

THE INFLUENCE OF CEMENT EXTENDERS ON THE MECHANICAL AND DURABILITY PROPERTIES OF CONCRETE INCORPORATING WASTE TYRE RUBBER AGGREGATES

by

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DECLARATION

I, the undersigned, hereby affirm that the thesis submitted by me for the Master of Engineering in Civil Engineering degree at the Central University of Technology, Free State, is the result of my own independent research. I also confirm that this work has not been presented to any other university or faculty for the purpose of obtaining a degree. Furthermore, I transfer the copyright of this thesis to the Central University of Technology, Free State.

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ABSTRACT

South Africa faces critical ecological issues stemming from the mismanagement of waste tyres, leading to the atmosphere, hydrosphere and lithosphere pollution due to improper disposal and incineration practices. This environmental concern extends to the mining and manufacturing of aggregates and cement. To mitigate these ecological effects, researchers have used waste tyres as fine-crumb-rubber aggregates (FCR) and coarse-crumb-rubber aggregates (CCR) in concrete technology to create rubberised concrete. However, incorporating these tyre-derived aggregates in concrete has compromised its durability and mechanical characteristics, thus limiting their use in construction projects.

To address the limitations posed by rubber aggregates, a comprehensive review of existing literature, coupled with in-depth experimental analysis, was performed. As a result, this study explored the influence of cement extenders, such as Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBFS), when combined with either Portland Cement (PC) or FA, on enhancing the concrete mechanical properties, namely compressive and splitting tensile strength and improving the durability characteristics, such oxygen permeability index, water absorption, porosity, and chloride conductivity, of concrete containing FCR aggregates. This improvement was achieved by modifying and mixing these extenders with alkaline solutions composed of sodium silicate and sodium hydroxide, a process known as geopolymerisation or alkali activation. The cement extenders in this context are commonly known as alkali-activated binders or geopolymer binders.

The experimental methodology was categorised into three stages (A, B, and C). Stages A and B involved utilising a water-to-cement (w/c) ratio of 0.6 and sand replaced with 10% and 20% of FCR aggregates, as well as Portland cement-CEM I 52R (PC) substituted with 10% and 20% FA. Stage C involved using geopolymer binders of FA, a blend of 40%PC+60%GGBFS, and 40% FA+60% GGBFS blend and sand replaced with 10% and 20% FCR aggregates. All concrete specimens in these stages were tested for workability, durability index and mechanical tests.

The study thus concludes that while FCR aggregates can enhance certain durability characteristics, including water sorptivity and chloride ion conductivity, they adversely affect mechanical properties. Furthermore, FA negatively impacts both the mechanical and durability characteristics of conventional concrete as well as concrete that incorporates FCR aggregates. However, geopolymer binders improve the mechanical characteristics of concrete incorporating FCR aggregates.

These binders also exhibit varying effects on durability properties, with some specimens showing improvements in oxygen permeability index (OPI) while others demonstrate increased water sorptivity (WS) and porosity. The choice of binder and the presence of FCR aggregates significantly influence chloride conductivity (CC), with some specimens displaying poor resistance to chloride ion diffusion. Lastly, the geopolymer concrete mix design made of 40% PC and 60% GGBFS demonstrated superior mechanical and durability characteristics compared to other mix designs.

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LIST OF ABBREVIATIONS

AL/GB	Alkaline solution/Geopolymer binder ratio
C&CI	Cement and Concrete Institute
CBD	Compacted bulk Density
CR	Crumb Rubber
CCR	Coarse Crumb Rubber
DI	Durability Index
FA	Flyash
FM	Fineness Modulus
FCR	Fine Crumb Rubber
GPC	Geopolymer Concrete
GGBFS	Grounded granulate blast furnace slag
LSB	Loose Bulk Density
OPC	Ordinary Portland Cement
PC	Portland Cement CEMI
RD	Relative Density
SATRP	South Africa Tyre Recycling Process Company
SF	Silica Fume
SANS	South Africa National Standards
CR	Waste tyre rubber

CHAPTER 1 : INTRODUCTION

The surge in tyre production in South Africa, which is driven by increasing vehicle demand has led to an alarming annual accumulation of approximately 160,000 tons of waste tyres. Unfortunately, around 150,000 tons of these tyres are either incinerated or illegally dumped, thus resulting in significant environmental distress across soil, air, surface and groundwater. This distress stems from the release of toxic fumes during burning and the non-biodegradable nature of tyres. Remarkably, only a small fraction of about 10,000 tons undergoes recycling through milling processes to produce various products like aggregates, brake pads, and tarred road surfaces (SA Tyre Recyclers, 2020).

