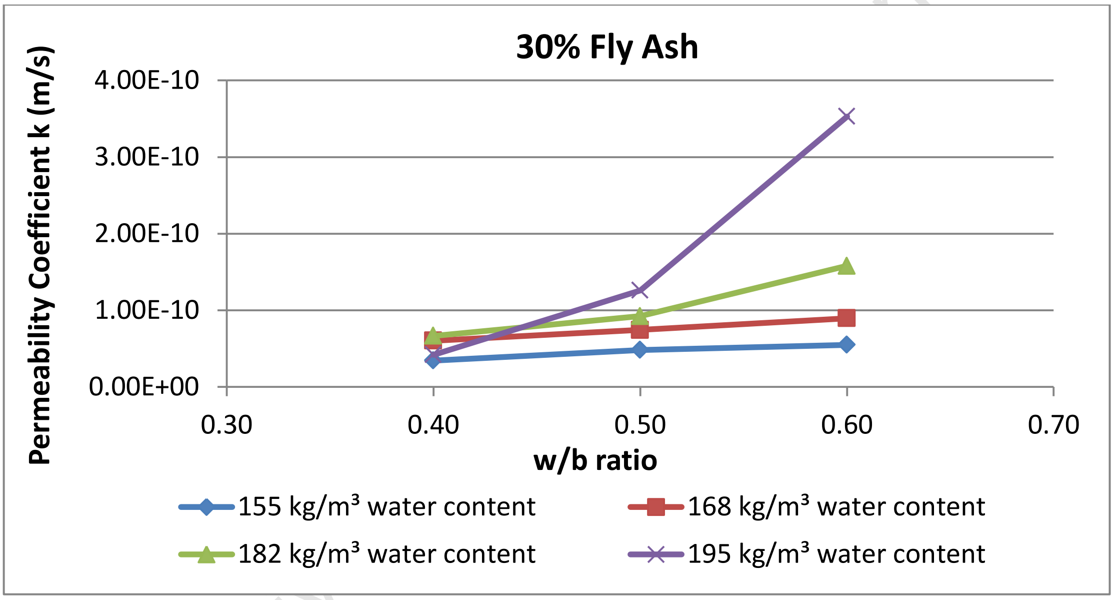


Figure 72: Influence of w/b ratio and paste volume on permeability of Fly Ash concretes

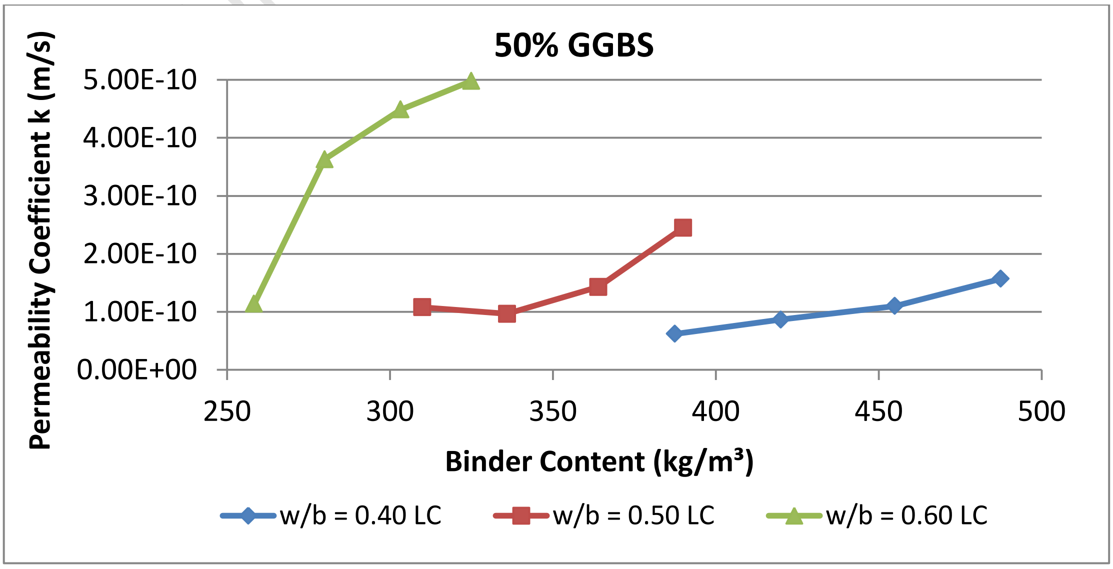


Figure 73: Influence of binder content and paste volume on permeability of GGBS concretes

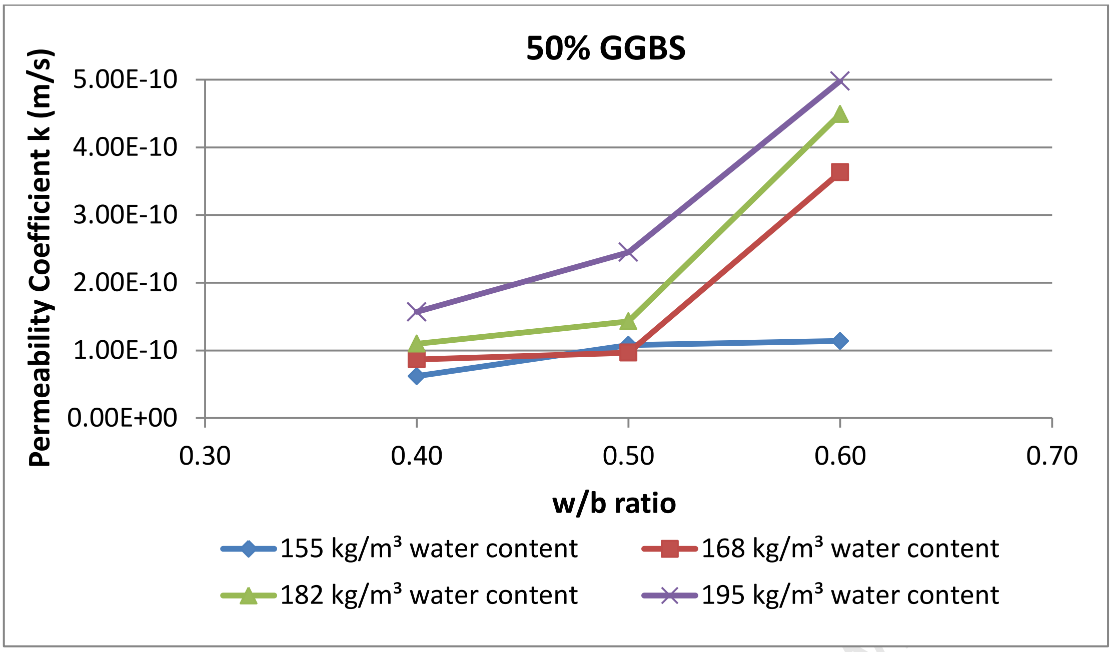


Figure 74: Influence of w/b ratio and paste volume on permeability of GGBS concretes

It is clear from Figure 69 that an increase in paste content (higher binder content for a fixed w/b ratio) in CEM I concretes caused an increase in permeability. This was due to a higher permeable portion of the concrete system, as noted in previous sections. For CEM I concretes an increase in w/b ratio did not have a pronounced effect on permeability. This trend can be better seen in Figure 70 and can probably be attributed to the fineness of the CEM I 52.5 N particles rendering permeability insensitive to changes in w/b ratio, as noted previously with reference to the effect of binder content on compressive strength. In blended concretes, increases in paste content also generally led to increases in permeability, more so for low w/b ratios than high ones (Figures 71 and 73). This is because at low w/b ratios, even when the paste volume is increased, there is still a refining effect that occurs in the microstructure due to the unhydrated binder particles. This is more prominent in blended concretes due to a higher degree of homogeneity in the paste and is also observed in Figures 72 and 74.

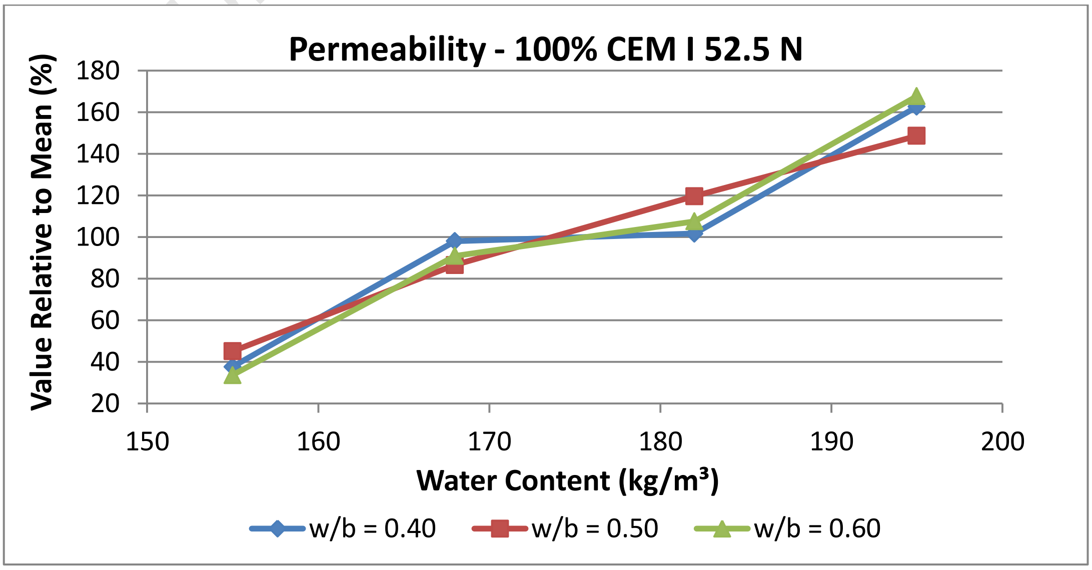


Figure 75: CEM I concretes - relative permeability with respect to water content (paste content)

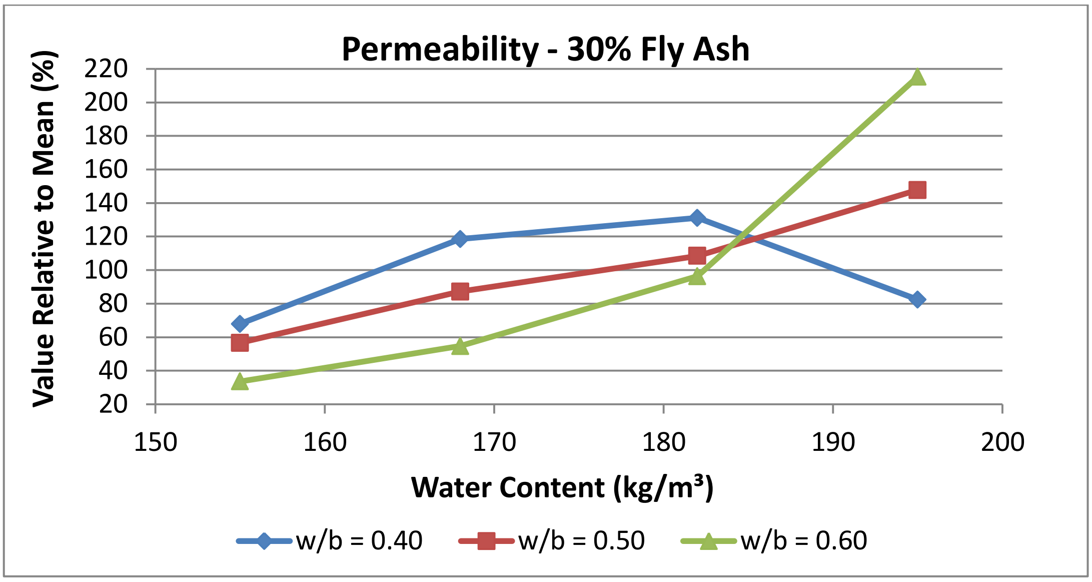


Figure 76: Fly Ash concretes - relative permeability with respect to water content (paste content)

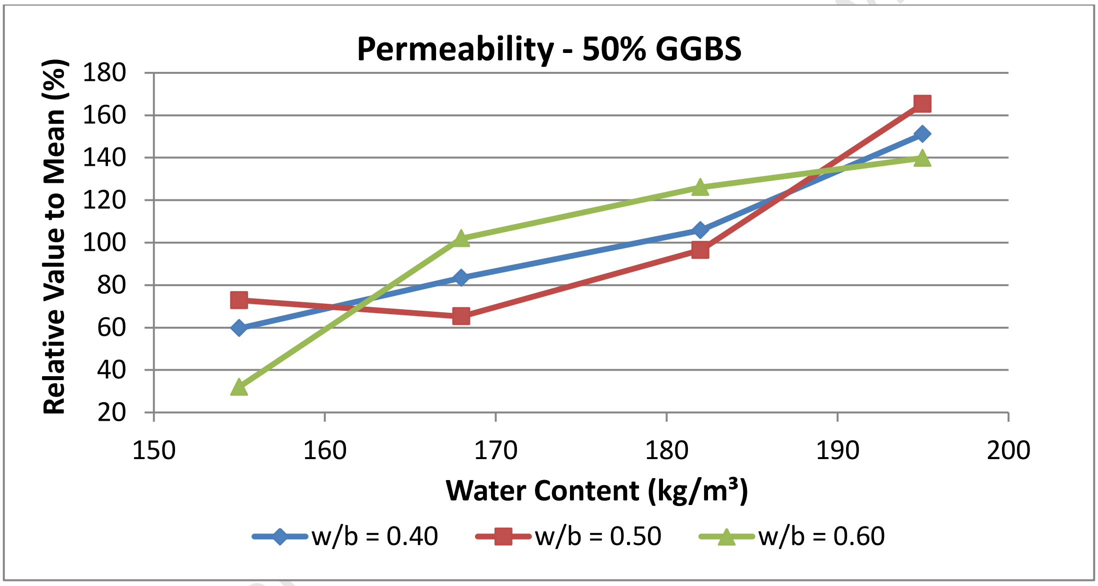


Figure 77: GGBS concretes - relative permeability with respect to water content (paste content)

In Figures 75 – 77, permeability results are presented as a function of water content for different w/b ratios (paste volume). Permeability values were averaged to find a mean for each w/b ratio and each value was then divided by the mean to obtain a percentage relative value. These figures clearly show that, regardless of binder type or w/b ratio, permeability of concrete is very sensitive to changes in paste content and that designing concretes with low paste contents can be effective in reducing permeability. Tabulated data used for plotting figures 75 – 77 and the corresponding figures for water sorptivity, porosity and conductivity can be found in Appendix C.

Water Sorptivity

Results for water sorptivity are given below in Figures 78 – 83.

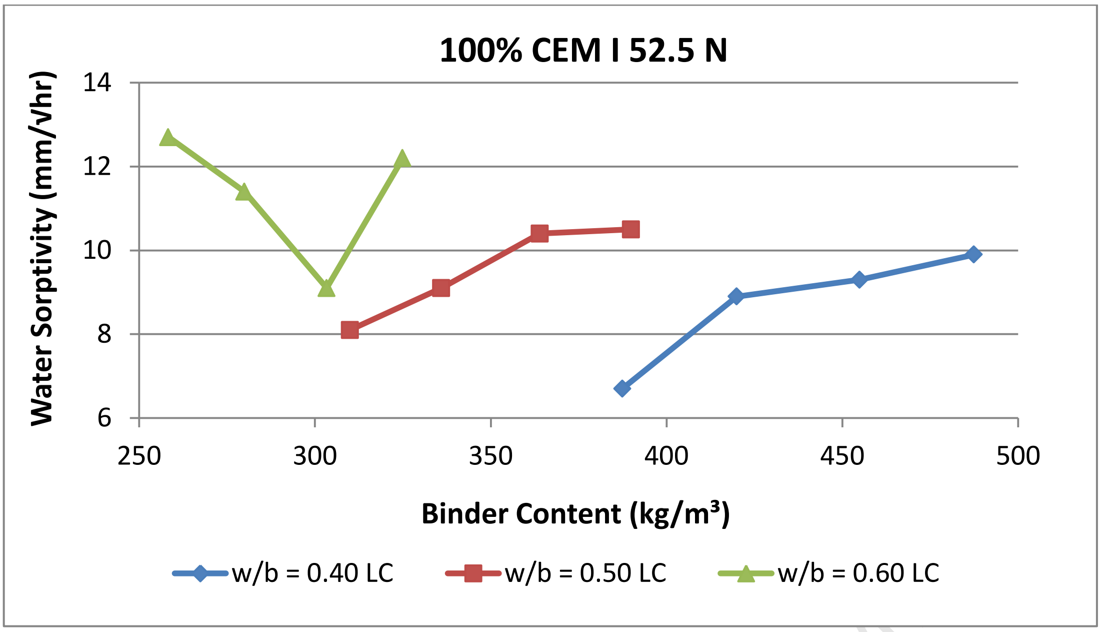


Figure 78: Influence of binder content and paste volume on water sorptivity of CEM I concretes

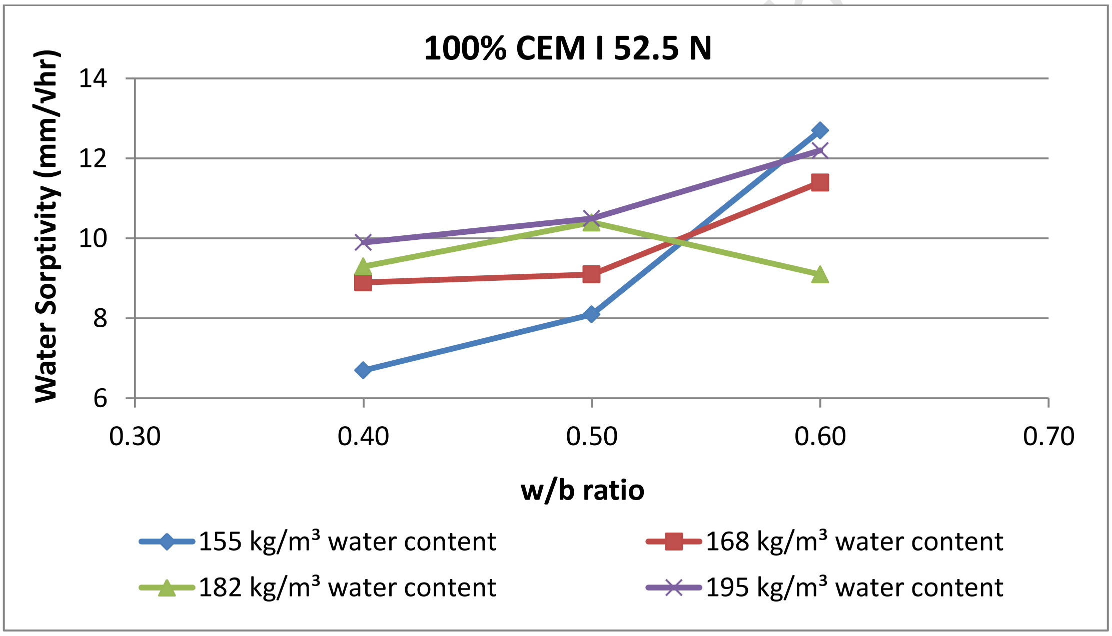


Figure 79: Influence of w/b ratio and paste volume on water sorptivity of CEM I concretes

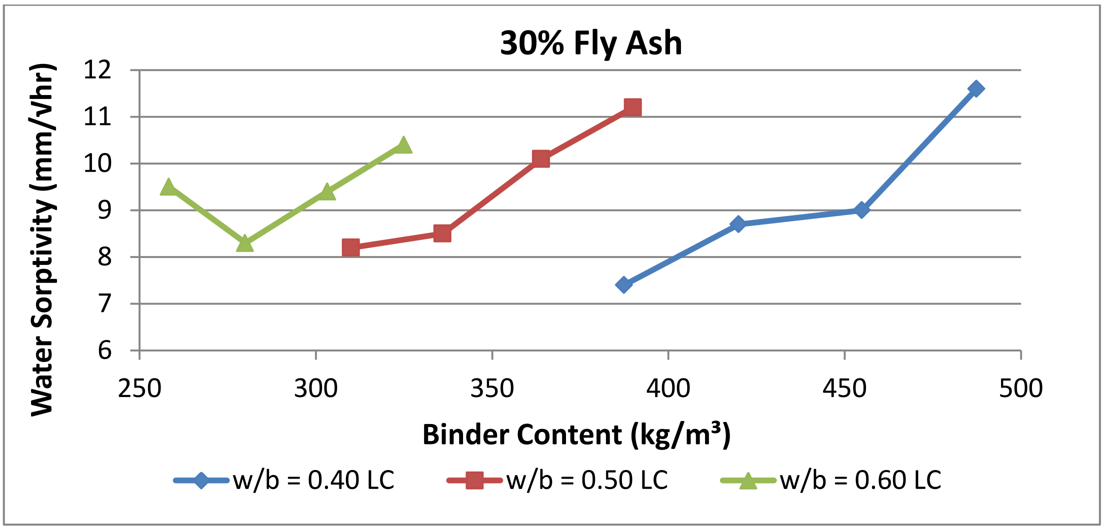


Figure 80: Influence of binder content and paste volume on water sorptivity of Fly Ash concretes

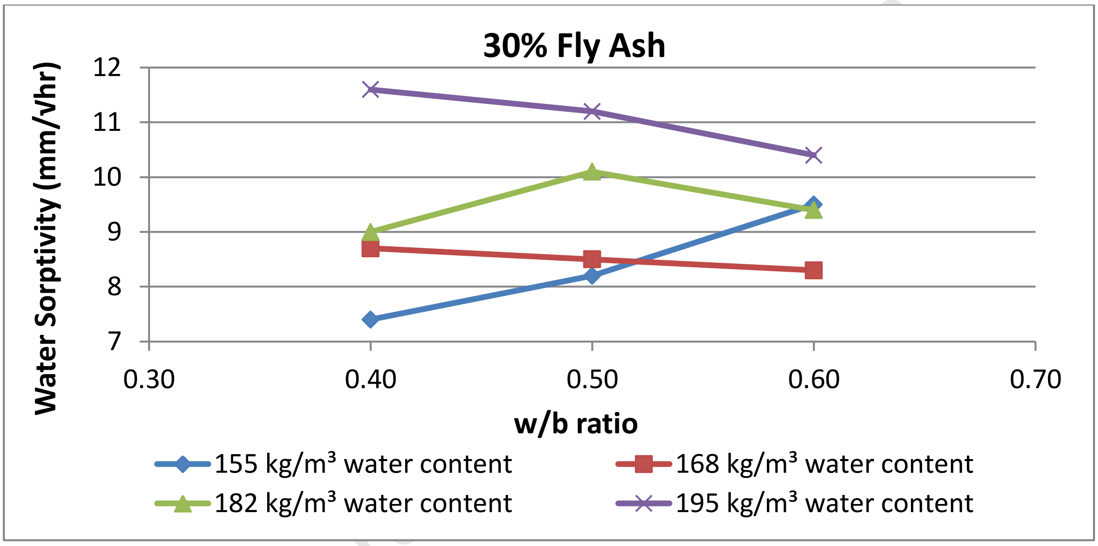


Figure 81: Influence of w/b ratio and paste volume on water sorptivity of Fly Ash concretes

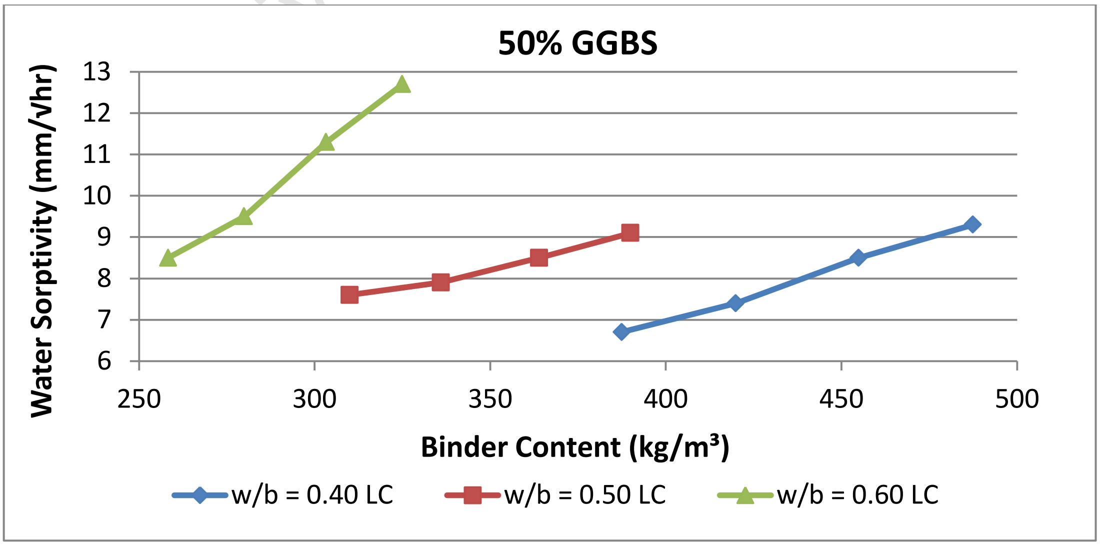


Figure 82: Influence of binder content and paste volume on water sorptivity of GGBS concretes

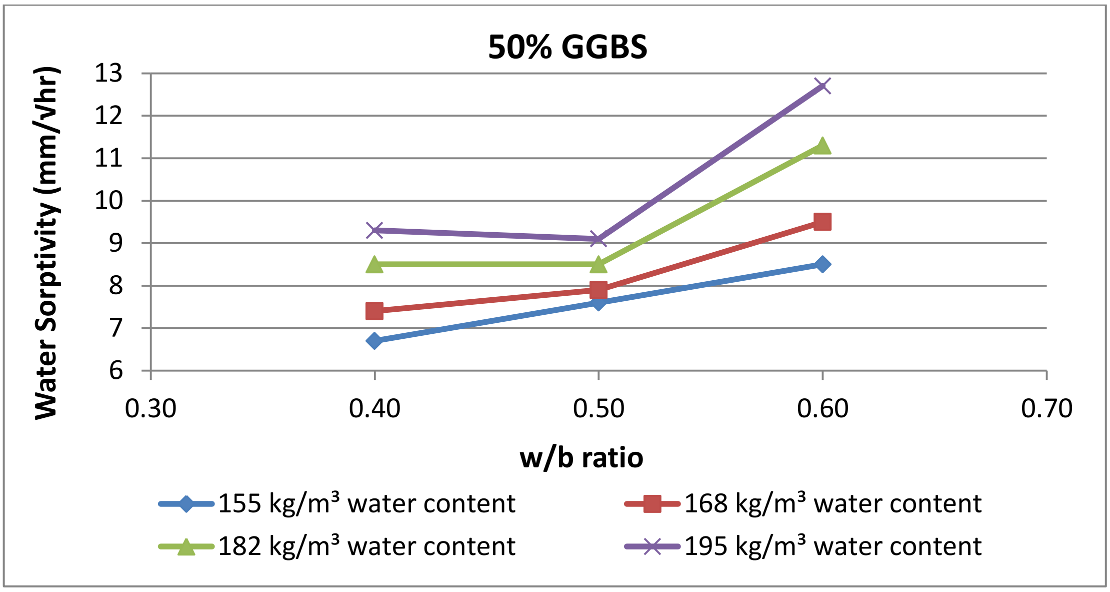


Figure 83: Influence of w/b ratio and paste volume on water sorptivity of GGBS concretes

The general observation identified for all binder types and w/b ratios was that increases in paste volume led to an increase in water sorptivity (Figures 78, 80 and 82). This made sense initially by using the same reasoning as in the permeability analysis. It is unclear as to why the increase in water sorptivity values of CEM I concretes did not always correspond to an increase in paste volume, as in the case for 182 kg/m^3 water content. The effect of w/b ratio on water sorptivity was not the same for all binder types. For CEM I and GGBS concretes (Figures 79 and 83 respectively), increases in w/b ratio led to an increase in water sorptivity values, while there was no clear trend in the influence of w/b ratio on the sorptivity of fly ash concretes (Figure 81). It is not clear as to why this occurred.

It must be noted, though, that water sorptivity calculations are made by accounting for paste volume, since sorptivity results are normalised with porosity (refer to South African DI manual, 2010). These results were therefore not expected. This is addressed in more detail in the explanation of Figures 84 – 89 below.

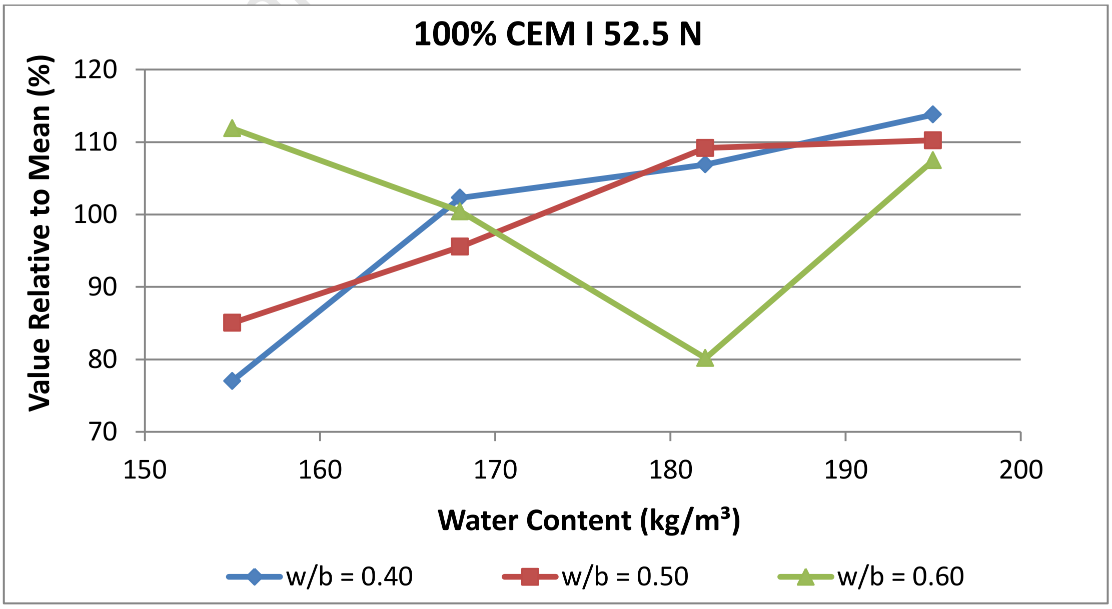


Figure 84: CEM I concretes - relative water sorptivity with respect to water content (paste content)

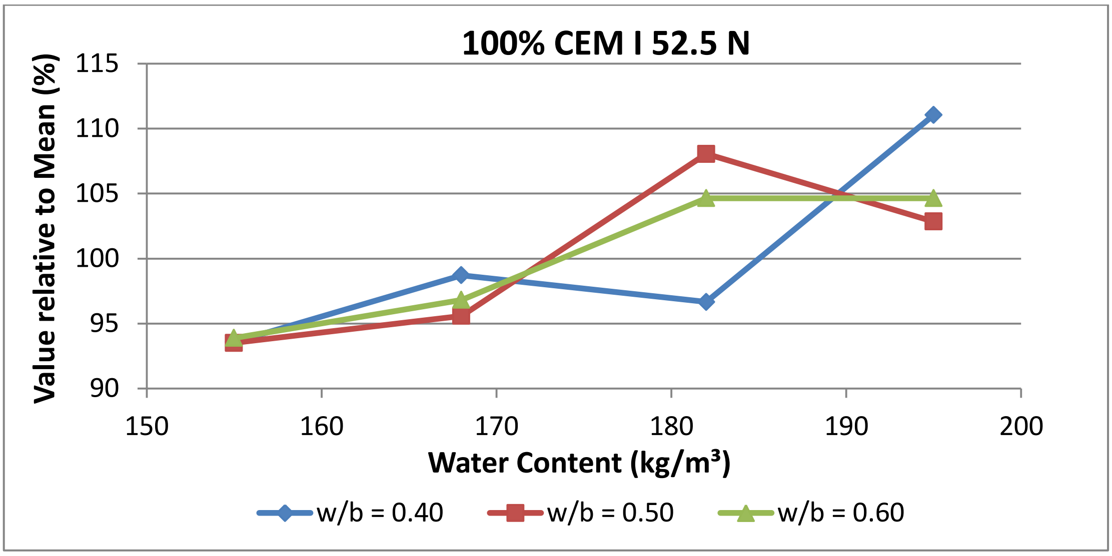


Figure 85: CEM I concretes - relative porosity with respect to water content (paste content)

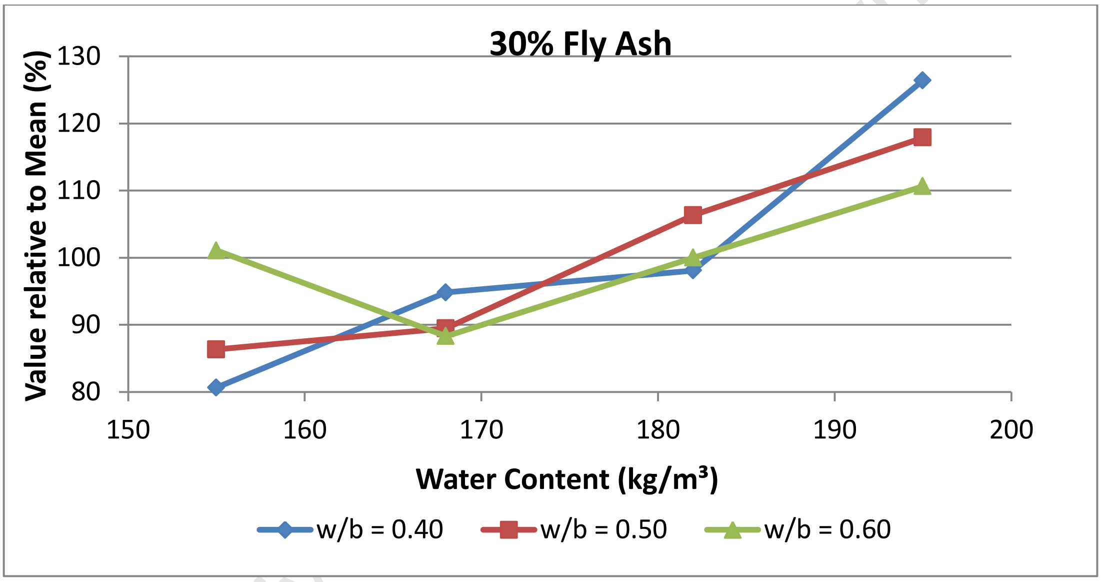


Figure 86: Fly Ash concretes - relative water sorptivity with respect to water content (paste content)

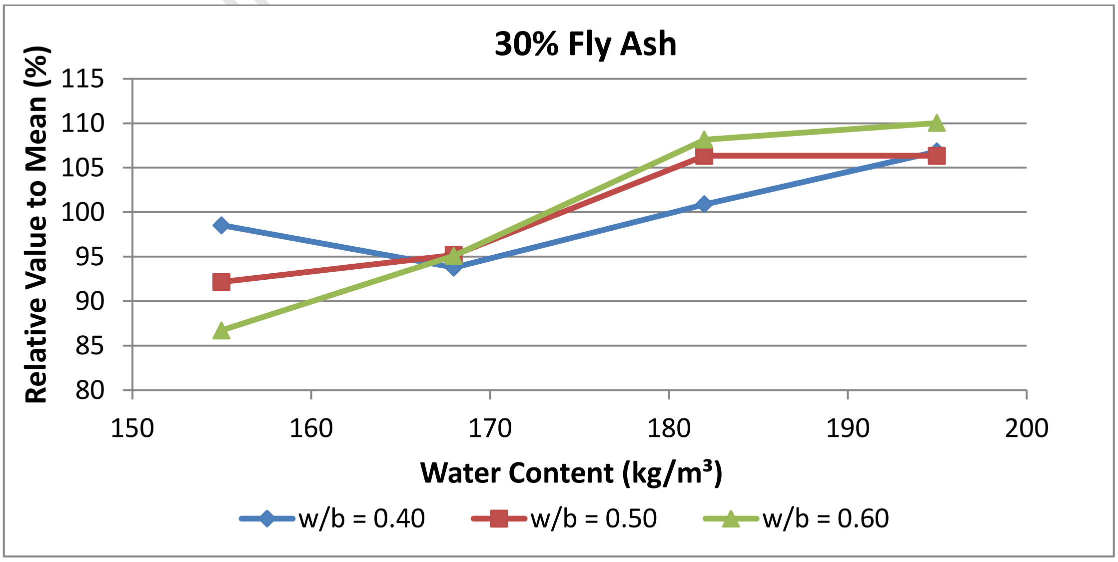


Figure 87: Fly Ash concretes - relative porosity with respect to water content (paste content)

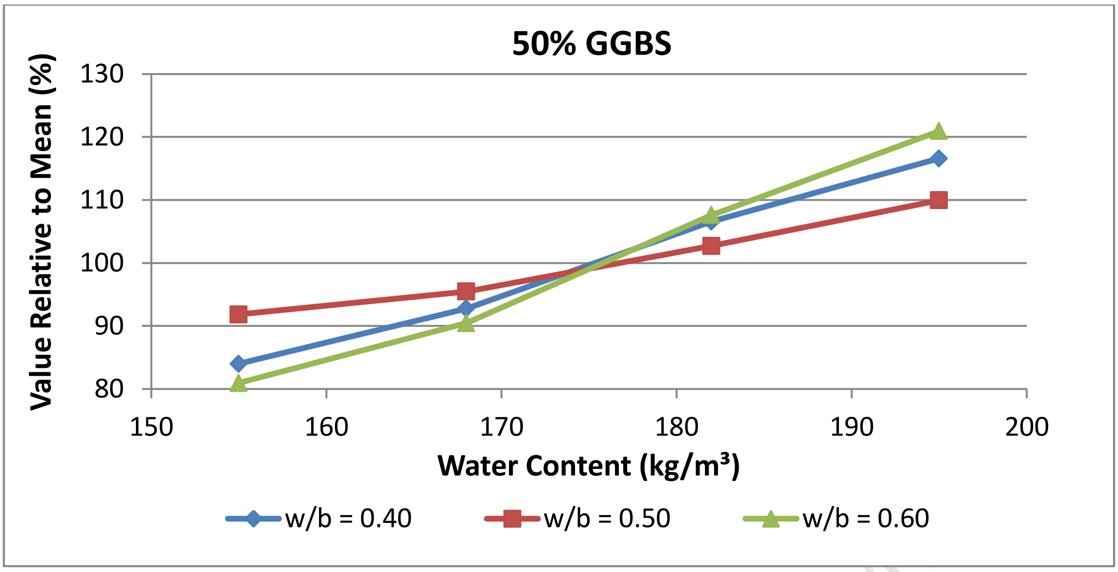


Figure 88: GGBS concretes - relative water sorptivity with respect to water content (paste content)

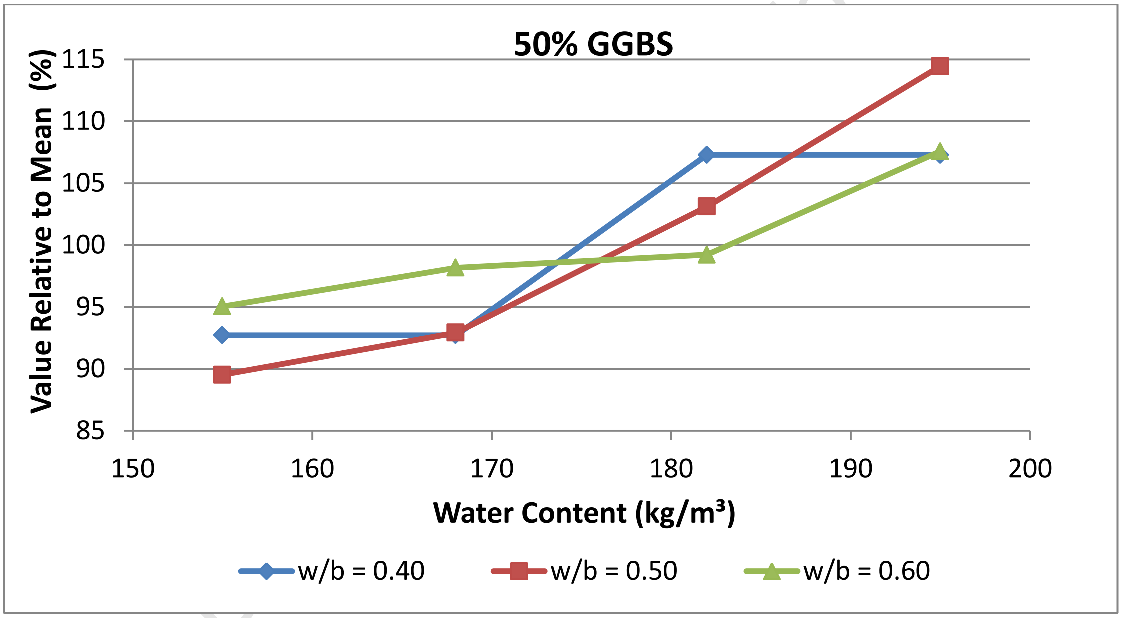


Figure 89: GGBS concretes - relative porosity with respect to water content (paste content)

It is clear that increasing paste volume led to a more pronounced increase in water sorptivity values than the increase in porosity values of the concretes. Hence, when results were normalised, higher sorptivity values were divided by porosity values that increased at a more gradual rate, thus sorptivity experienced an overall increase. Porosity is a measure of the bulk concrete (in this case of the sample), expressed as a percentage with respect to pore volume. Sorptivity is the measure of the absorption rate of the cover layer. Since both properties link directly to pore size distribution, it may be that pore size distribution of the concrete was affected in such a way as to cause a more pronounced change in sorptivity properties than in the total porosity of the sample. This cannot be verified at this stage, but what these results strongly show is that water sorptivity is also affected negatively by increasing paste contents for constant w/b ratios. This negative influence is however not as pronounced as the influence of paste content on permeability, but still needs to be considered in mix design.

Chloride Conductivity

Unlike permeability, resistance to chloride conductivity provided by the paste is both a physical and chemical mechanism; physical because chloride ions move by diffusion through the paste; and chemical because a portion of these ions is bound by the aluminates in the cement/binder. Since chloride conductivity values can be linked to the ingress of chlorides into the concrete, it is important to remember that values obtained for concretes with similar water contents but different binder types may display similar physical characteristics (same paste volume) but different chemical characteristics (different chemical proportions which affect chloride binding capabilities). Results are displayed in Figures 90 – 95.

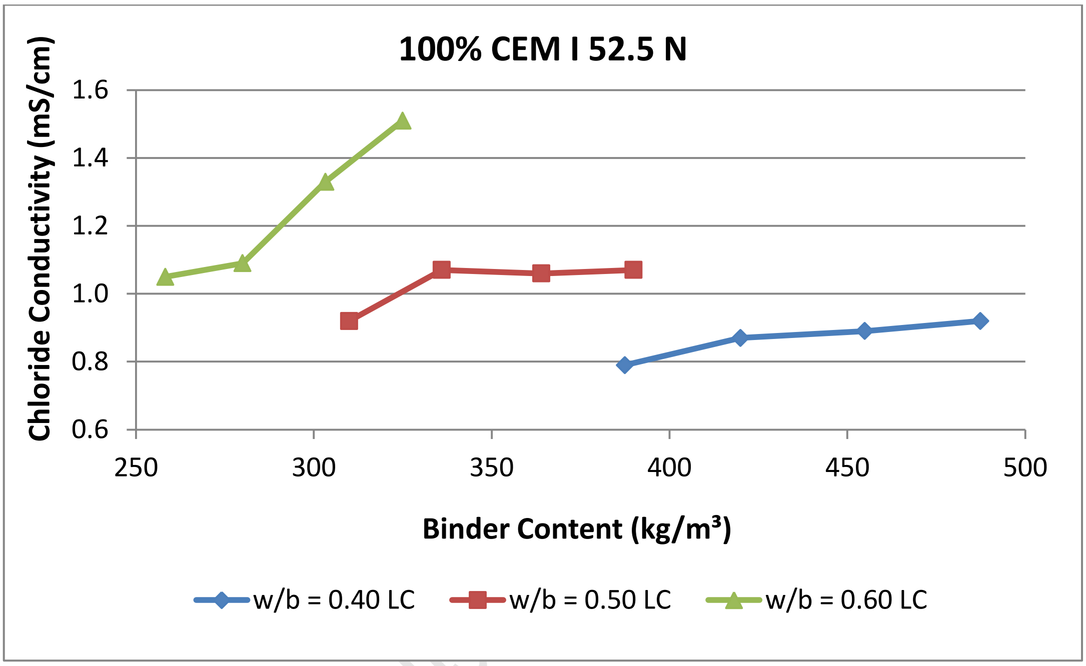


Figure 90: Influence of binder content and paste volume on chloride conductivity of CEM I concretes

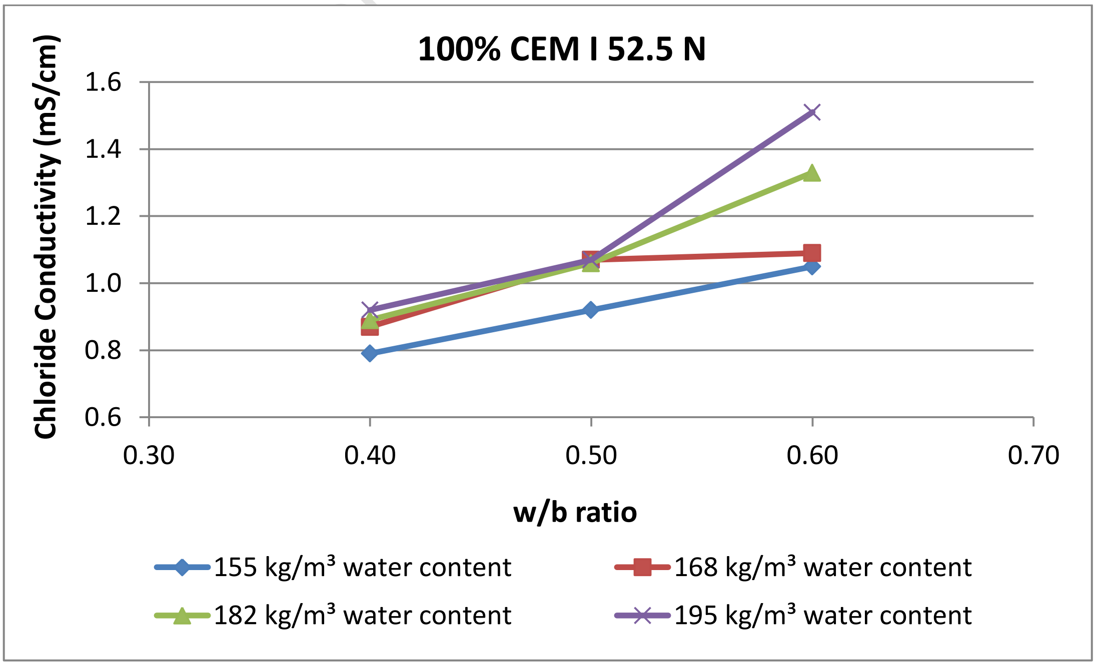


Figure 91: Influence of w/b ratio and paste volume on chloride conductivity of CEM I concretes