In addressing the disposal management of waste tyres as well as mitigating their incineration or dumping, waste tyres found a secondary use within the domain of concrete technology by replacing sand and coarse aggregates. In this domain, waste tyres are classified into two types of rubber aggregates, which are FCR aggregates and CCR aggregates achieved through the milling of waste tyres. FCR aggregates consist of finely powdered or ground rubber particles, while CCR aggregates comprise chipped or shredded rubber particles (Sofi, 2016).

FCR and CCR aggregates contribute positively to concrete production by yielding non-shrinkage concrete, lightweight concrete, and concrete suitable for roadside barrier walls (Bjegović, Baričević and Serdar, 2011; Dumne, 2013; Fiore *et al.*, 2014). However, despite these advantages, their integration into concrete formulations reduces concrete's durability and mechanical properties. This decrease is primarily attributed to the insufficient bonding between the rubber aggregate interface and the cement paste, thus limiting their suitability for application in load-bearing structural components (Lesia, Gopinath and Kiliswa, 2019).

1.1 Problem Statement

The utilisation of Fine Crumb Rubber (FCR) aggregates in concrete has raised concerns regarding the potential decrease in mechanical and durability properties. As evidenced by Ganjian, Khorami and Maghsoudi (2009); Bjegović, Baričević and Serdar (2011); Dumne (2013); Bala, Sehgal and Saini (2014); Fiore *et al.* (2014); Kumar, Sandeep and Sudharani (2014); Wakchaure and Chavan (2014); Gupta, Sharma and Chaudhary (2015); Yazdi *et al.* (2015); Porwal and Dwivedi (2016); Thomas and Gupta (2016); Reddy, Reddy and Krishnan (2017) and Sowmiya and Soundhirarajan (2017), these concerns are the result of the inadequate bond between the binder and the FCR aggregates matrix, which negatively impacts the concrete properties.

However, these studies, on the one hand, present conflicting conclusions regarding the optimal replacement percentages for FCR aggregates and their impact on concrete properties. While some suggest an ideal replacement range between 5% and 30%, others recommend limitations below 7.5% or 20% to prevent significant reductions in mechanical strength. Furthermore, findings regarding the influence of FCR aggregates on water absorption, concrete workability, compressive, flexural, and tensile strengths vary significantly among studies.

On the other hand, researchers like Patankar, Jamkar and Ghugal (2013) have demonstrated that when pozzolanic materials or cement extenders like FA, GGBFS are alkali-activated by mixing them with high alkaline elements (activators) such as Sodium Hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3) solutions and cured at a certain temperature, they form an inorganic alumino-silicate polymer product through a geopolymerisation reaction process, which produces a polymetric Si-O-Al-O bond known as geopolymer gel.

This gel strengthens the bonding capacity between the aggregates and binder matrix, thus enhancing concrete's mechanical and durability properties. The reaction process is also called geopolymerisation, while alkali-activated extenders are called geopolymer binders or alkali-activated binders. However, research on the impact of

these geopolymer binders on the mechanical and durability characteristics of concrete with FCR aggregates (rubberised concrete) is limited.

This knowledge gap hinders understanding their effect on concrete's mechanical and durability characteristics with FCR aggregates and establishing a standardised mix design for efficient and sustainable utilisation of CR aggregates in concrete production. This study, therefore, intends to bridge the gaps by thoroughly assessing how the durability and mechanical characteristics of concrete containing 10% and 20% FCR aggregates are influenced by different cement extenders like FA, modified FA, GGBFS+FA, and GGBFS+PC.