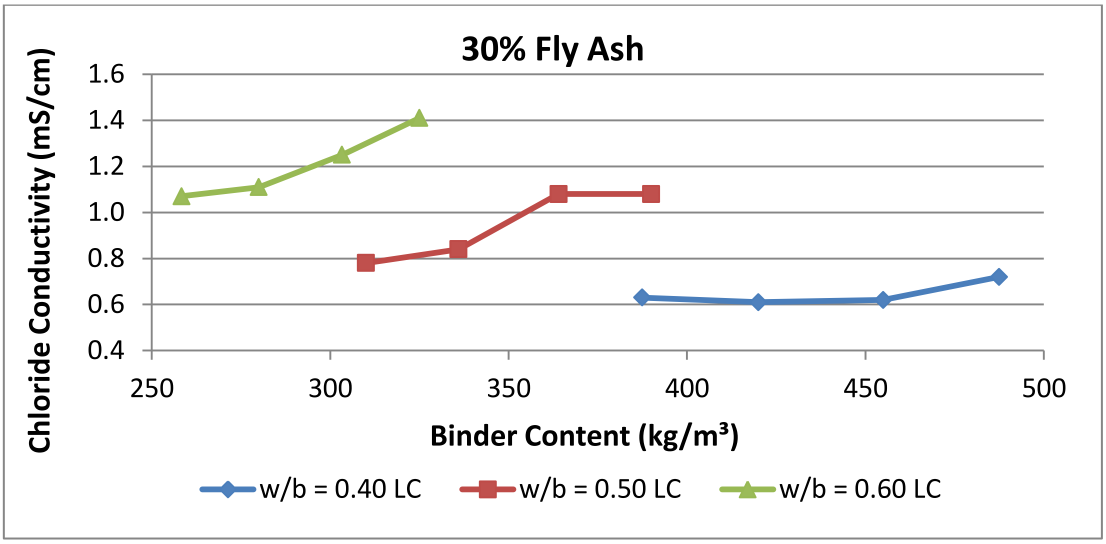


Figure 92: Influence of binder content and paste volume on chloride conductivity of Fly Ash concretes

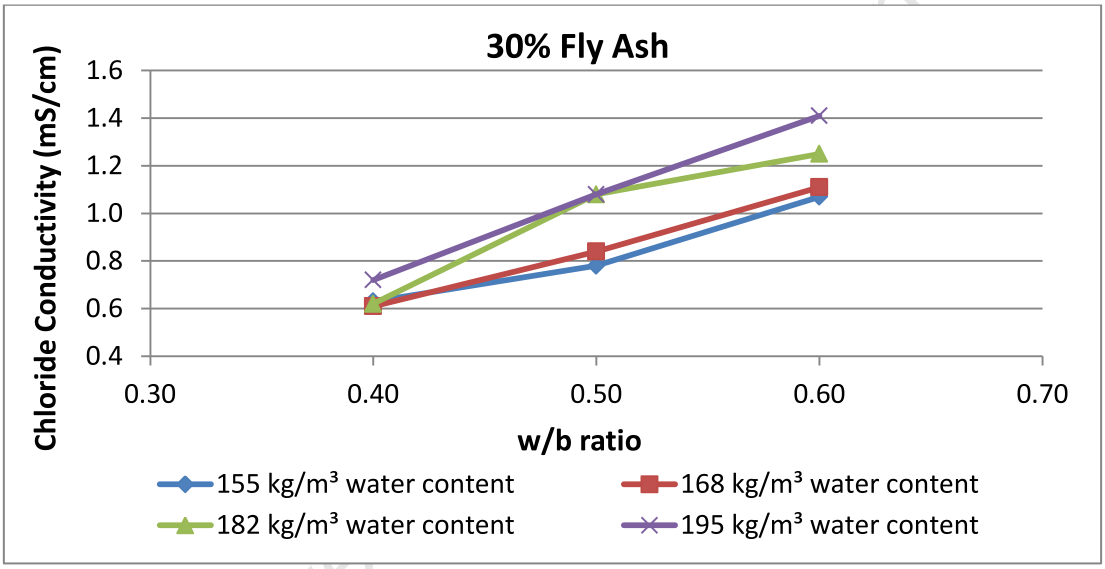


Figure 93: Influence of w/b ratio and paste volume on chloride conductivity of Fly Ash concretes

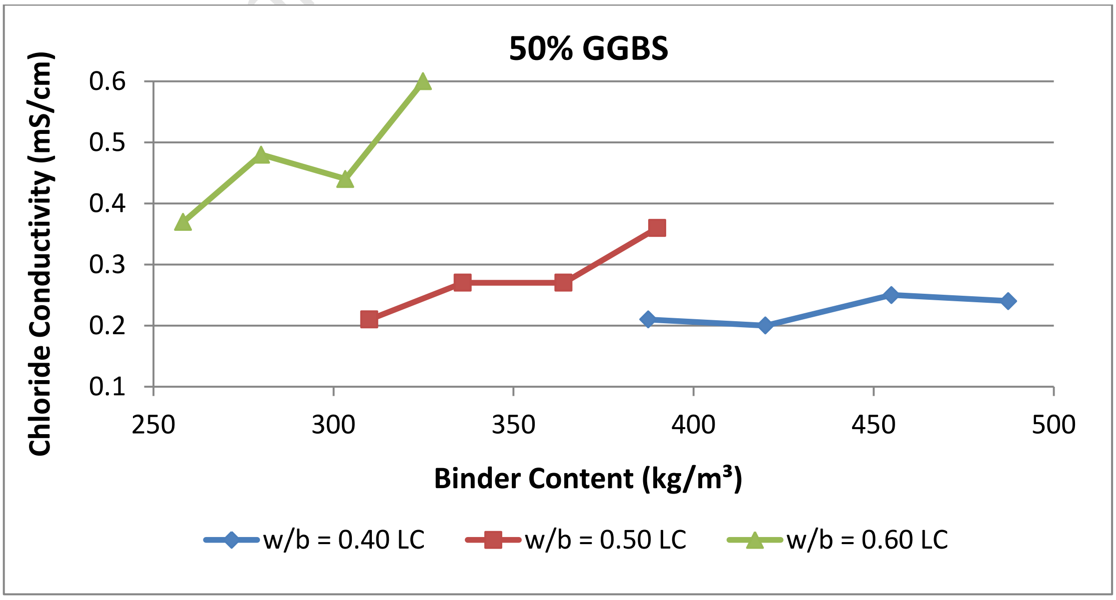


Figure 94: Influence of binder content and paste volume on chloride conductivity of GGBS concretes

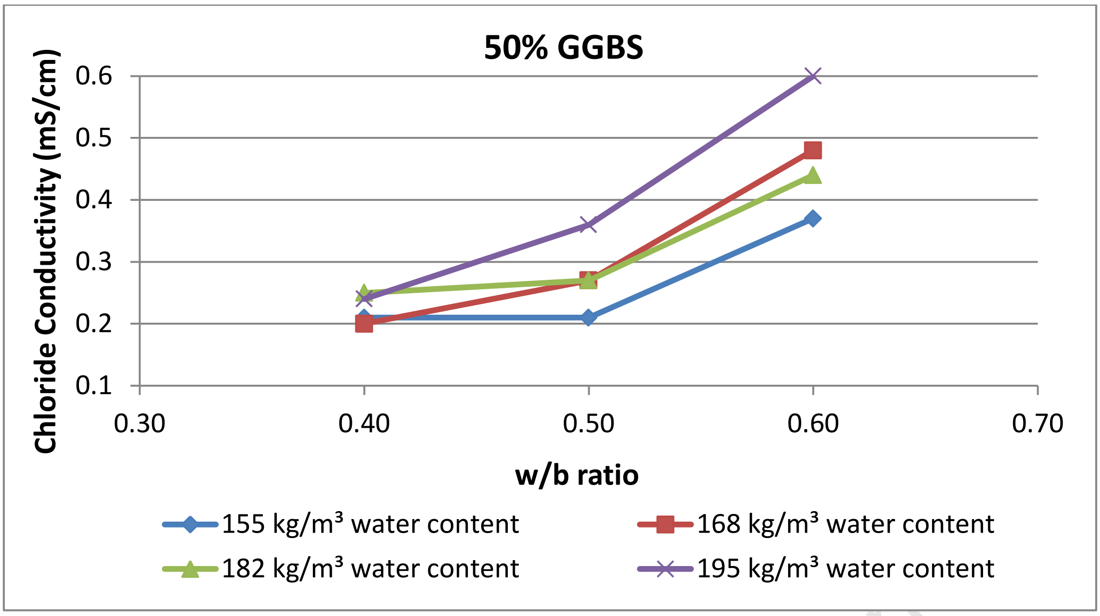


Figure 95: Influence of w/b ratio and paste volume on chloride conductivity of GGBS concretes

From the displayed results, increases in paste content generally caused an increase in chloride conductivity values. This made sense since it coincided with the results observed in previous sections for permeability. The difference in conductivity values between w/b ratios is also evident in the results, with increases in paste volume at low w/b ratios having a more gradual effect on the quality deterioration of the concretes. As the w/b ratio was increased, this effect was more pronounced. Reasoning behind this is similar to that noted for permeability. The values obtained for the fly ash were generally lower than CEM I values. This is attributed to the better chloride binding capabilities of the fly ash due to the higher amount of aluminates. GGBS concretes displayed the lowest values relative to all the experimental mixes. This was due to their enhanced chloride binding capabilities, more than concretes made with CEM I or fly ash. The effect of GGBS on chloride resistance properties of concrete, and its increased use over other extenders for this purpose, is well documented in literature. Such results were thus expected.

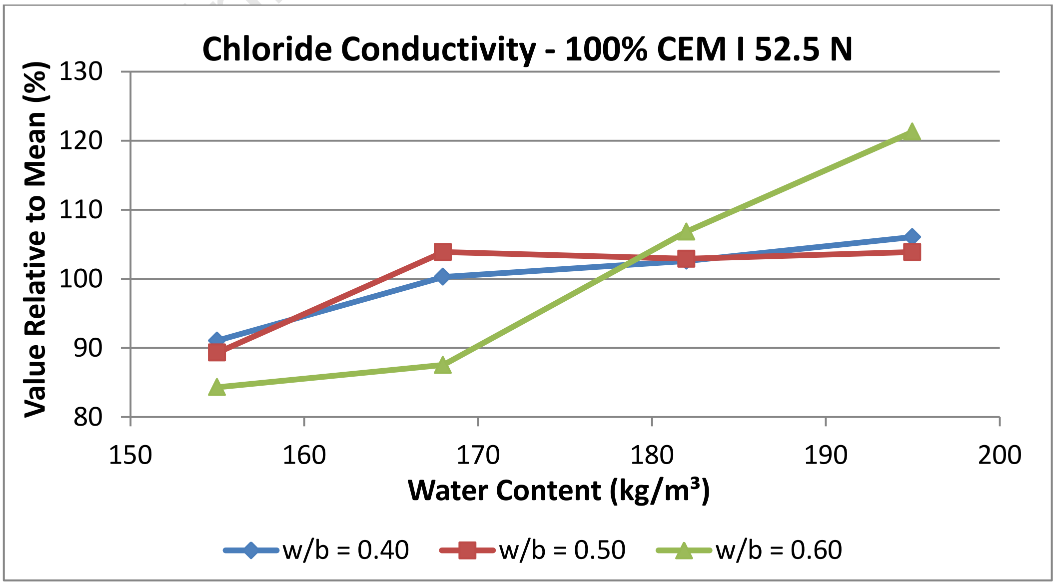


Figure 96: CEM I concretes - relative conductivity with respect to water content (paste content)

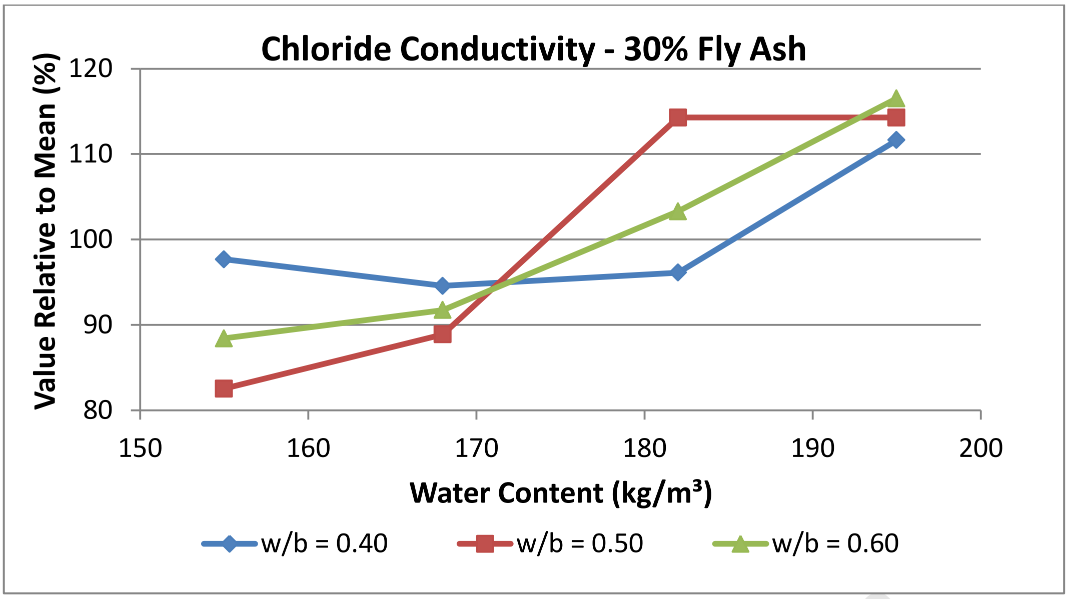


Figure 97: Fly Ash concretes - relative conductivity with respect to water content (paste content)

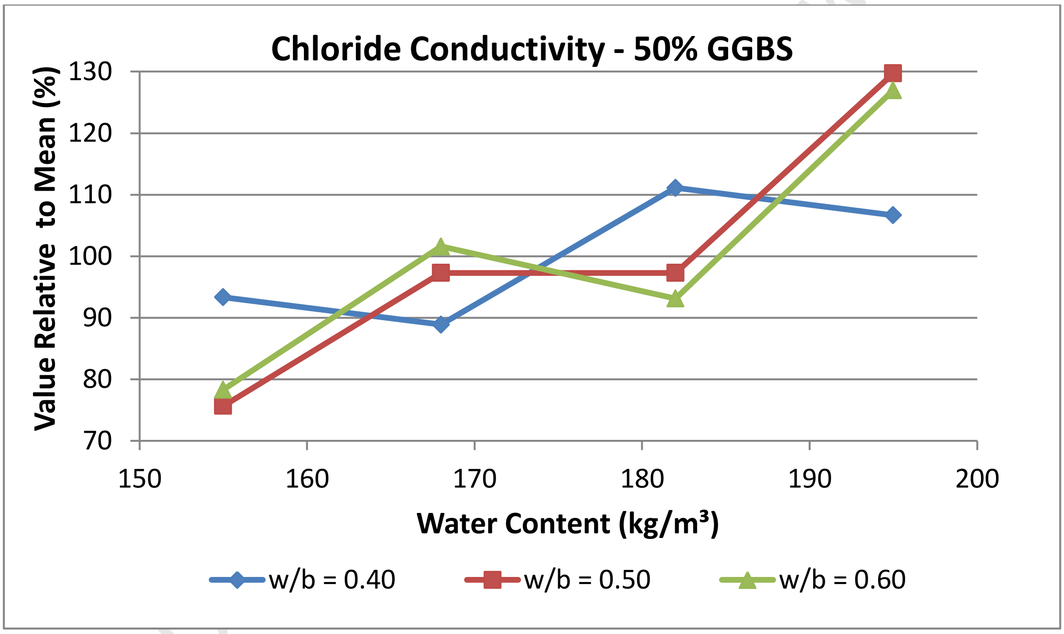


Figure 98: GGBS concretes - relative conductivity with respect to water content (paste content)

Figures 96 – 98 summarise the results presenting them in relation to a mean conductivity value, as was done for permeability and water sorptivity. These figures further highlight the negative influence that increasing paste content has on chloride conductivity properties. It is also worthwhile mentioning that, as in sorptivity, increases in conductivity were not of the same extent as those identified in permeability. Reason for this could be that resistance to chloride conductivity is provided by both physical means (nature of the microstructure) and chemical means (chloride binding). Hence the combination of the two somewhat reduced the negative effect on conductivity imparted by increasing paste contents in relation to permeability. This would imply that the physical aspect i.e. the nature of the microstructure has a larger influence on chloride conductivity properties. This coincides with trends identified in literature (Ballim et al, 2009). A summary of durability index results for all binder types and curing regimes can be found in Appendix C.

5.5 Results Summary

The trends identified in the analysis of results differ in their onset according to which binder type and durability index parameter is being considered. Hence the following section provides a summary on how w/b ratio and binder content affect durability indices. This is achieved by discussing the effects of the two parameters with reference to paste content, a parameter that has been identified as significant in understanding the link between durability indices and concrete microstructure.

5.5.1 Compressive Strength

The relationship between w/b ratio and compressive strength is fundamental and well-documented. A reduction in w/b ratio is brought on by either reducing the water content or increasing the binder content in a concrete mixture. Binder particles are then situated in closer proximity and stronger hydration products develop over shorter distances. Concretes with lower w/b ratios are stronger because of the predominance of "inner product" in the paste (Hover, 2011), but also because they essentially have a smaller proportion of paste diluting a larger proportion of aggregates; recall Figure 11 (Malhotra, 1994), which compares the microstructure of low w/b ratio and high w/b ratio concretes. This means that the energy required for a fracture crack to propagate is higher when there are more obstacles (aggregates) to encounter. For all binder type combinations, the influence of w/b ratio on compressive strength was clear. As w/b ratio is increased, compressive strength is reduced. This result coincides with results shown in previously published research (Hover, 1998; Kolias et al, 2005; Wasserman et al, 2009) and is a well established result. The influence of paste content on compressive strength, however, had to be dealt with separately for each binder type.

In Portland cement concretes, increasing the paste content for a constant w/b ratio had no identifiable effect on compressive strength (similar trend observed in work conducted by Wasserman et al in 2009). When analysing the results with respect to the aggregate mass/cementitious mass ratio, this trend was further confirmed, though it differed from results obtained by Grdić et al. (2010). Possible reasons for this were identified in the finer nature of the CEM I 52.5 N particle, which could result in a denser, stronger microstructure.

For blended concretes, the opposite was observed. Increasing the paste volume had detrimental effects on the mechanical characteristics of blended concretes. This also coincided with previously published results (Kolias et al, 2005; Yiğiter et al, 2007). Investigation into the aggregate mass/cementitious mass ratio revealed that in blended concretes, with higher paste homogeneity, low paste contents possibly result in an improvement in microstructure of the ITZ. This allows better interaction between aggregates and cement paste. Increases in paste volume were thus detrimental as they resulted in excessive amounts of paste to bind the aggregates.

The effects of increasing paste content were therefore identified in the current experimental study as being negligible towards strength development of Portland cement concretes. For blended concretes, they caused detrimental effects to strength development.

5.5.2 Permeability

In Portland cement concretes, increasing w/b ratio for a given paste content seemed to have a negligible effect on permeability characteristics, seemingly due to the fine nature of the CEM I 52.5 N particles. This seemed strange since the higher proportion of paste in higher w/b ratio concretes should have resulted in higher pore fraction and thus higher permeability. However it is possible that the fine nature of CEM I 52.5 N particles resulted in more hydration per unit time and thus made permeability fairly insensitive to changes in w/b ratio. When binder content was changed for a constant w/b ratio, the resulting increase in paste content had a significant effect on permeability. This made sense since increasing the paste content meant increasing the volume of the phase which contributed highly to penetrability of the concrete system.

In the blended concretes (fly ash and GGBS), the effect of w/b ratio on permeability was somewhat more evident than in CEM I concretes, but only for higher paste contents. This may have been attributed to the homogeneous microstructure of blended concretes, resulting in improved constituent phases such as cementitious paste and ITZ. Previous results (Alexander & Magee, 1999; Kolias et al, 2005; Grieve, 2009) showed that increasing w/b ratio and increasing paste content are detrimental to permeability. In the current study similar trends for w/b ratio were identified, but only for blended concretes. In CEM I concretes, no prominent influence of w/b ratio on permeability could be identified. Based on the above observations, it can be deduced that permeability is very susceptible to changes in paste content for a constant w/b ratio and also to changes in w/b ratio, depending on the binder type.

5.5.3 Water Sorptivity

In Portland cement concretes, changes in w/b ratio did not result in pronounced changes in water sorptivity, though they still managed to have an effect. This could have been due to the fine nature of the CEM I 52.5 N particles, which could have resulted in a denser and less porous microstructure despite changes in w/b ratios for a constant paste content. Changes in binder content for a constant w/b ratio proved to be more influential.

In the case of blended concretes, the influence of w/b ratio on fly ash concretes could not be generalised since it resulted in different trends observed for different paste contents. It is unclear as to why this occurred. Increases in paste content did however cause increases in water sorptivity values. In GGBS concretes trends were more identifiable. Water sorptivity was affected negatively by increases in w/b ratio for a constant paste content, as well as increases in paste content for a constant w/b ratio, with the latter being more pronounced.

In previously published work, the observed trend was that increasing w/b ratio caused a pronounced increase in water sorptivity (Mackechnie & Alexander, 2001b; Grieve, 2009). Little evidence is found in literature investigating the influence of paste content on water sorptivity. In the current study, w/b ratio was found to have somewhat of an influence on water sorptivity (except for fly ash concretes, where observed trends were not clear). Increasing paste content for a constant w/b ratio was however identified as detrimental for all binder types.

5.5.4 Chloride Conductivity

In Portland cement concretes, increasing w/b ratio for a given paste content had a detrimental effect on chloride conductivity characteristics. Increases in w/b ratio caused an increase in the penetrability of the concrete system, hence this was expected. When binder content was changed for a constant w/b ratio, the resulting increase in paste content also had a detrimental effect on chloride conductivity. Here the mechanisms consisted in the combination of physical resistance (increase in paste content meant more penetrable material for diffusion of chloride ions) and chemical resistance (increase in paste content also implied more hydration products to provide chloride binding capabilities). The dominance of physical resistance to chemical was highlighted by the fact that at low w/b ratios, increases in paste content still caused a slight increase in conductivity values.

Similar trends were observed for blended concretes (fly ash and GGBS). The effect of w/b ratio on conductivity was fairly evident for all paste contents. Increasing paste content for a constant w/b ratio did, however, cause more prominent changes in conductivity values. At low w/b ratios, the homogeneous nature of the microstructure of the blended concretes, coupled with the filler effect at low w/b ratios, resulted in conductivity not changing significantly with increasing paste content. At higher w/b ratios, paste proportion already played a significant role initially and thus increases in paste content resulted in larger increases in chloride conductivity values.

Results from previously published work (Kolias et al, 2005; Yiğiter et al, 2007; Grieve, 2009; Wasserman et al, 2009) highlighted the detrimental effects on chloride conductivity associated with increasing w/b ratio and increasing paste content. In the current study, similar trends were identified for all experimental concretes. The negative effect of increasing paste content at a constant w/b ratio on chloride conductivity was more prominent than increasing w/b ratio for a constant paste volume. Hence it can be deduced that conductivity is much more sensitive to changes in paste content for a constant w/b ratio than to changes in w/b ratio for a constant paste content.

5.5.5 General Comments

Increases in paste content (water content and binder content) for a constant w/b ratio were identified as detrimental to strength development of fly ash and GGBS concretes. Their effects on the strength development of Portland Cement concrete was identified as negligible, possibly due to some unknown effects imparted by the finer nature of the new CEM I 52.5 N. Investigation into the influence of compressive strength on DI parameters in Section 5.3 revealed the general trend that increases in strength generally resulted in improvements in DI parameters. Since higher strengths are generally associated with denser microstructure, this result was expected. This trend was observed for all binder types and curing regime, though the extent and nature of the improvement largely depended on the binder type combination and curing regime selected.

5.6 Practical Implications for Concrete Mix Design

In the previous sections, investigations were carried out into the effects of various parameters on concrete durability indices. Where applicable, clear trends were identified and discussed. The aim of this section was to therefore transcribe these trends into guidelines for the mix design process. Trends discussed in this chapter were analysed in a simplified manner in order to draw practical conclusions applicable to real-life structural scenarios. The objective was to clarify what to aim for in mix design for a particular project.

The trends identified and discussed in this chapter were grouped together with respect to the concrete property parameter in question for each binder type. The legend, displayed in Table 22 was used to simplify the findings in a practical manner for the purposes of this section.

Table 22: Legend used for simplified trends

Description	Symbol
Significant Positive Influence	✓✓
Slight Positive Influence	✓
None/Negligible Influence	□
Slight Negative Influence	×
Significant Negative Influence	××

Two analyses were carried out. The first one evaluated the effect that changes in w/b ratio and paste content had on compressive strength. The second analysis evaluated the effects that changes in compressive strength, w/b ratio, paste content and curing had on permeability and chloride conductivity. These two durability indices were chosen because of the relationships that have been identified in previous research between OPI values and carbonation depths, as well as between chloride conductivity values and chloride ingress (Mackechnie & Alexander, 2001a).

Changes in the dependent variables in this analysis were symbolised by a (-) for decreases and a (+) for increases. Results are displayed in Tables 23 to 25 respectively.

Table 23: Influence of mix design parameters - compressive strength

	CEM I	**FA**	**GGBS**
w/b ratio (-)	✓✓	✓✓	✓✓
paste content (+)	□	×	×

From Table 23, a reduction in w/b ratio has a significantly positive influence on strength, while increasing paste content had a negligible influence on the strength of CEM I concretes and a slight negative influence on the strength of blended concretes. Depending on the nature of the project at hand and the exposure environment, different binder combinations may have to be selected. For example, in large scale structures like dams, GGBS is usually useful for maintaining low heats of hydration. Selection of an appropriate w/b ratio would be made based on strength requirements. However, given the adverse effects associated with increasing paste content in blended concretes, consideration must also be made with respect to the paste content. In cases where CEM I concrete is used, increasing paste content may have negligible effects on strength, but should still be considered for economical reasons (cement is an expensive component of concrete and increases in paste content should be minimised if not justified), as well as other durability concerns such as shrinkage and ASR.

As mentioned before, a good correlation has been identified between oxygen permeability indices and concrete carbonation depth. Hence requirements for OPI become quite important if the exposure environment makes the structure susceptible to carbonation-induced corrosion. EN 206 labels such exposure environments XC (recall Table 2 in Chapter 2 of this study). The selection of mix design parameters and curing regime can play a significant role in determining the permeability of concrete.

Table 24: Influence of strength and mix design parameters – oxygen permeability

	CEM I	**FA**	**GGBS**
w/b ratio (-)	□	✓	✓
paste content (+)	××	××	××
Fc (+)	□	✓	✓
Water Curing to Lab Curing	×	××	×

Table 24 shows the results of the simplified permeability analysis. In CEM I concretes it was found that changes in both compressive strength and w/b ratio did not cause any significant changes in values of permeability coefficient. Increase in paste content, however, had a significantly negative influence on permeability of CEM I concretes. Lab curing in relation to water curing also had a negative influence, although slight. Blended concretes resembled each other's trends, with increasing paste content found to have a significant negative influence on permeability. Reduction in w/b ratio, however, had a positive influence. Changing from water curing to lab curing had a negative influence on both blended concretes. Such results suggest that when designing concrete mixes to minimise permeability, paste content can have a larger influence than w/b ratio or curing regime.

Another good correlation identified in previous research is the one between chloride conductivity values and chloride ingress, and thus chloride-induced corrosion in concrete. For structures such as ports, harbours or any building located in coastal environments, exposure to chlorides becomes a crucial consideration. Specifically in ports and harbours (denoted as XS in EN 206), zones that are affected by the tidal wetting and drying cycles are the most vulnerable to the onset of corrosion. This occurs because the following happens in these zones:

- There is a continuous change in concentration gradient of chlorides – from unsaturated in dry conditions, to saturated in wet conditions.

- The same change in concentration gradient occurs for oxygen, a key requirement for the onset of the corrosion process. Hence oxygen is continuously able to penetrate the concrete and take part in the corrosion mechanisms.

Previous research, some of which is present in this study, has shown the benefits of using fly ash and GGBS in minimising chloride-induced corrosion. Apart from binder type selection, curing regime and selection of mix design parameters can also help in reducing chloride conductivity, which can have a positive impact on the onset of chloride-induced corrosion.

Table 25: Influence of strength and mix design parameters – chloride conductivity

	CEM I	**FA**	**GGBS**
w/b ratio (-)	✓	✓	✓
paste content (+)	××	××	××
Fc (+)	✓	✓	✓
Water Curing to Lab Curing	☐	××	☐

Table 25 displays the results of the simplified analysis with respect to chloride conductivity. The influence of w/b ratio was the same for all binder types, as was that of compressive strength. A reduction in w/b ratio (corresponding to an increase in compressive strength) had a positive influence on the chloride conductivity characteristics. The negative effect of increasing paste content was, however, much more pronounced. When looking at the influence of curing, it was interesting to see that in CEM I concrete and GGBS concrete, no significant effects were identified. It is not clear as to why. The highly negative influence on fly ash concrete is evidence of the pozzolanic reaction’s requirement for moisture. These results point to the fact that variations in the paste content of a concrete mix also affect chloride conductivity highly, more so than changes in w/b ratio or compressive strength. The design of concretes to be exposed in a marine environment should therefore aim at achieving a sufficiently dense microstructure (low w/b ratios and thus high compressive strength), but to do so while also minimising the paste content.

5.7 Strength and DI Comparative Analysis-Experimental vs Prescriptive

The experiments conducted in this investigation yielded results from which specific trends were identified. One such trend of particular importance is that the influence of increasing binder content cannot be associated with beneficial effects on concrete durability index parameters. The prescriptive specifications found in BS EN 206 Part 1 consist in limiting values such as minimum binder content, maximum w/b ratio and minimum compressive strength for durability enhancing purposes. Since the results obtained by the experimental study seem to suggest that the impact of such factors like binder content on concrete durability cannot be simply expressed in terms of prescriptive parameters, a comparative analysis between the experimental concretes and concretes designed according to the prescriptive specifications would be quite useful to further validate this discovery.

In a previous study conducted in 2009 by Wieland, different service life design approaches (prescriptive approaches) for the design of reinforced concrete structures, mainly focusing on carbonation and chloride attack, were compared theoretically in relation to each other. Furthermore, a comparison between these prescriptive approaches and the South African performance-based approach for durability was carried out by means of experimental work. The prescriptive approach used by Wieland was the approach specified in the National UK Annex of the Eurocode 2. Reason for this was that the info given in the UK National Annex was relatively more detailed than the other methods reviewed in his work with regard to strength classes in combination with exposure class. Furthermore, the National Annex gives the strength class in combination with binder type combinations, nominal cover, w/b ratio, cover depth and minimum binder content and its specifications are therefore seen as fairly strict and of the recipe type. Hence the following analysis will be conducted by selecting parameters specified in the UK National Annex.

For the purpose of this exercise, two environmental exposure classes were chosen:

- XS3 – tidal splash and spray zones; chloride-induced corrosion.
- XC4 – cyclic wet and dry; carbonation-induced corrosion.

Table 26: Prescriptive mix design parameters as for XS3 exposure class selected from Table NA 2 – cover = 50 mm (UK National Annex to BS EN 1992 -1-1:2004):

Minimum binder content (kg/m^3)	380
Maximum w/b ratio	0.40
Minimum Cube Strength Class f_{cu} (MPa)	45

Selection of only two exposure environments was deemed sufficient since these are associated with the most severe exposure conditions that the structure can be subject to with respect to chloride-induced corrosion from sea water and carbonation-induced corrosion. The prescriptive limiting parameters are summarised in Table 26 and Table 27:

Table 27: Prescriptive mix design parameters as for XC4 exposure class selected from Table NA 2 – cover = 50 mm (UK National Annex to BS EN 1992 -1-1:2004):

Minimum binder content (kg/m^3)	300
Maximum w/b ratio	0.50
Minimum Cube Strength Class f_{cu} (MPa)	37

Since chloride conductivity can be related to the ingress of corrosion-inducing chlorides in the concrete, conductivity properties become of crucial importance for the selected exposure environment XS3. Maximum chloride conductivity values at 28 days are usually specified according to a specific value of cover to the reinforcement for different exposure classes and binder types (XS3b denotes exposure to abrasion).These values are in accordance with the method of Durability Index value specification known as the deemed-to-satisfy approach (Alexander et al. 2008) and are given in Table 28.

Table 28: Maximum chloride conductivity values (mS/cm) for common structures – cover = 50 mm (Alexander et al, 2008):

EN 206 Class	70:30 CEM I:Fly Ash	50:50 CEM I:GGBS
XS3a	1.35	1.60
XS3b	1.10	1.25

OPI values can be related to the onset of carbonation, and as such become of crucial importance for exposure environment XC4. There are various standards that specify minimum recommended values for OPI based on cover and exposure environment. The value found in the latest SANRAL specifications for the selected XC4 exposure class and cover of 50 mm is 9.30. Based on the prescribed parameters and allowable chloride conductivity and OPI values given for the exposure classes XS3b and XC4, results from lab cured samples were selected from the current experimental study and were compared to the specifications set out in BS EN 1992-1-1:2004, EN 206 (Tables 26 and 27) and SANRAL. Lab-cured results were chosen as they were deemed more relevant than control samples since they represent more closely the real behaviour of concretes exposed to the respective environments. A summary of the results used in this comparative analysis is given in Tables 32 and 33. Concrete Set A and B denote results obtained in the current study.

The concretes selected for XS3 exposure class adhered to the prescriptive specifications of maximum w/b ratio, with all of them having a w/b ratio of 0.40. Results are displayed in Table 29, with w/b ratio and binder content well adhering to the limiting values of prescriptive specifications.

Table 29: Summary of results – XS3 Exposure Class

<table>
<tr><th></th><th colspan="2">Prescriptive Specs (BS EN 1992-1-1: 2004)</th><th>Concrete A
(70:30 CEM I:FA)</th><th>Concrete B
(50:50 CEM I:GGBS)</th><th>Concrete C
(100 CEM I 52.5 N)</th></tr>
<tr><td>Binder Content (kg/m³)</td><td colspan="2">380 (min)</td><td>388</td><td>388</td><td>388</td></tr>
<tr><td>w/b ratio</td><td colspan="2">0.40 (max)</td><td>0.40</td><td>0.40</td><td>0.40</td></tr>
<tr><td>Compressive Strength (MPa)</td><td colspan="2">45 (min)</td><td>63</td><td>63</td><td>61</td></tr>
<tr><td rowspan="2">Chloride Conductivity (mS/cm)</td><td>70:30 CEM I:FA</td><td>50:50 CEM I:GGBS</td><td rowspan="2">0.63</td><td rowspan="2">0.21</td><td rowspan="2">0.79</td></tr>
<tr><td>1.10</td><td>1.25</td></tr>
</table>

From Table 29, it is clear to see that all concretes achieved higher target strengths and lower chloride conductivity values than the specified values, regardless of the binder type combination. Concrete C, which represented 100% Portland cement, which is seldom used for environmental exposure class XS3, also displayed better results than the specified values. Taking concrete A as an example, even with binder content exceeding the specified minimum by only 8 kg/m^3, minimum strengths were exceeded by approximately 40% and chloride conductivity value was extremely low. This is arguably an overdesign which could also have possible implications of high heats of hydration, thermal cracking, high autogeneous shrinkage and ASR.

Table 30: Summary of results – XC4 Exposure Class

	Prescriptive Specs (BS EN 1992-1-1: 2004)	**Concrete A** **(70:30 CEM I:FA)**	**Concrete B** **(50:50 CEM I:GGBS)**	**Concrete C** **(100 CEM I 52.5 N)**
Binder Content (kg/m^3)	300 (min)	310	310	310
w/b ratio	0.50 (max)	0.50	0.50	0.50
Compressive Strength (MPa)	37 (min)	53	54	50
OPI (SANRAL Specs)	9.30 (min)	10.32	9.97	10.67

From Table 30, one can see that concretes selected for XC4 exposure class also adhered to prescriptive specifications. In all cases, the minimum recommended strength was exceeded by almost 50%, while differences in OPI values were also found to be fairly substantial (OPI is the negative log of the permeability coefficient k, hence such differences can result in large differences in permeability coefficient values). Adherence to these specifications can also lead to an overdesign which can have similar implications as the ones listed above. This comparative analysis further confirms that prescriptive specifications are often misinterpreted by treating parameters such as minimum binder content as isolated factors that determine durability. If not properly understood, these do not prove to be effective means of specification, resulting in overdesign and ultimately negative effects.

6. CONCLUSIONS & RECOMMENDATIONS

Prescriptive specifications used in mix design use limiting values of parameters such as maximum w/b ratio, minimum compressive strength and minimum binder content for “enhancing durability”. Such prescriptive specifications may have been valid in earlier times, when advances in materials technology had not been made yet (there was no availability of chemical admixtures to enable low w/b ratio concretes with adequate workability; the need for fines could not be met by the use of fillers currently available in industry; use of supplementary cementitious materials was not common). Despite modern advances in materials technology (water-reducing admixtures, industrial fillers and cement extenders), prescriptive specifications are still dominantly used.

Review of the available literature has shown that there is ample research that has been conducted on the influence of prescriptive parameters on concrete durability, particularly the negative influence of increasing paste volume (increasing binder content for a constant w/b ratio). Research into the South African Industry Sector (Chapter 3) showed that interpretation of prescriptive specifications results in the use of high, at times excessive, binder contents, potentially leading to over-design with respect to both compressive strength and durability indices. A likely outcome of adopting such trends is the use of concretes that are uneconomical and less sustainable due to the high amounts of cement used. Furthermore, they may also display technical flaws imparted by high binder contents such as high shrinkage, thermal deformation and alkali-silica reactions.

Adherence of prescriptive specifications is aided by the general opinion among professional engineers that high binder contents are a guarantee for higher durability. This was one of the initial arguments of this thesis and was later verified in Chapter 3. What this suggests is that there is a severe misunderstanding of concrete durability and how the choices made during the mix design process can affect it i.e. the influence on durability of the selection of mix design parameters, and thus, indirectly, compressive strength. The aim of this research was to investigate the relationships between durability and such factors. This would serve as a thorough and complete study to describe how changes in microstructure, resulting from selection of different parameters during mix design, influence concrete durability.

The parameters chosen for the investigation were mostly intrinsic in nature. This was done so as to emphasise the influence of the choice of specific mix design parameters on the resulting microstructure. Parameters consisted of w/b ratio, binder content and binder type combination. Quantities were chosen to encompass mixes representing structural concretes conventionally used in industry, but also to include mixes with low and high water contents to better identify experimental trends. For this reason, the range of water contents was maintained between 155 L/m^3 and 195 L/m^3 for all binder types and w/b ratios. Curing regime, an extrinsic parameter, was also selected to simulate site-curing and highlight differences between material potential (full-water curing) and as-built quality (lab-curing).

From the results obtained in the study it can be concluded that the durability of concrete cannot be generalised in terms of limiting parameters, but that it needs to be considered as a “system” concept, where numerous interrelated factors (intrinsic and extrinsic) affect specific aspects of durability of certain binder types in different ways.

6.1 Compressive Strength

Compressive strength of blended concretes was found to be positively affected by reductions in paste content (water content and binder content for a constant w/b ratio). Increases in strength were generally associated with improvements in durability indices. The extent of the improvement depended on the binder type in question. For example, permeability of CEM I concretes was negligibly affected by increases in strength, while the influence on blended concretes was more pronounced.

The influence of w/b ratio on strength was prominent for all binder types, with reductions in w/b ratio causing significant improvements in strength, as expected. Controlling w/b ratio remains an effective way of controlling compressive strength, but it can be argued that in projects where environmental exposure requires the use of alternative binders and where compressive strength is a primary concern, minimising paste volume can be an additional tool. Minimising paste content can hence impart additional benefits to obtain the desired results.

6.2 Permeability

Permeability was generally found to be extremely sensitive to changes in paste content, with all binder types experiencing increases in permeability as paste content increased. The influence of increasing w/b ratio was identified as negative in blended concretes and negligible in CEM I concretes. Curing was also identified as an influencing factor for permeability, with all binder types performing better when full water curing was carried out.

Fly ash experienced the largest difference between the two regimes due to the moisture requirement of the pozzolanic reaction. From a practical point of view, given the range of water contents chosen in this study, this implies that making concretes with low paste volumes (low water and binder content for a constant w/b ratio) is highly beneficial to permeability. Any increases in paste content would deteriorate the concrete quality. Curing should be carried out as effectively as possible depending on the specific project. Where permeability performance is a crucial requirement (Exposure category XC in BS EN 206), paste contents should be treated as a primary criterion in the mix design process.

The use of fly ash binary blends can be beneficial for enhancing permeability if thorough curing measures are implemented, while also allowing a reduction in the use of cement. This would make for more ecological and economical concretes.

6.3 Water Sorptivity

Increases in paste content for a constant w/b ratio led to increases in water sorptivity values. The influence of increasing w/b ratio was identified as negative for CEM I and GGBS concretes, but could not be clearly identified for fly ash concretes. When analysing the influence of curing and binder type, it was found that water sorptivity values did not differ significantly between curing regimes across all binder types. Based on the results obtained, the primary factor that seems to influence water sorptivity characteristics is paste content (water content and binder content for a constant w/b ratio).

The practical value of such an observation would be to design concrete mixes with a paste content as low as possible. Since water sorptivity is not often a primary design criterion for any environmental exposure class, paste content should be decided based on main requirements (exposure, structural) and the decision analysed by considering other additional requirements like workability.

6.4 Chloride Conductivity

Chloride conductivity proved to be sensitive to changes in both w/b ratio and paste content for all binder types. From these results it was also concluded that the physical resistance to chloride conductivity provided by the microstructure seems to play a larger role than the chemical resistance of the cementitious materials.

Curing was highly influential to fly ash concretes, but had negligible influence on CEM I and GGBS concretes. Based on these results, it can be concluded that, similarly to permeability, paste content seems to have the highest influence on chloride conductivity values. When designing concretes for exposure environments categorised as XS in BS EN 206 (chloride-induced corrosion), minimising paste content should be a primary criterion to consider in the mix design process.

Choice of binder type is also extremely important in minimising chloride conductivity values, with GGBS binary blends yielding the best results. Since GGBS concretes generally adopt the highest cement replacement levels for the most effective results, use of GGBS concretes with low paste contents would thus make for more ecological and economical concretes.

6.5 Recommendations for Further Work

Results of the study showed that current trends in industry of associating increases in binder content with enhanced durability are incorrectly used and interpreted. This study identified that durability is not a simplistic concept that can be determined by prescriptive specifications imposing limiting values on mix design parameters. A performance-based design approach would be more efficient Based on this, the following recommendations are made:

- The experimental concretes encompassed within them a range of concretes that are nowadays practical in their application in industry. Increasing the selection of experimental parameters by selecting specific binder contents directly instead of water contents for each w/b ratio, would allow a more extensive set of data to analyse. Concretes could also be formulated to obtain a constant consistence (slump) with similar levels of workability. This could be done by adjusting the coarse aggregate content and using chemical admixtures such as stabilisers and high-range water reducing admixtures. This would ensure that experimental mixes would not have significant differences in fresh properties, which would affect hardened properties.
- This would possibly lead to an improved identification of optimisation trends for specific binder contents, instead of water contents, with respect to durability indices.

- An extensive selection of parameters should include parameters applicable to other varieties of concretes, such as self-compacting or high-performance concretes, as well as different cement types. Designing experimental concretes with w/b ratios associated with poorer quality (high w/b ratio) and high-strength concretes (low w/b ratios), each with the same binder content, would allow the data to be analysed meaningfully form a statistical point of view and possibly identify more prominent trends with regard to the determination of an optimal range of binder contents.
- In-depth materials testing, as well as tests on mortars, should be included in future research. This would need to be done in order to shed light on the influences of newer materials, such as the CEM I 52.5 N. This would in turn allow the explanation of observed trends to be clear.
- Analysis of the influence of binder content on compressive strength can be enhanced in the form of microstructure modelling. Future research could focus on the fracture mechanics of different concretes composed of different binder contents. This could broaden the understanding of what exactly happens in the microstructure as paste content is increased.
- Analysis of data in future research should look more into the implications on real-life scenarios. For example, different scenarios of parameters such as chloride threshold, environmental exposure class and cover depth can be investigated, each with a specific set of assigned mix design parameters (binder content, w/b ratio etc.). In this way, more detailed and useful information could be revealed.
- Future research should also consider investigating durability properties defined by other means either than durability indices. Properties such as heat of hydration, shrinkage and ASR should be looked into in more detail with regard to the influence that mix design parameters and compressive strength have on these properties.

Analysis of the results obtained revealed that prescriptive specifications in the form of minimum binder contents are not effective or practical. Hence prescriptive standards specifying minimum binder contents for durability purposes should be revisited. Future experimental work should be designed with the aim of ultimately attempting to include a more thoroughly promoted and formalised use of the DI Approach. This more formalised use should consist of a hybrid approach, composed mostly of performance-based specifications as well as selected prescriptive specifications.

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PERSONAL COMMUNICATIONS

Mrs Santie Gouws, 2011/11/14. Centre for Scientific and Industrial Research (CSIR). Pretoria.

Mr George Evans, 2011/11/14.. Cement & Concrete Institute (C & CI). Johannesburg.

Mr Amit Dawneerangen, 2011/11/15. Afrisam. Johannesburg.

Mr Dudley Fields, 2011/08/10. Ciolli Bros. Cape Town.

Mr Steve Crosswell, 2011/08/12. Pretoria Portland Cement (PPC). Cape Town.

Mr Lawrence Hendricks, 2012/05/30. Megamix Pty Ltd, Cape Town.

Mr Amit Kenny, 2012/12/20, Post-doc at Technion Institute of Technology, Haifa, Israel.

APPENDIX A – DI TESTING PROCEDURES

OXYGEN PERMEABILITY TEST PROCEDURE

The apparatus used for carrying out the test included:

- Oven capable of maintaining temperature of 50 ± 2ºC, used in pre-conditioning test specimen for a period of 7 days ± 4 hours.
- Permeability cell with a volume of 5L.
- Compressible rubber collars that fit around specimen ensuring a tight fit and eliminating leakage.
- Desiccators that are large enough to hold as many specimens that are tested simultaneously as possible. The specimens should be kept in the desiccators for no less than 2 hours and not more than 4 hours.
- Temperature and relative humidity in the laboratory should be maintained at 23 ± 2ºC and ± 60% respectively.

Upon removal from the oven, the samples were conditioned in the desiccators as shown in Figure 99.

Figure 99: Disc-shaped specimens are placed in a desiccator after being removed from the oven for cooling and to prevent atmospheric pressure uptake

After having been removed from the desiccators, the disc-shaped specimens were placed in compressible collars within a rigid sleeve. The rubber collar was then fitted within the rigid sleeve and checks for gaps between the two were made to ensure that there could be no leakage of air during the running of the test. The sample, collar and rigid sleeve were then placed on top of the test chamber to cover the top of the permeability cell. The top screw was tightened and both the inlet and outlet valves in the permeability cell were open for approximately 5 seconds to allow flow of oxygen gas. This ensured purging of gases other than oxygen from each chamber. The OPI test set-up is shown in Figure 100.

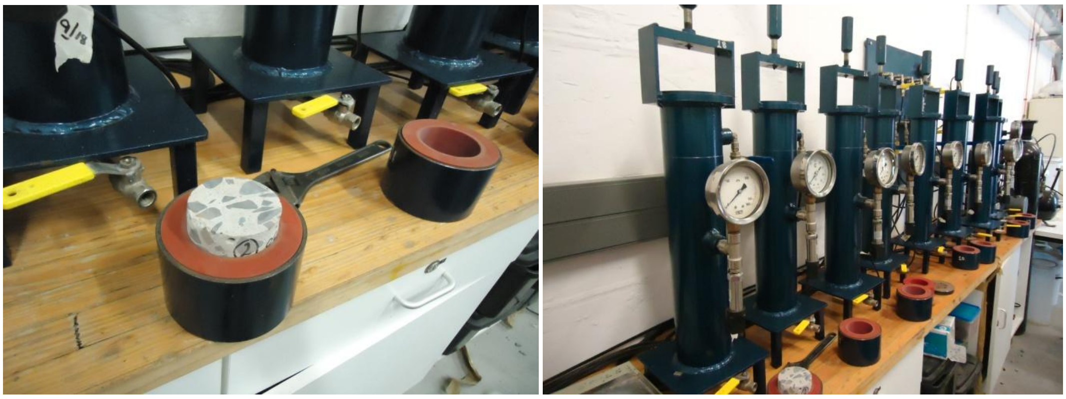


Figure 100: A concrete sample is placed within the flexible collar in the rigid sleeve before it is placed on top of its permeability chamber

After setting the initial pressure to 100 ± 5kPa for each chamber, the test was commenced. The initial time and pressure were recorded, and readings of pressure were obtained at intervals of 2 minutes. In most cases it is possible to make use of automated readings using specialised software such as the Observer II software, which was used in this study. Readings from this software were exported to an Excel spreadsheet developed in UCT for computations. The test was terminated when pressure had dropped to 50 ± 2.5kPa or after 6 hours ± 15 minutes, whichever happened first.

WATER SORPTIVITY TEST PROCEDURE

The apparatus used for carrying out the test included:

- Oven capable of maintaining temperature of 50 ± 2ºC, used in pre-conditioning test specimen for a period of 7 days ± 4 hours.
- Vacuum saturation facility as shown in Figure 101.
- Tray of depth ± 20 mm made of steel or plastic and large enough to hold as many samples as will be simultaneously tested.
- Absorbent paper towel (10 layers).
- Vernier Caliper capable of measuring to the nearest 0.02 mm.
- Mass Scale with an accuracy of 0.01 g.
- Tap water solution saturated with calcium hydroxide. (5 grams of $Ca(OH)_2$ per 1 litre of water), maintained at 23 ± 2°C.
- One stopwatch (more can be used, depending on the number of samples that will be simultaneously tested).
- Sealing material around the vertical curved edges of the specimens to make sides watertight e.g. packaging tape.
- Desiccators that are large enough to hold as many specimens that are tested simultaneously as possible. The specimens should be kept in the desiccators for no less than 2 hours and not more than 4 hours.

- Temperature and relative humidity in the laboratory should be maintained at 23 ± 2ºC and ± 60% respectively.

Upon removal from the oven, the samples were conditioned in the desiccators. After having removed them from the desiccators, the sides of the specimens were sealed with tape, the specimens were weighed and the dry mass recorded. The 10 layers of absorbent paper were placed in the tray and the $Ca(OH)_2$ solution was poured into the tray. The discs were then placed in the tray (depicted in Figure 101) and mass readings were taken at specific time intervals for the duration of the test (3, 5, 7, 9, 12, 15, 20 and 25 minutes).

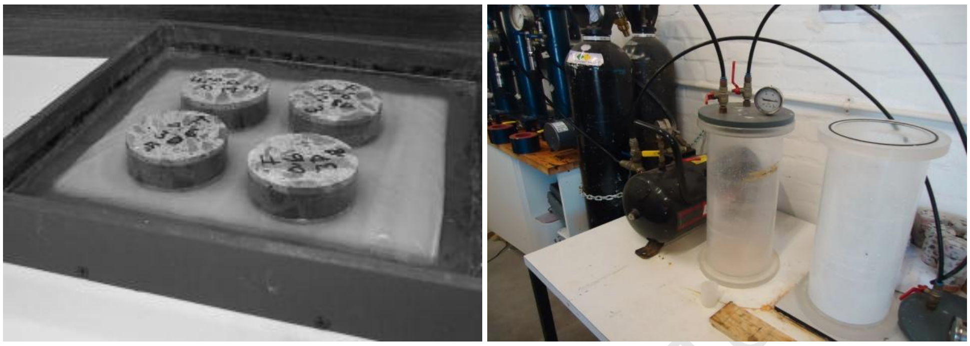


Figure 101: Set-up for the sorptivity test (Alexander et al. 2010) and a vacuum saturation facility used for conditioning of samples after completion of the test

Thereafter, the samples were conditioned in the vacuum saturation facility shown in Figure 101. A vacuum of between -75 kPa and – 80 kPa was established for 3 hours ± 15 minutes. Thereafter, the samples were soaked in the $Ca(OH)_2$ solution and the vacuum re-established for another hour ± 15 minutes. Finally, the vacuum was released and the samples were left to soak for a period of 18 hours ± 1 hour. The samples were then removed, surface dried and the saturated mass was measured and recorded. Calculations were carried out using an Excel spreadsheet developed in UCT.

CHLORIDE CONDUCTIVITY TEST PROCEDURE

The apparatus used for carrying out the test included:

- Oven capable of maintaining temperature of 50 ± 2ºC, used in pre-conditioning of test specimens for a period of 7 days ± 4 hours.
- Vacuum saturation facility as in the water sorptivity test set up.
- Conduction cell, with anode and cathode clearly marked on the outside of the cell, consisting of two half cells and a rigid sleeve with flexible collar to place the concrete sample in.
- DC Power supply. 0 – 12 Volt, 0 – 1 Ampere stabilised.
- Two digital multimeters (voltmeter and ammeter) with electrical cables and plugs.
- Mass Scale with an accuracy of 0.01 g.
- CP grade NaCl solution (99% purity).

- Desiccators that are large enough to hold as many specimens that are tested simultaneously as possible. The specimens should be kept in the desiccators for no less than 2 hours and not more than 4 hours.
- Temperature and relative humidity in the laboratory should be maintained at 23 ± 2ºC and ± 60% respectively.

Figure 102: Typical chloride conductivity test set-up

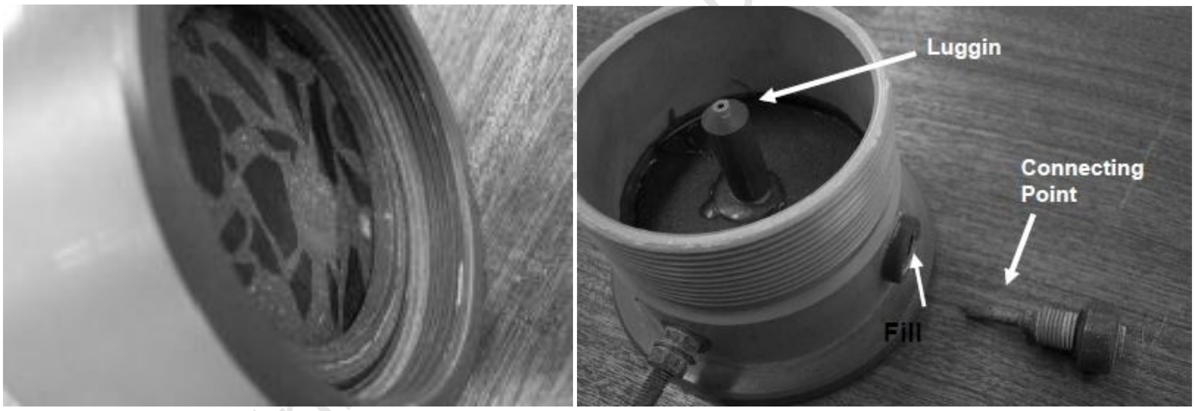


Figure 103: Correct placement of sample in rigid sleeve and the components of the half cell (Alexander et al. 2010)

After preconditioning in the desiccators, specimens were soaked in NaCl solution for 18 hours ± 1 hour. Thereafter, they were removed, surface dried and the saturated mass was recorded before commencing the test procedure. The luggin capillaries and cell chambers were filled with NaCl solution and the luggin capillaries were sealed off with screws. Each disc was placed within the flexible collar in the rigid sleeve, which was then screwed onto the half cells (Figure 103). The cell was then aligned horizontally and connected to the ammeters and the DC supply as depicted in Figure 102. The test was carried out by adjusting the DC power supply until the voltage applied across the specimen was approximately 10 V. The voltage and current readings displayed on the voltmeter and ammeter respectively were then recorded. The data collected was then processed through the use of an Excel spreadsheet developed in UCT to obtain the chloride conductivity values. A detailed overview of the calculations used in all test procedures is given in the Durability Index Testing Manual (Alexander et al. 2010).

APPENDIX B – COMPRESSIVE STRENGTH

Table 31: 100% CEM I 52.5 N - tabulated parameters for compressive strength and Ma/Mc ratio

w/b ratio	Binder Content (kg/m^3)	Aggregate Content (kg/m^3)	28 d fc (MPa)	Ma/Mc ratio
0.40	388	1917	61	4.9
	420	1856	60	4.4
	455	1791	63	3.9
	488	1730	57	3.5
0.50	310	1981	50	6.4
	336	1926	52	5.7
	364	1866	51	5.1
	390	1811	50	4.6
0.60	258	2024	45	7.8
	280	1972	42	7.0
	303	1916	42	6.3
	325	1865	42	5.7

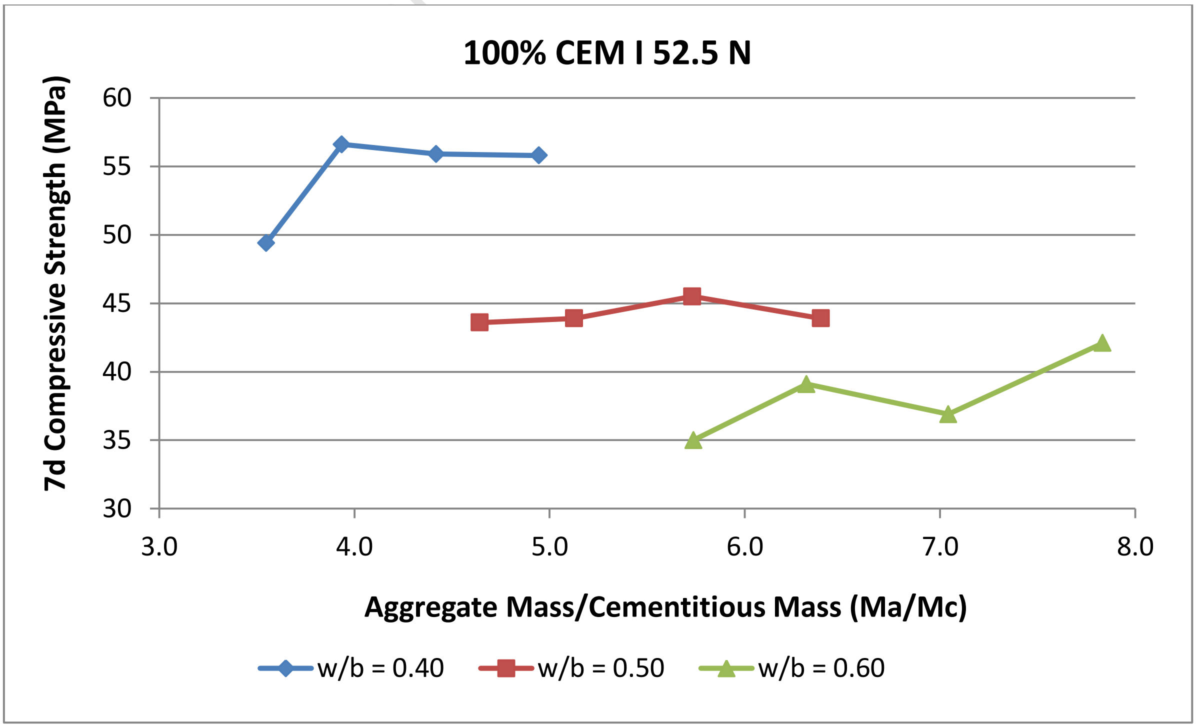


Figure 104: 7 day compressive strength of CEM I water cured concretes as a function of Ma/Mc ratio

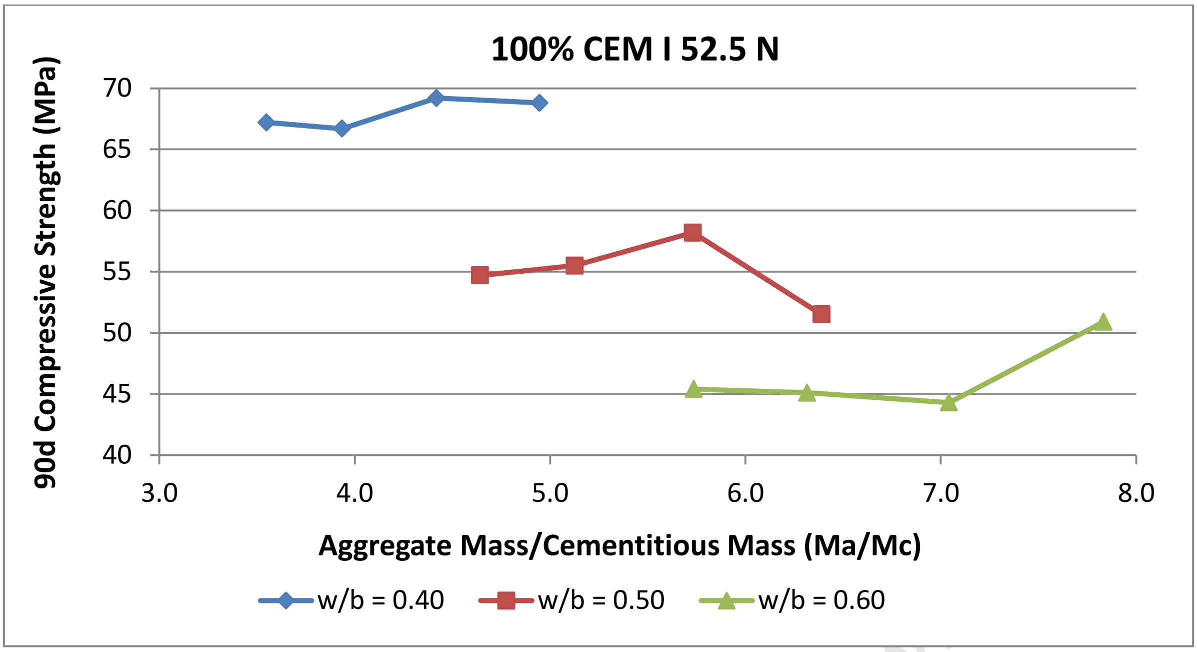


Figure 105: 90 day compressive strength of CEM I water cured concretes as a function of Ma/Mc ratio

Table 32: 30% Fly Ash - tabulated parameters for compressive strength and Ma/Mc ratio

w/b ratio	Binder Content (kg/m^3)	Aggregate Content (kg/m^3)	28 d fc (MPa)	Ma/Mc ratio
0.40	388	1882	63	4.9
	420	1818	62	4.3
	455	1750	62	3.8
	488	1686	60	3.5
0.50	310	1953	53	6.3
	336	1895	51	5.6
	364	1833	47	5.0
	390	1775	47	4.6
0.60	258	2000	42	7.7
	280	1947	42	7.0
	303	1889	39	6.2
	325	1835	37	5.6

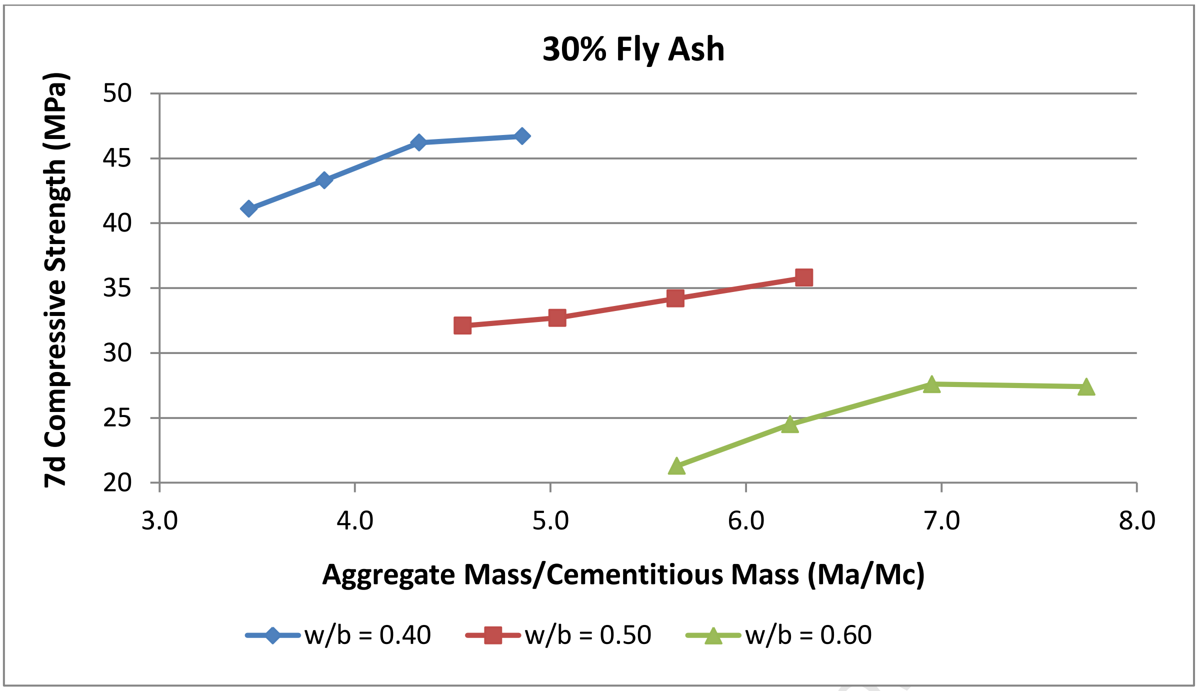


Figure 106: 7 day compressive strength of Fly Ash water cured concretes as a function of Ma/Mc ratio

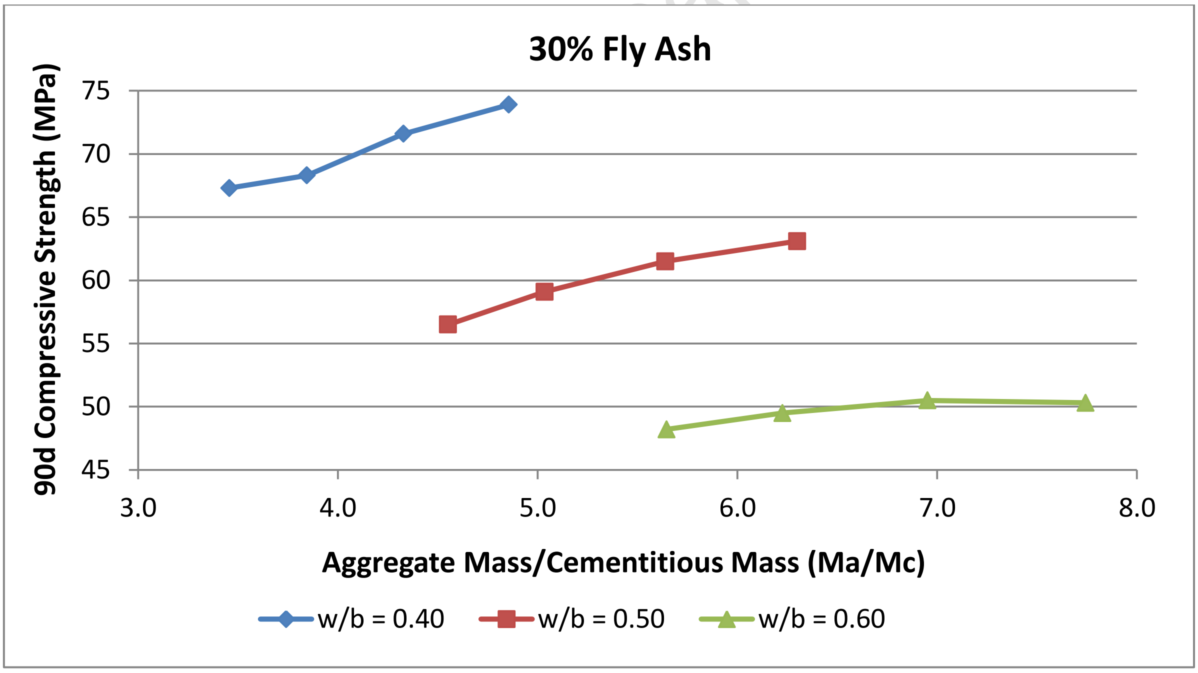


Figure 107: 90 day compressive strength of Fly Ash water cured concretes as a function of Ma/Mc ratio

Table 33: 50% GGBS - tabulated parameters for compressive strength and Ma/Mc ratio

w/b ratio	Binder Content (kg/m^3)	Aggregate Content (kg/m^3)	28 d fc (MPa)	Ma/Mc ratio
0.40	388	1904	63	4.9
	420	1842	62	4.4
	455	1775	59	3.9
	488	1713	61	3.5
0.50	310	1970	54	6.4
	336	1914	50	5.7
	364	1854	47	5.1
	390	1797	46	4.6
0.60	258	2015	44	7.8
	280	1963	40	7.0
	303	1906	36	6.3
	325	1854	36	5.7

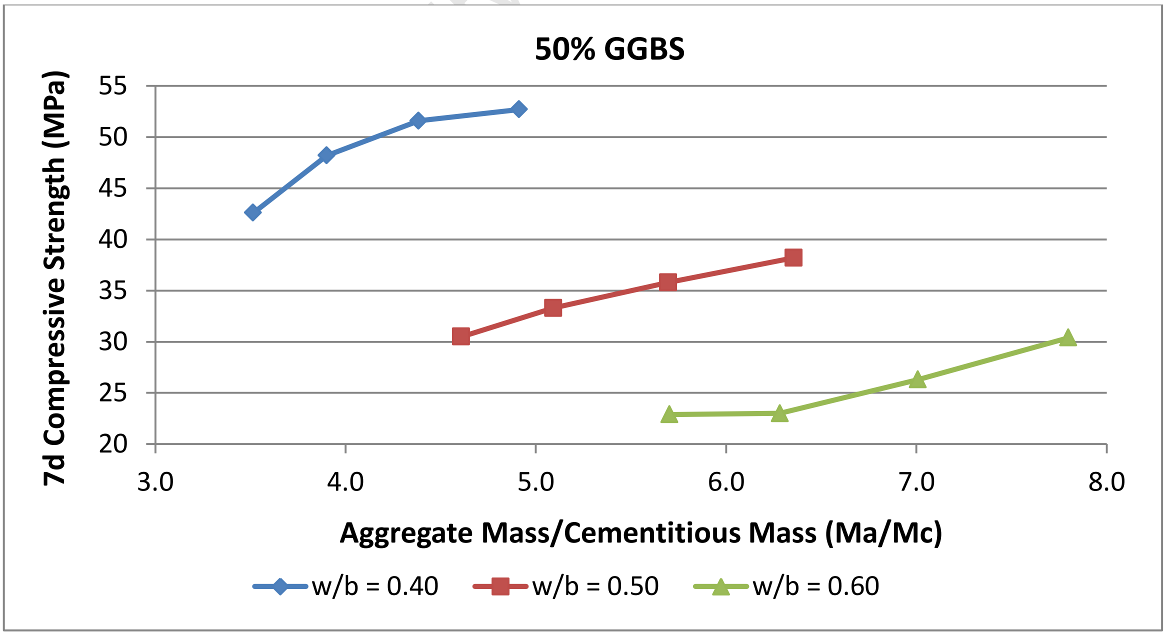


Figure 108: 7 day compressive strength of GGBS water cured concretes as a function of Ma/Mc ratio

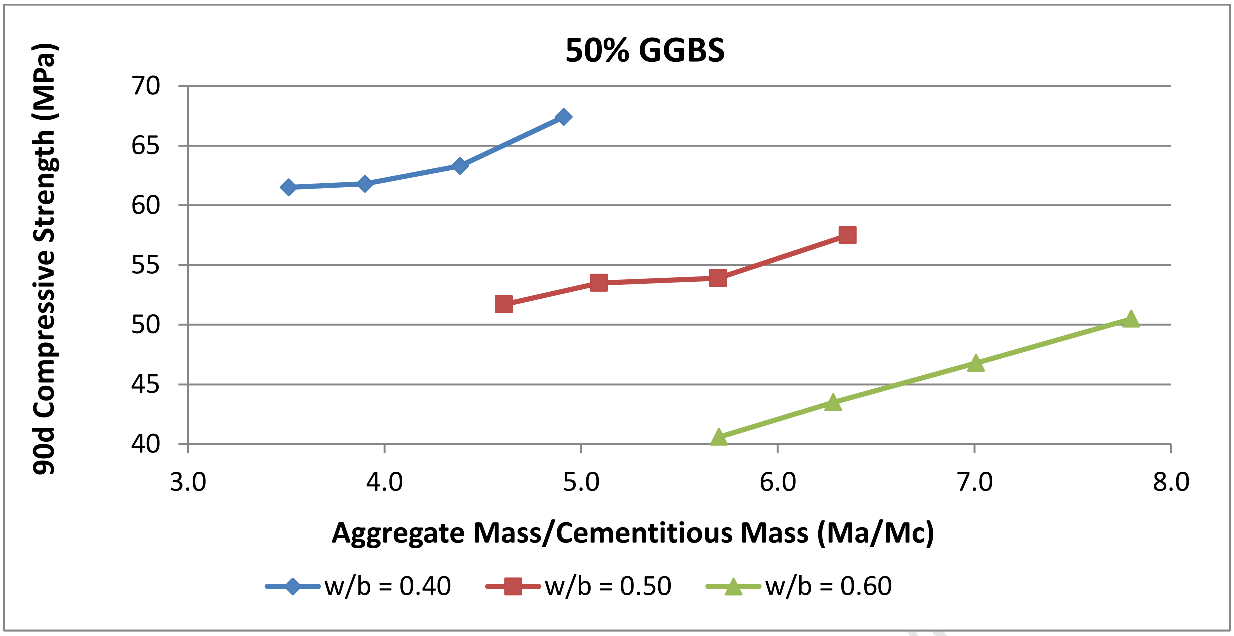


Figure 109: 90 day compressive strength of GGBS water cured concretes as a function of Ma/Mc ratio

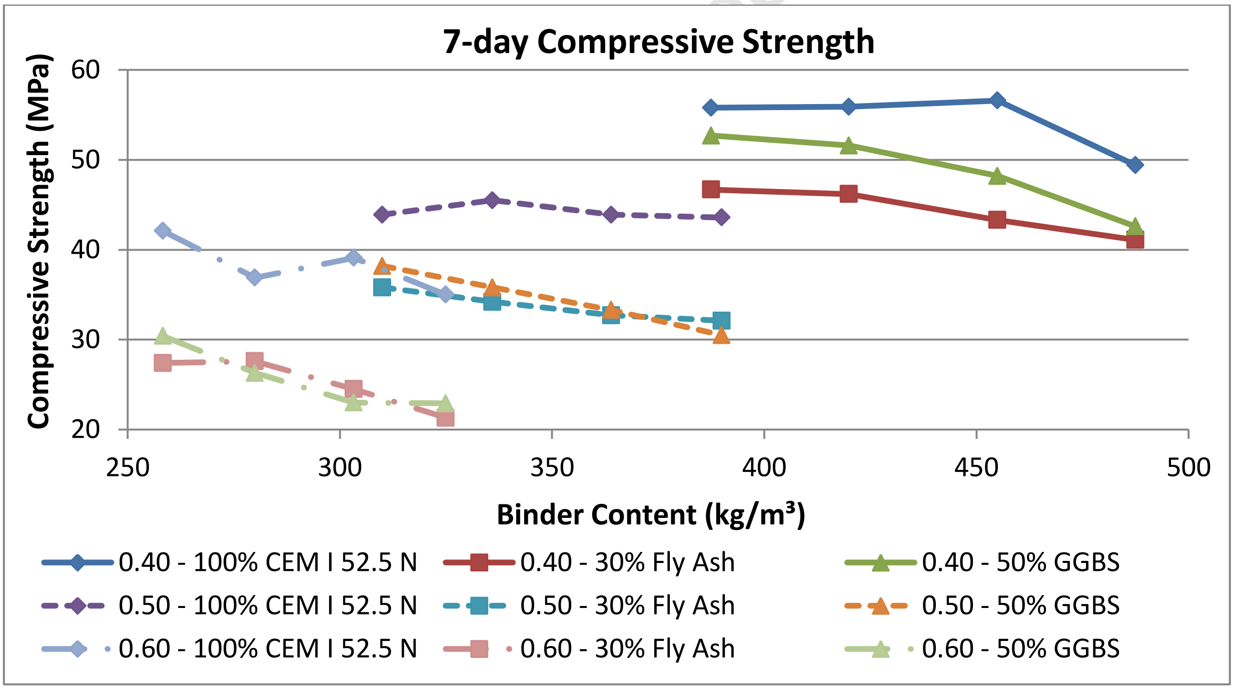


Figure 110: Compressive strength results at 7 days

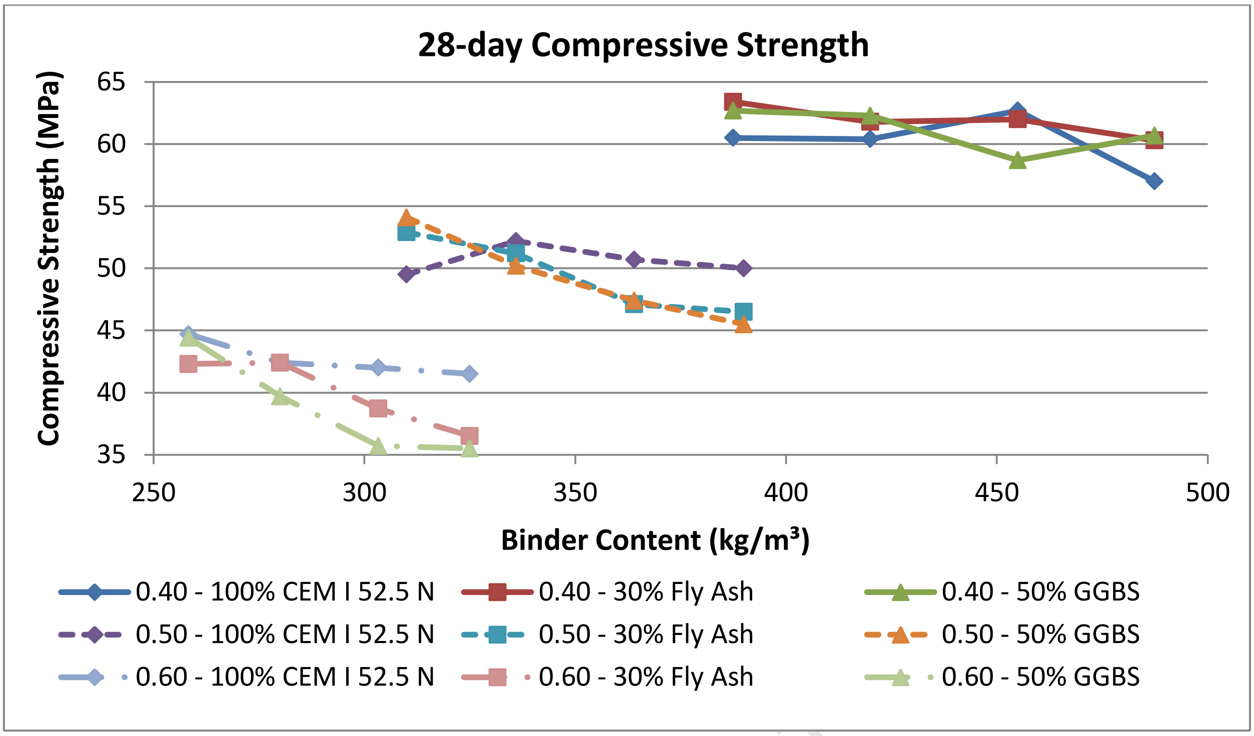


Figure 111: Compressive strength results at 28 days

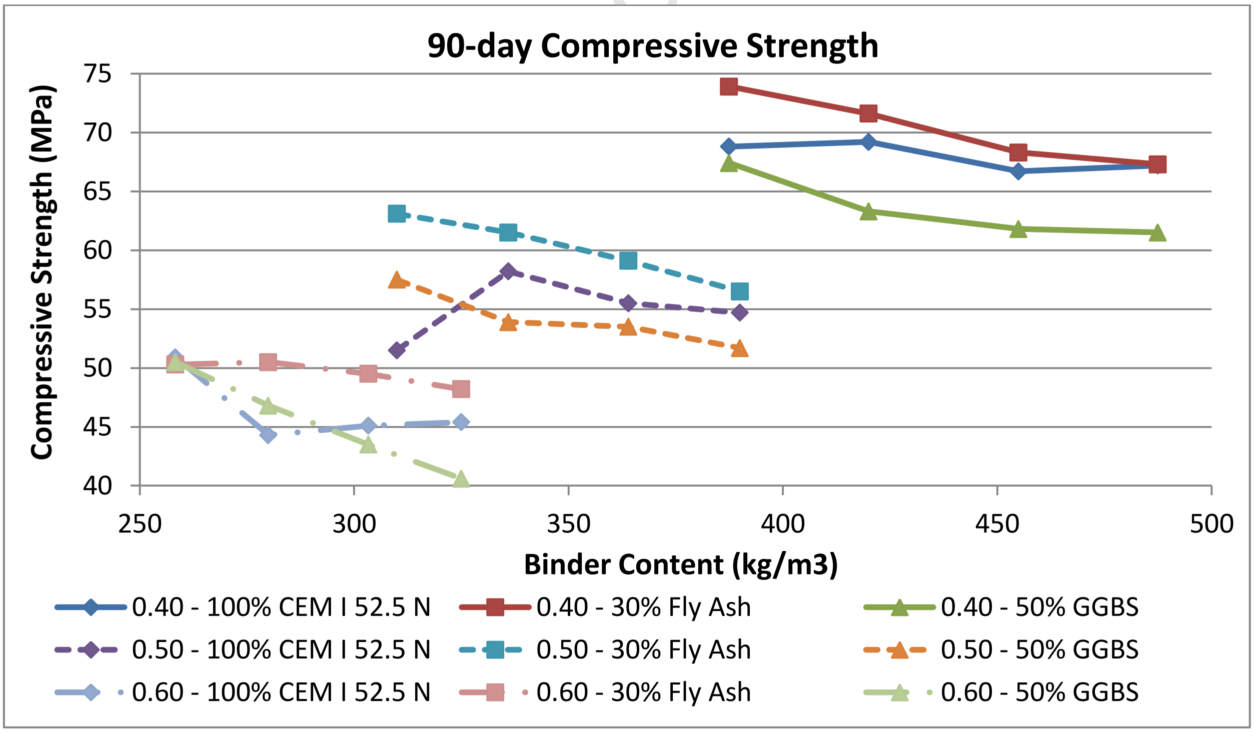


Figure 112: Compressive strength results at 90 days

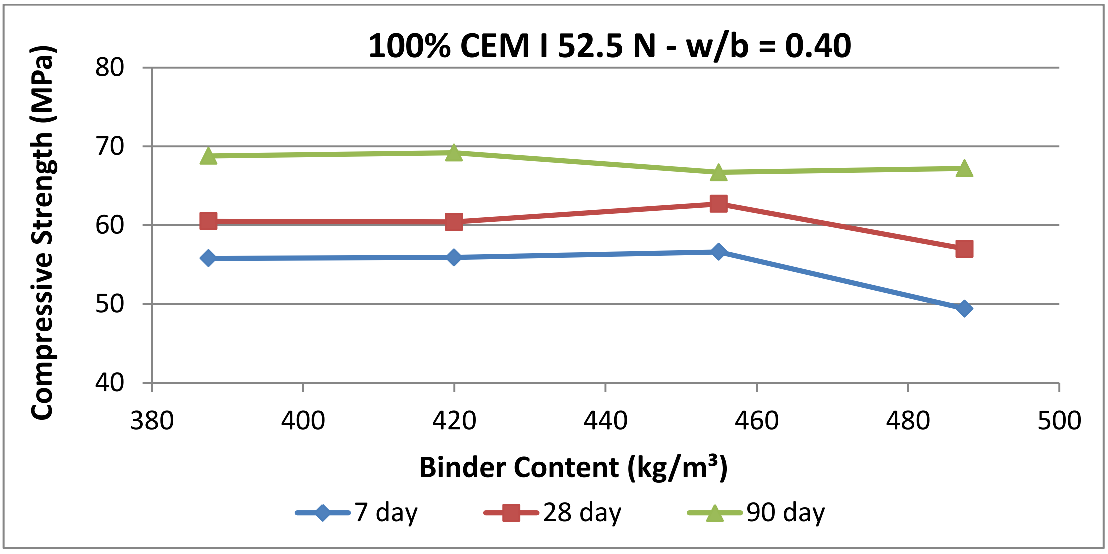


Figure 113: Compressive strength of 0.40 CEM I water cured concretes as a function of binder content

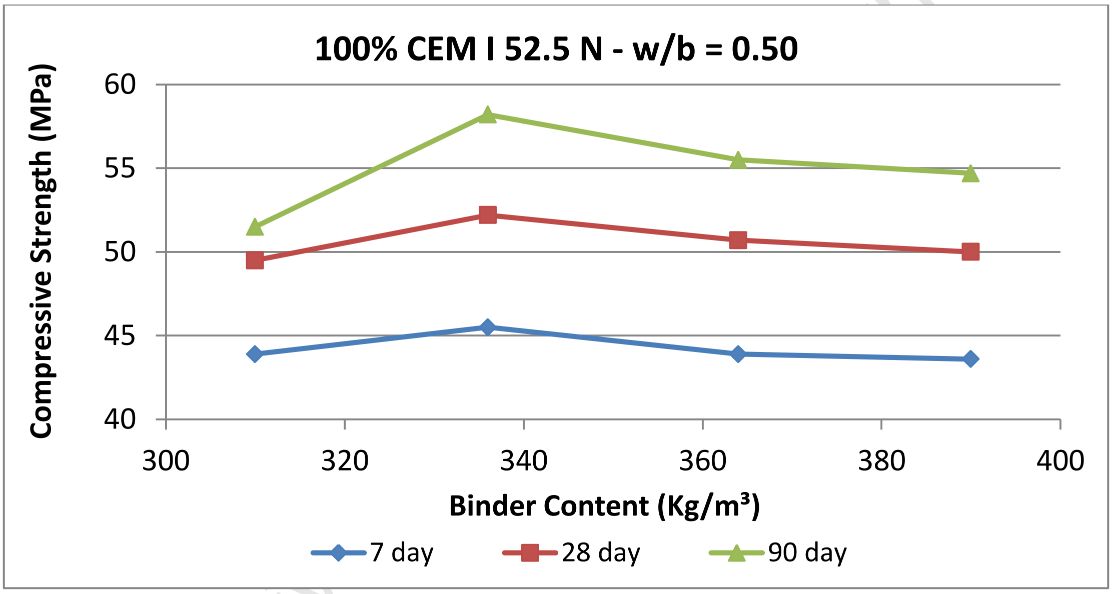


Figure 114: Compressive strength of 0.50 CEM I water cured concretes as a function of binder content

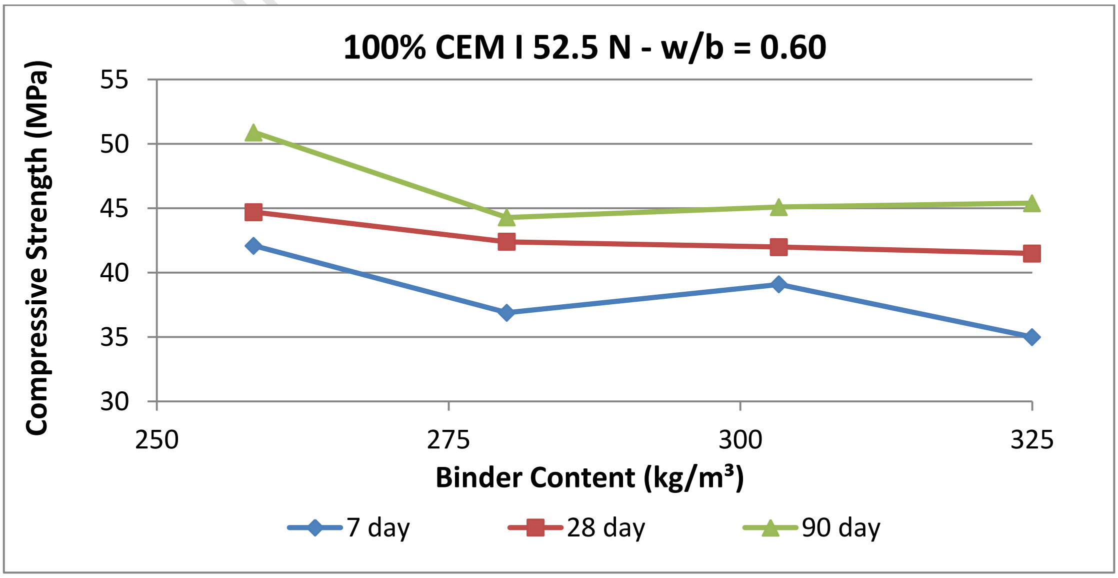
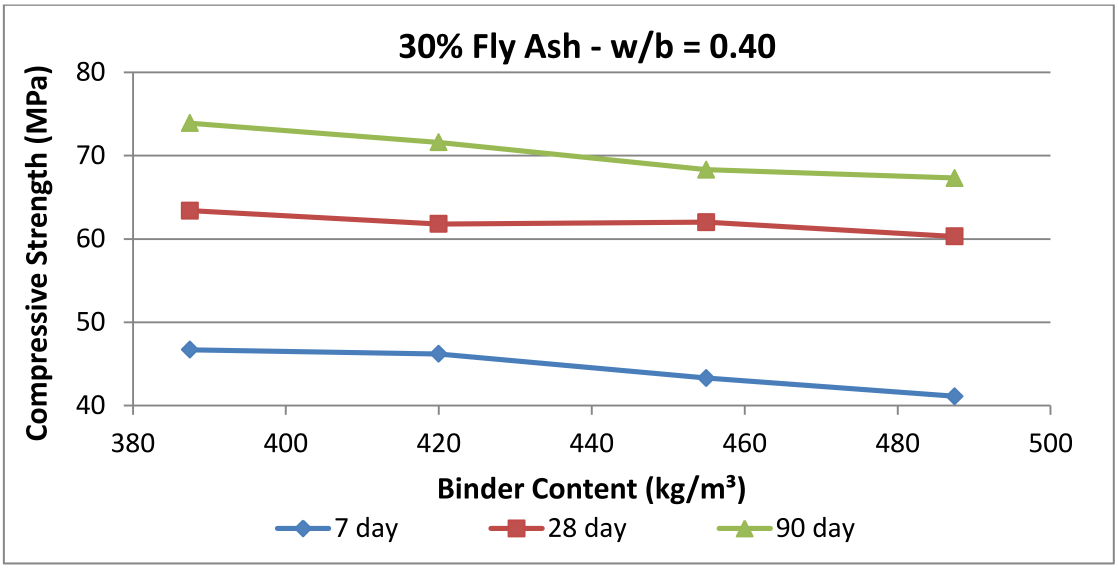


Figure 115: Compressive strength of 0.60 CEM I water cured concretes as a function of binder content



Compressive strength of 0.40 Fly Ash water cured concretes as a function of binder content

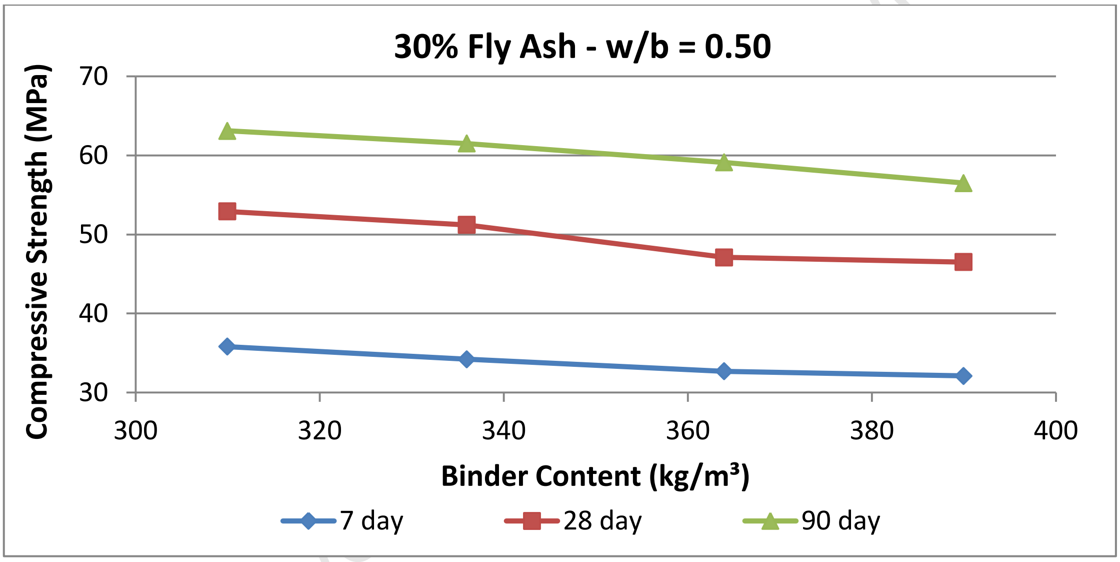


Figure 116: Compressive strength of 0.50 Fly Ash water cured concretes as a function of binder content

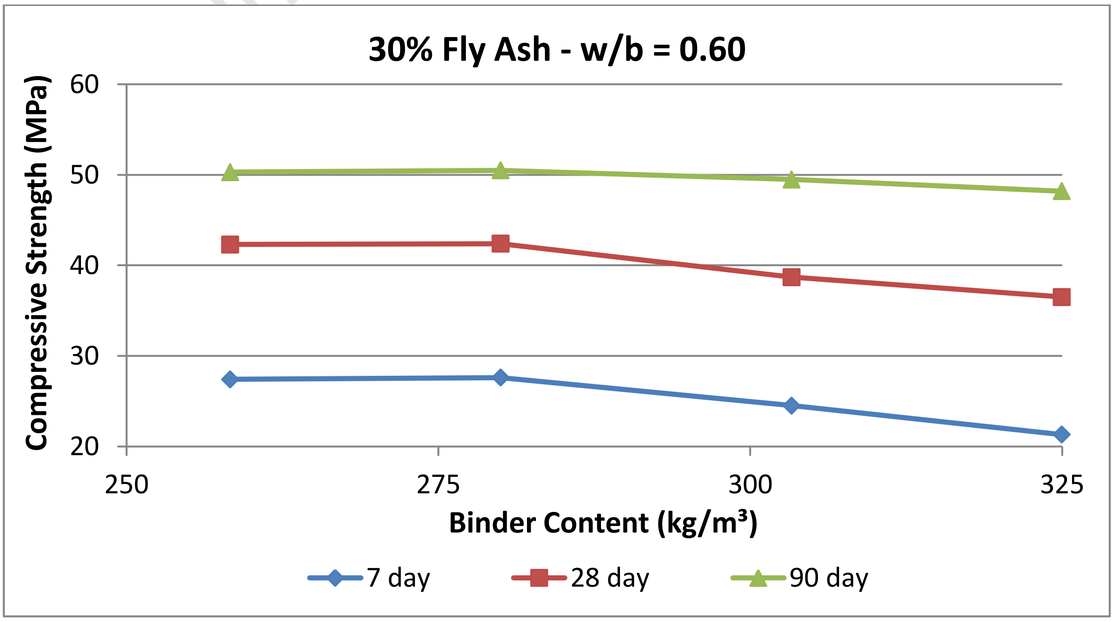


Figure 117: Compressive strength of 0.60 Fly Ash water cured concretes as a function of binder content

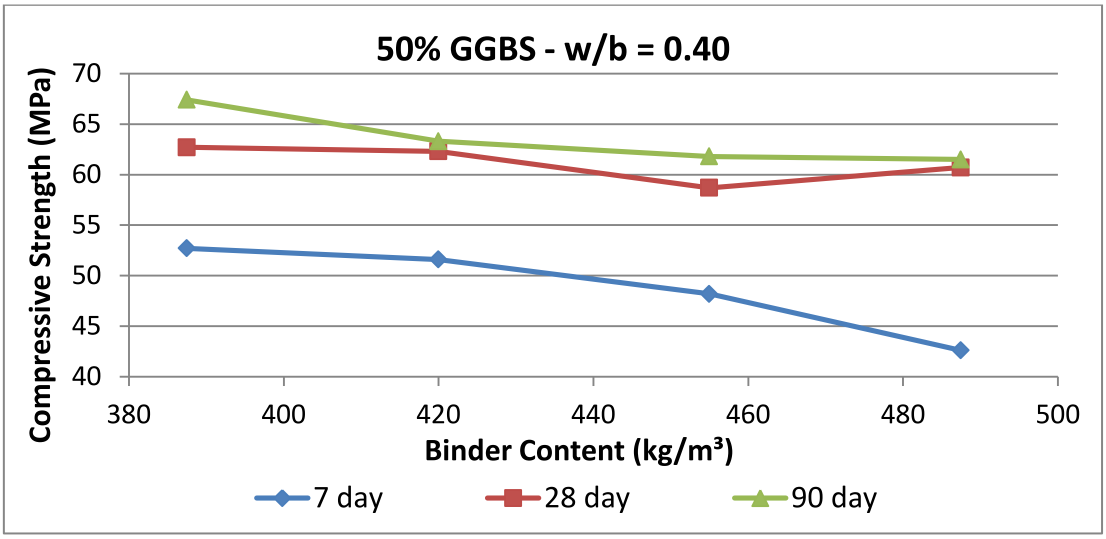


Figure 118: Compressive strength of 0.40 GGBS water cured concretes as a function of binder content

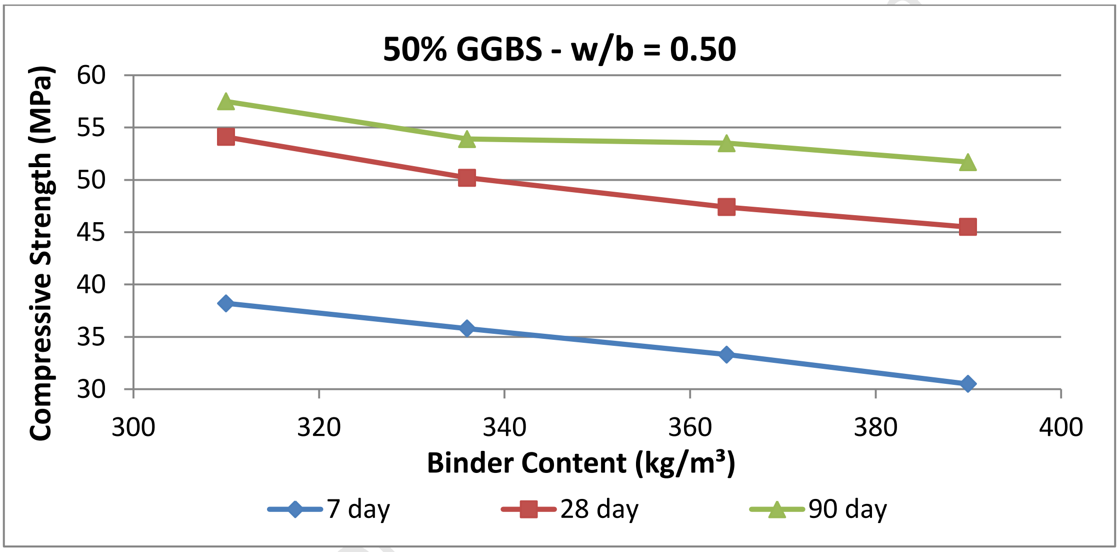


Figure 119: Compressive strength of 0.50 GGBS water cured concretes as a function of binder content

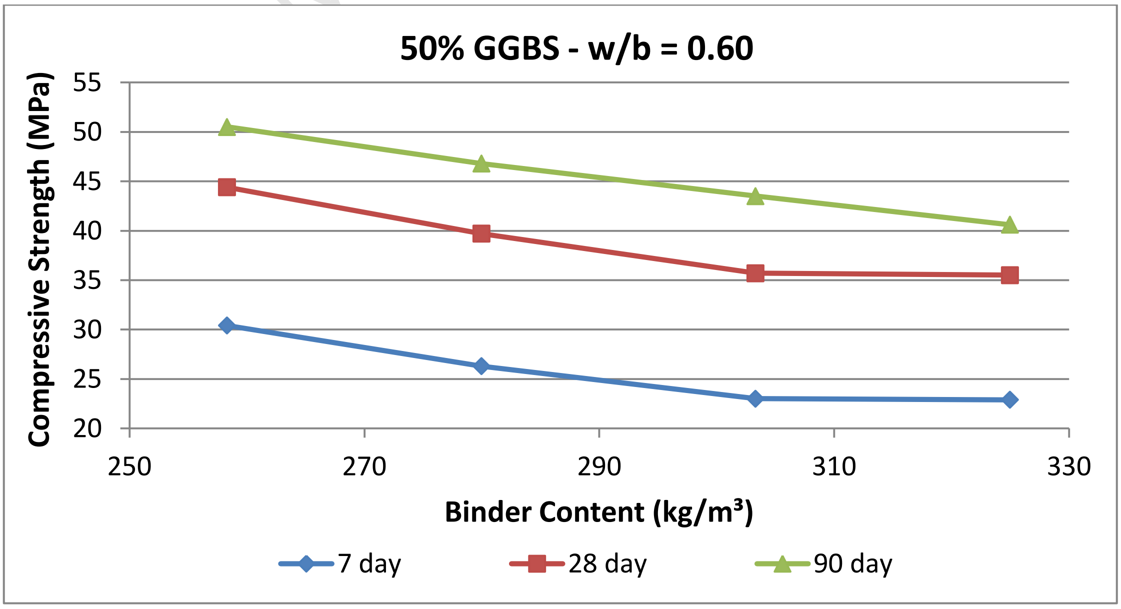


Figure 120: Compressive strength of 0.60 GGBS water cured concretes as a function of binder content

APPENDIX C – DURABILITY INDEX RESULTS

OPI RESULTS

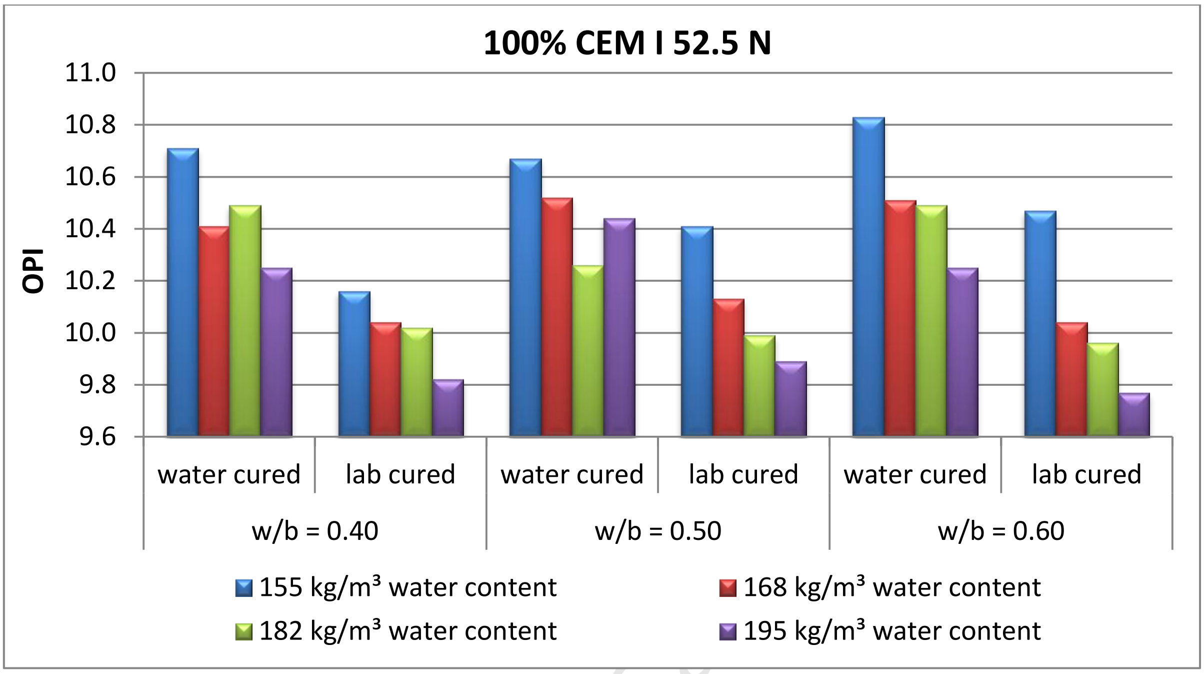


Figure 121: OPI results summary – 100% CEM I 52.5 N

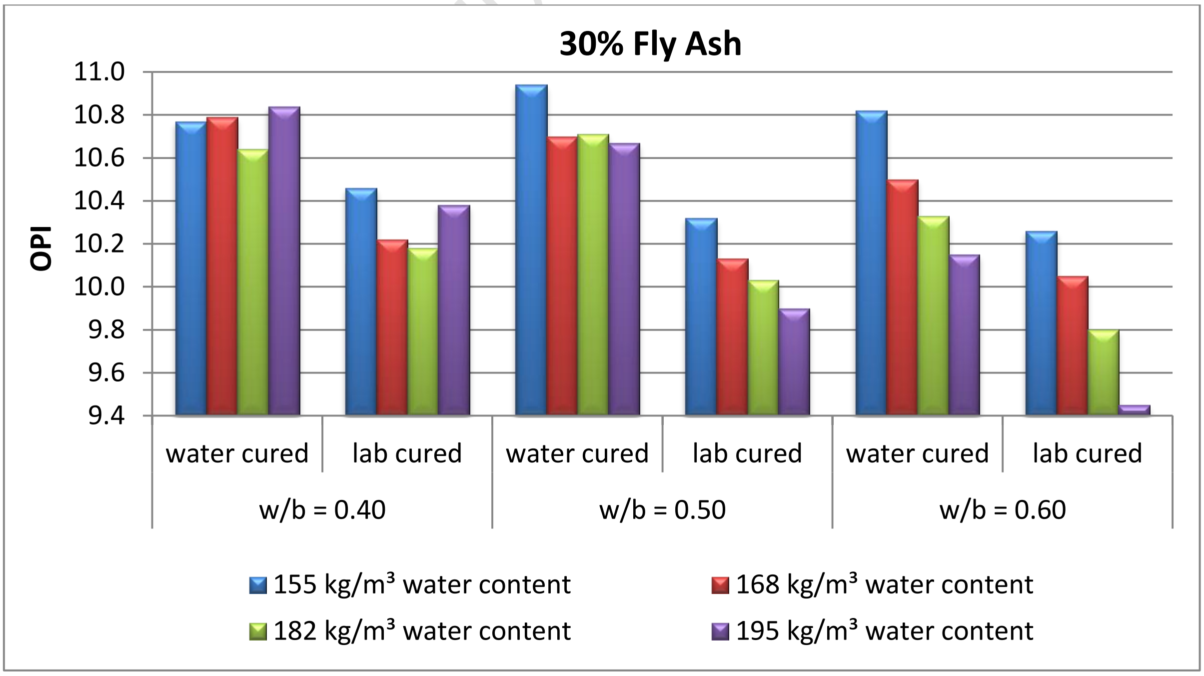


Figure 122: OPI results summary – 30% Fly Ash

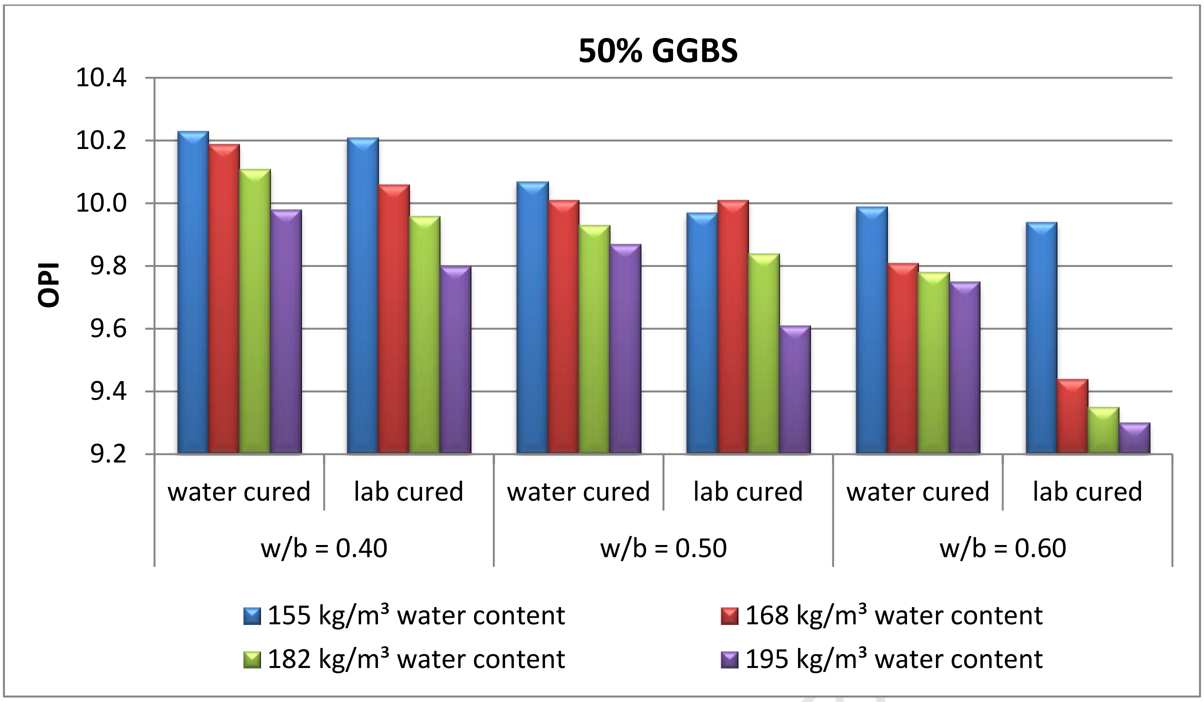


Figure 123: OPI results summary – 50% GGBS

DI SUMMARY – BINDER TYPE AND CURING REGIME

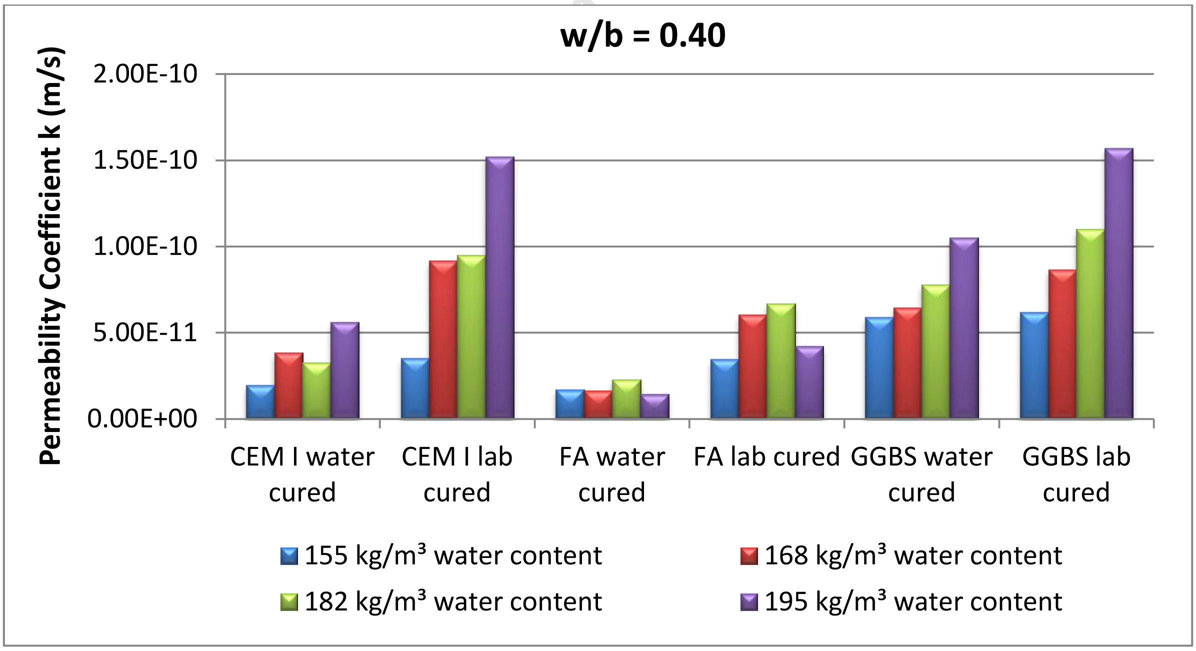


Figure 124: Summary of permeability results – w/b= 0.40

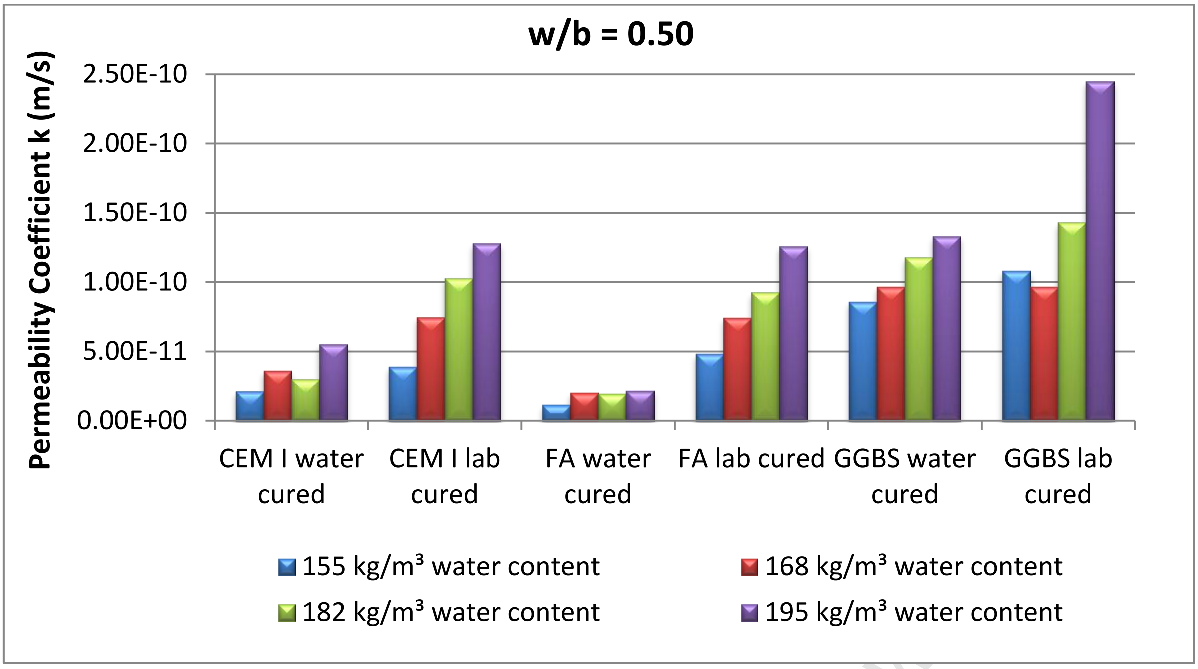


Figure 125: Summary of permeability results – w/b = 0.50

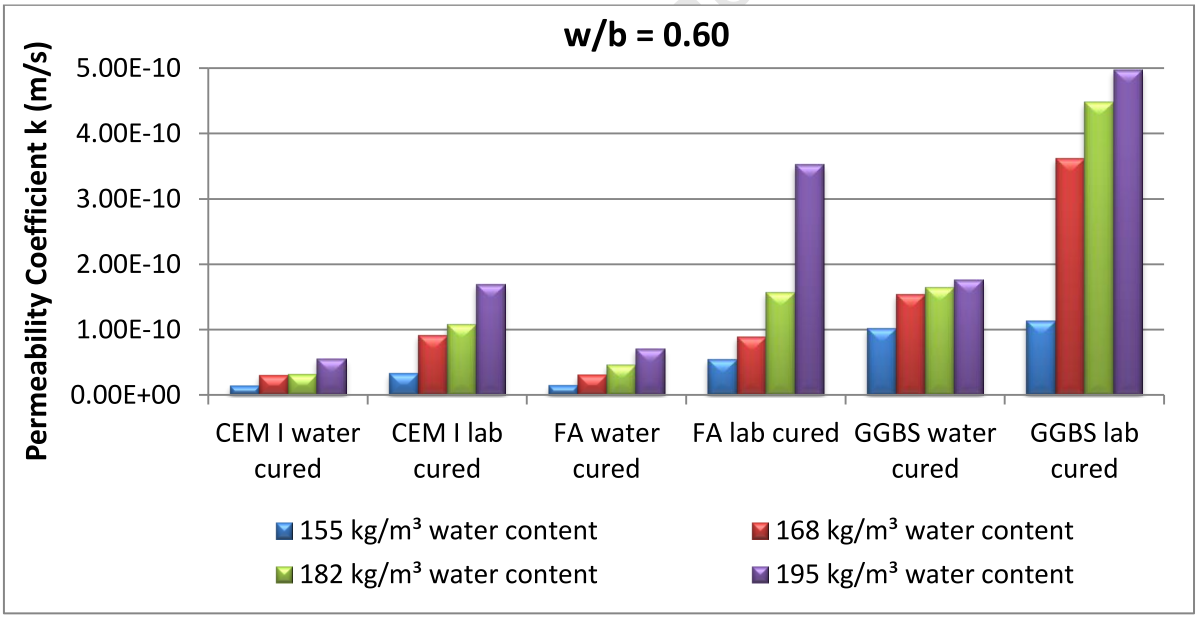


Figure 126: Summary of permeability results – w/b = 0.60

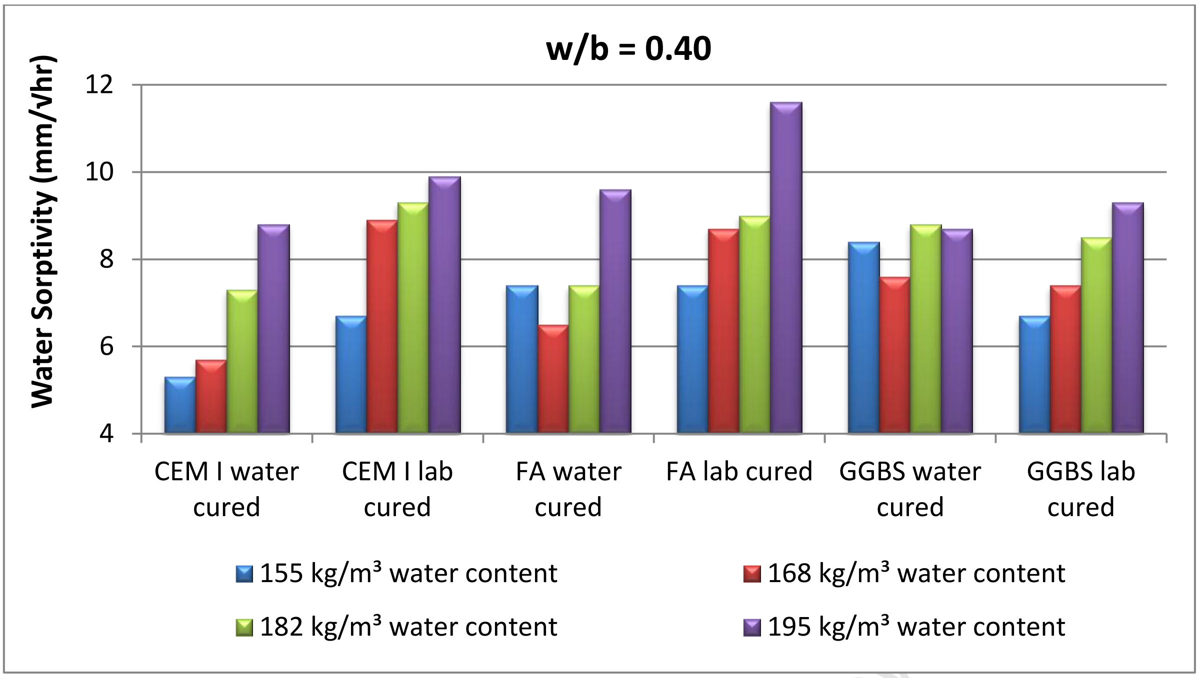


Figure 127: Summary of water sorptivity results – w/b = 0.40

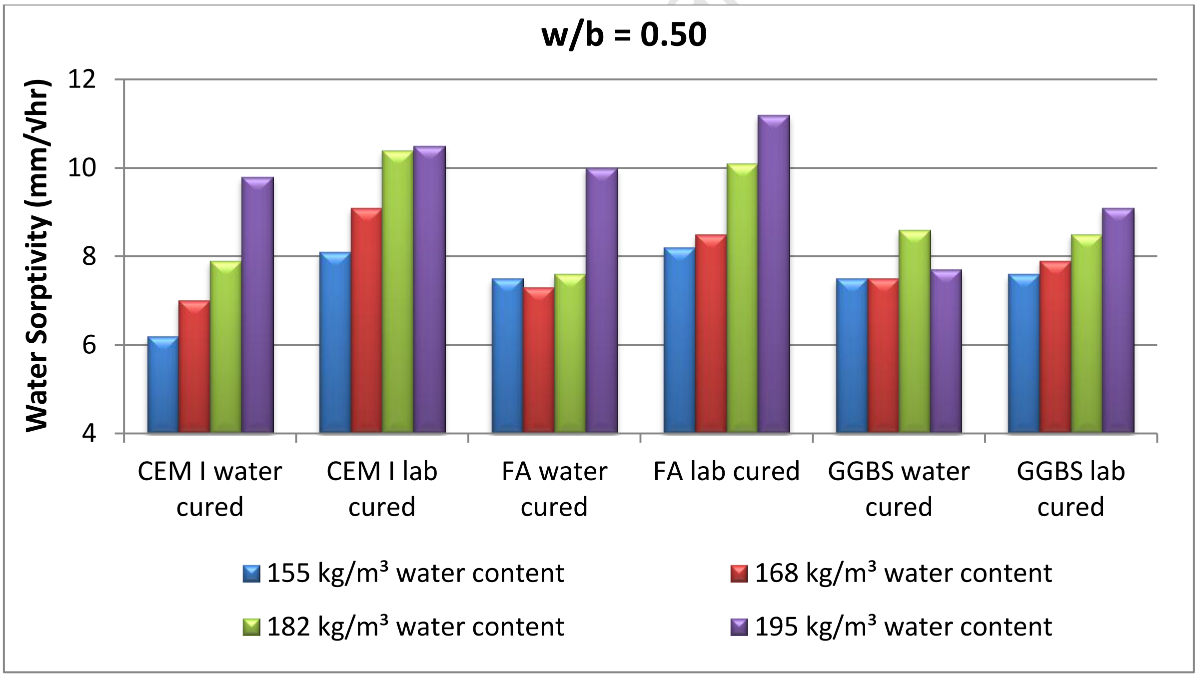


Figure 128: Summary of water soprtivity results – w/b = 0.50

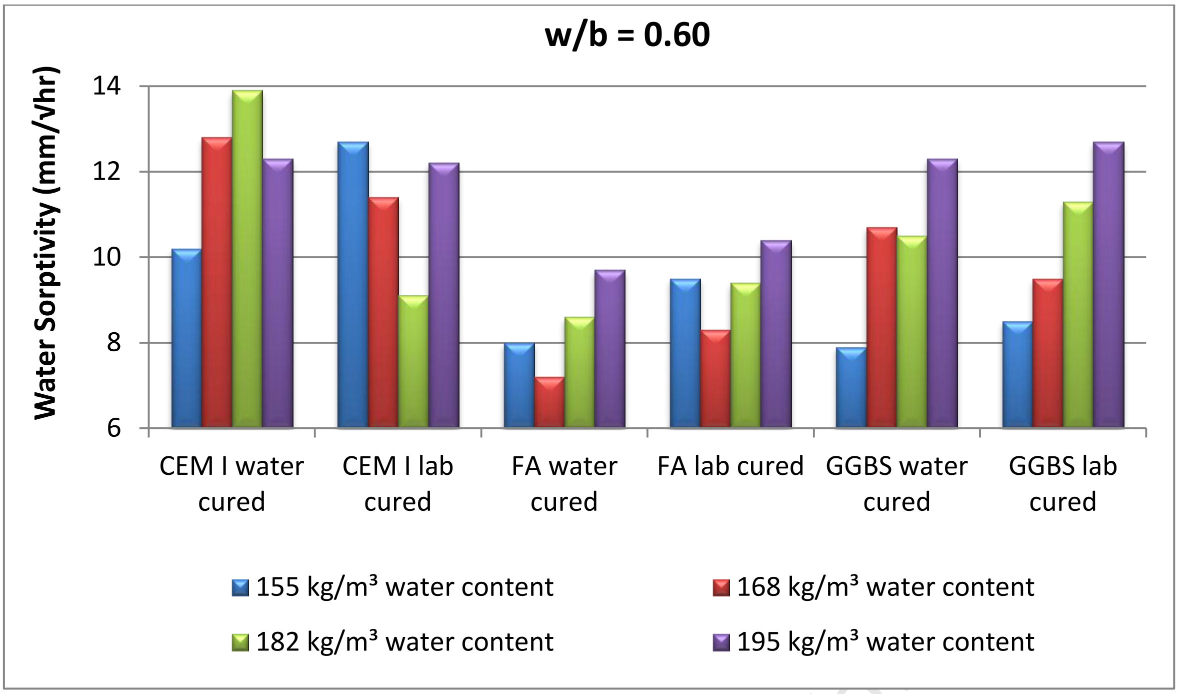


Figure 129: Summary of water sorptivity results – w/b = 0.60

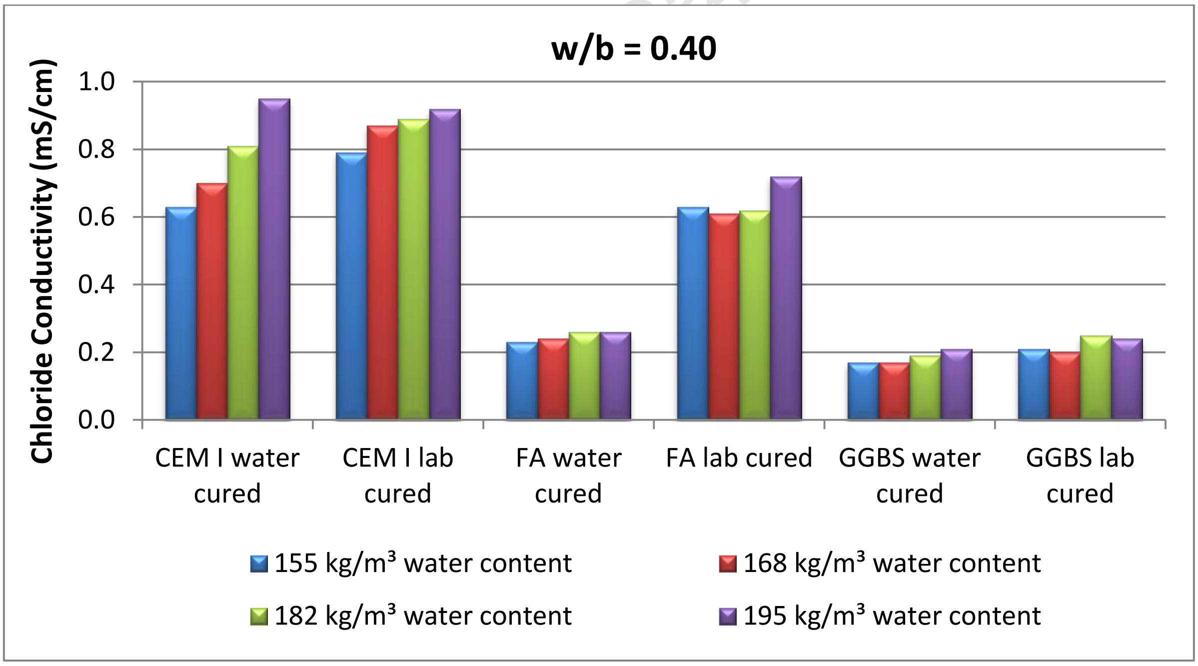


Figure 130: Summary of chloride conductivity results – w/b = 0.40

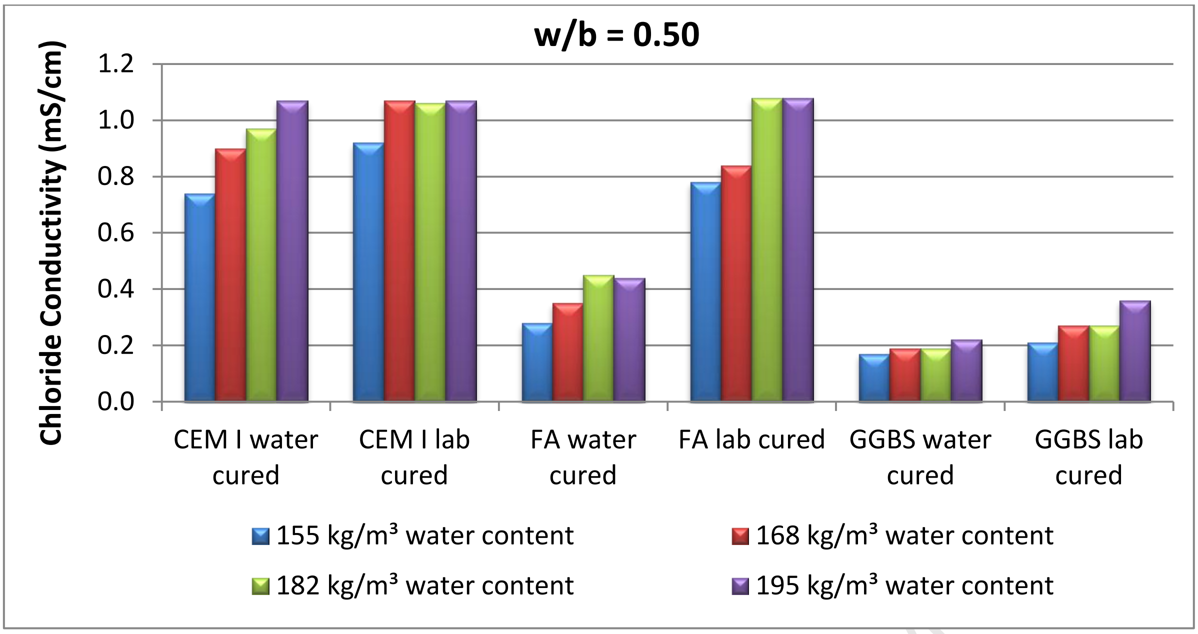


Figure 131: Summary of chloride conductivity results – w/b = 0.50

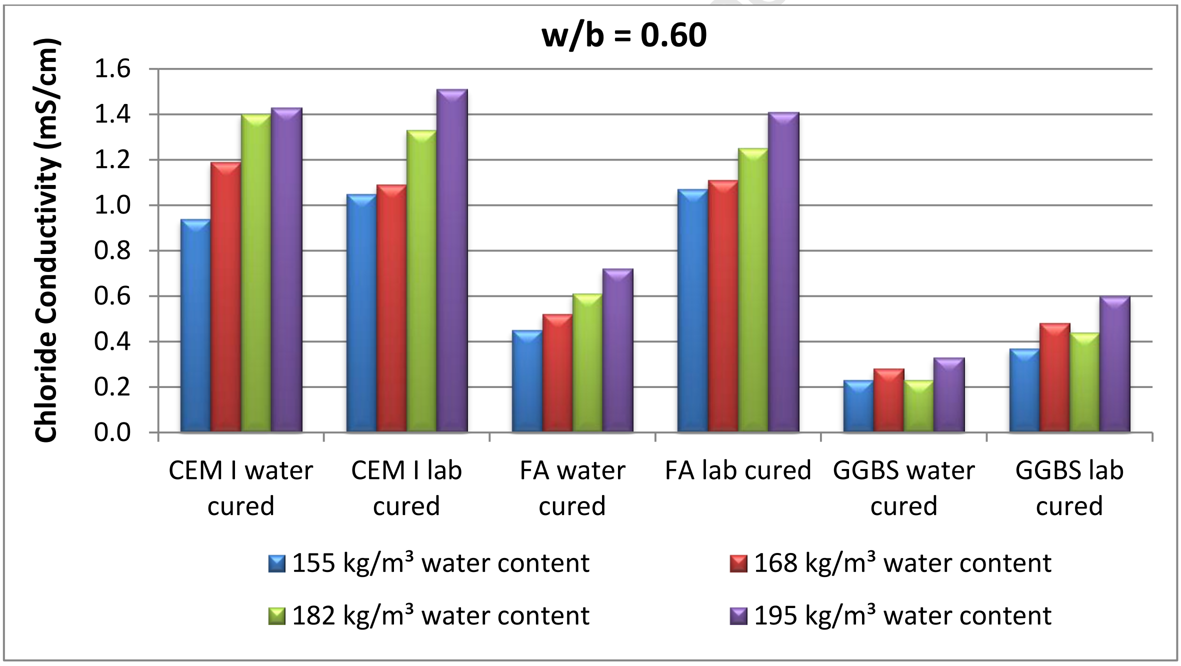


Figure 132: Summary of chloride conductivity results – w/b = 0.60

PERMEABILITY COEFFICIENT AND PASTE VOLUME

Table 34: Relative permeability results – 100% CEM I 52.5 N

w/b	Water content (L/m^3)	Binder Content (kg/m^3)	Permeability Coefficient k (x10^{-11} m/s)	Mean k value (x10^{-11} m/s)	% relative to mean
0.40	155	388	3.52	9.35	38
	168	420	9.16		98
	182	455	9.50		102
	195	488	15.2		163
0.50	155	310	3.88	8.61	45
	168	336	7.45		87
	182	364	10.3		120
	195	390	12.8		149
0.60	155	258	3.41	10.1	34
	168	280	9.22		91
	182	303	10.9		108
	195	325	17.0		168

Table 35: Relative permeability results – 30% Fly Ash

w/b	Water content (L/m^3)	Binder Content (kg/m^3)	Permeability Coefficient k (x10^{-11} m/s)	Mean k value (x10^{-11} m/s)	% relative to mean
0.40	155	388	3.46	5.10	68
	168	420	6.04		119
	182	455	6.68		131
	195	488	4.20		82
0.50	155	310	4.83	8.53	57
	168	336	7.44		87
	182	364	9.25		108
	195	390	12.6		148
0.60	155	258	5.51	16.4	34
	168	280	8.97		55
	182	303	15.8		96
	195	325	35.3		215

Table 36: Relative permeability results – 50% GGBS

w/b	Water content (L/m^3)	Binder Content (kg/m^3)	Permeability Coefficient k (x10^{-11} m/s)	Mean k value (x10^{-11} m/s)	% relative to mean
0.40	155	388	6.20	10.4	60
	168	420	8.67		83
	182	455	11.0		106
	195	488	15.7		151
0.50	155	310	10.8	14.8	73
	168	336	9.67		65
	182	364	14.3		97
	195	390	24.5		165
0.60	155	258	11.4	35.6	32
	168	280	36.3		102
	182	303	44.9		126
	195	325	49.8		140

WATER SORPTIVITY & POROSITY AND PASTE VOLUME

Table 37: Relative water sorptivity results – 100% CEM I 52.5 N

w/b	Water content (L/m^3)	Binder Content (kg/m^3)	Water Sorptivity (mm/√hr)	Mean Value (mm/√hr)	% relative to mean
0.40	155	388	6.7	8.7	77
	168	420	8.9		102
	182	455	9.3		107
	195	488	9.9		114
0.50	155	310	8.1	9.5	85
	168	336	9.1		96
	182	364	10.4		109
	195	390	10.5		110
0.60	155	258	12.7	11.4	112
	168	280	11.4		100
	182	303	9.1		80
	195	325	12.2		107

Table 38: Relative water sorptivity results – 30% Fly Ash

w/b	Water content (L/m^3)	Binder Content (kg/m^3)	Water Sorptivity (mm/√hr)	Mean Value (mm/√hr)	% relative to mean
0.40	155	388	7.4	9.2	81
	168	420	8.7		95
	182	455	9.0		98
	195	488	11.6		126
0.50	155	310	8.2	9.5	86
	168	336	8.5		89
	182	364	10.1		106
	195	390	11.2		118
0.60	155	258	9.5	9.4	101
	168	280	8.3		88
	182	303	9.4		100
	195	325	10.4		111

Table 39: Relative water sorptivity results – 50% GGBS

w/b	Water content (L/m^3)	Binder Content (kg/m^3)	Water Sorptivity (mm/√hr)	Mean Value (mm/√hr)	% relative to mean
0.40	155	388	6.7	8.0	84
	168	420	7.4		93
	182	455	8.5		107
	195	488	9.3		117
0.50	155	310	7.6	8.3	92
	168	336	7.9		95
	182	364	8.5		103
	195	390	9.1		110
0.60	155	258	8.5	10.5	81
	168	280	9.5		90
	182	303	11.3		108
	195	325	12.7		121

Table 40: Relative porosity results – 100% CEM I 52.5 N

w/b	Water content (L/m^3)	Binder Content (kg/m^3)	Porosity (%)	Mean Value (%)	% relative to mean
0.40	155	388	9.1	9.7	94
	168	420	9.6		99
	182	455	9.4		97
	195	488	10.8		111
0.50	155	310	9.0	9.6	94
	168	336	9.2		96
	182	364	10.4		108
	195	390	9.9		103
0.60	155	258	9.6	10.2	94
	168	280	9.9		97
	182	303	10.7		105
	195	325	10.7		105

Table 41: Relative porosity results – 30% Fly Ash

w/b	Water content (L/m^3)	Binder Content (kg/m^3)	Porosity (%)	Mean Value (%)	% relative to mean
0.40	155	388	8.3	8.4	99
	168	420	7.9		94
	182	455	8.5		101
	195	488	9.0		107
0.50	155	310	9.1	9.9	92
	168	336	9.4		95
	182	364	10.5		106
	195	390	10.5		106
0.60	155	258	9.3	10.7	87
	168	280	10.2		95
	182	303	11.6		108
	195	325	11.8		110

Table 42: Relative porosity results – 50% GGBS

w/b	Water content (L/m^3)	Binder Content (kg/m^3)	Porosity (%)	Mean Value (%)	% relative to mean
0.40	155	388	7.0	7.6	93
	168	420	7.0		93
	182	455	8.1		107
	195	488	8.1		107
0.50	155	310	7.9	8.8	90
	168	336	8.2		93
	182	364	9.1		103
	195	390	10.1		114
0.60	155	258	9.1	9.6	95
	168	280	9.4		98
	182	303	9.5		99
	195	325	10.3		108

CHLORIDE CONDUCTIVITY AND PASTE VOLUME

Table 43: Relative chloride conductivity results – 100%CEM I 52.5 N

w/b	**Water content (L/m^3)**	**Binder Content (kg/m^3)**	**Chloride Conductivity (mS/cm)**	**Mean Value (mS/cm)**	**% relative to mean**
0.40	155	388	0.79	0.87	91
	168	420	0.87		100
	182	455	0.89		103
	195	488	0.92		106
0.50	155	310	0.92	1.03	89
	168	336	1.07		104
	182	364	1.06		103
	195	390	1.07		104
0.60	155	258	1.05	1.25	84
	168	280	1.09		88
	182	303	1.33		107
	195	325	1.51		121

Table 44: Relative chloride conductivity results – 30% Fly Ash

w/b	Water content (L/m^3)	Binder Content (kg/m^3)	Chloride Conductivity (mS/cm)	Mean Value (mS/cm)	% relative to mean
0.40	155	388	0.63	0.65	98
	168	420	0.61		95
	182	455	0.62		96
	195	488	0.72		112
0.50	155	310	0.78	0.95	83
	168	336	0.84		89
	182	364	1.08		114
	195	390	1.08		114
0.60	155	258	1.07	1.21	88
	168	280	1.11		92
	182	303	1.25		103
	195	325	1.41		117

Table 45: Relative chloride conductivity results – 50% GGBS

w/b	Water content (L/m^3)	Binder Content (kg/m^3)	Chloride Conductivity (mS/cm)	Mean Value (mS/cm)	% relative to mean
0.40	155	388	0.21	0.23	93
	168	420	0.20		89
	182	455	0.25		111
	195	488	0.24		107
0.50	155	310	0.21	0.28	76
	168	336	0.27		97
	182	364	0.27		97
	195	390	0.36		130
0.60	155	258	0.37	0.47	78
	168	280	0.48		102
	182	303	0.44		93
	195	325	0.60		127

Figure 133: Compressive Strength vs Binder Content at different ages – 50% GGBS