1.2 Research Objectives

This study aimed to investigate the impact of cement extenders in concrete by incorporating FCR aggregates to enhance concrete durability and mechanical properties. The detailed study objectives are to investigate the following:

- a) Different methods or approaches to improve/modify the cement extender properties (FA and GGBFS).
- b) The impact of PC replacement with normal and modified cement extenders in concrete incorporating FCR aggregates.
- c) Optimum mix design of concrete incorporating cement extenders and FCR aggregates.

1.3 Hypothesis

Enhancing the Interfacial adhesion between the binder paste and FCR aggregates within concrete can improve durability and mechanical properties. The replacement of 10% and 20% Portland cement (PC) with FA is expected to fill voids within the concrete structure, thereby enhancing permeability. Moreover, FA-based geopolymer binder and binary geopolymer binders comprising FA+GGBFS and PC+GGBFS are anticipated to initiate a geopolymerisation reaction, resulting in the geopolymer gel formation, which is theorised to act as an adhesive, which fosters stronger adhesion between the aggregate surface and the binder paste matrix.

Based on these assumptions, it is hypothesised that using geopolymer binders in rubberised concrete will lead to notable improvements in various concrete properties. Specifically, enhancements are anticipated in splitting tensile strength, compressive strength, oxygen permeability, water sorptivity, porosity, and chloride conductivity tests. The formation of this adhesive gel through the geopolymerisation process is anticipated to positively influence the overall performance of concrete incorporating FCR aggregates, thus reinforcing its mechanical integrity and durability.

1.4 Study Scope

The study encompassed three distinct stages (A, B and C) to comprehensively assess the effects of FA and geopolymer binders on the properties of concrete with FCR aggregates. In stage A, the substitution of Umgeni River sand with 10% and 20% FCR aggregates, sized 0.075-1mm, and the substitution of PC with 10% and 20% FA by mass of material was examined. Stage B focused on the impact of incorporating 10% and 20% FA into concrete with 10% and 20% FCR aggregates.

Stage C extended the investigation by employing FA, 40%PC+60%GGBFS, and 40%FA+60%GGBFS geopolymer binders in concrete with 10% and 20% FCR aggregates. Alkaline-to-binder ratio of 0.4, NaOH/Na₂SiO₃ ratio of 2.5, and 16M concentration of NaOH were adopted during the alkali-activation process. The testing phase included evaluations of 7-day and 28-day splitting tensile and compressive strength alongside durability index tests conducted 28 days after specimen casting.

1.5 Limitations

Several limitations need to be acknowledged. The study's narrow focus on specific substitution percentages and binder formulations may limit the generalisability of the findings to broader substitution ranges or different binder compositions. Additionally, the 28-day testing duration does not adequately capture long-term effects or ageing properties that could emerge over extended periods in real-world applications. The study's restricted focus on specific parameters and test durations could constrain the comprehensive assessment of all potential effects on concrete properties.

Moreover, the study may not consider all environmental or external factors that could influence the performance of rubberised concrete in real-world scenarios. Lastly, due to the large quantities of specimens generated from stages A, B and C, there was a limited water curing facility. Hence, all specimens were subjected to controlled temperature conditions until the testing period, which could have influenced the results, particularly for stages A and B.

1.6 Dissertation Layout

The layout of the dissertation is structured as follows:

Chapter 1: Introduction

The chapter provides the introduction of the study, which includes the problem statement and the scope and limitations of the study.

Chapter 2: Literature Review

The chapter overviews how waste tyre rubber aggregates affect concrete's durability and mechanical properties. It explores the influence of cement extenders such as FA and GGBFS on concrete that incorporates waste tyre rubber aggregates. Additionally, a comprehensive assessment of the literature on the alteration of cement binders through geopolymerisation and its impact on the durability and mechanical characteristics of conventional and concrete with FCR aggregates is carried out.

Chapter 3: Research Methodology

The chapter addresses the materials used, details the various tests conducted on both materials and fresh and hardened concrete and outlined the mix designs that determined the mass of material proportions necessary for the study.

Chapter 4: Result and Discussion

This chapter showcases the experimental outcomes, analyses the results, and then discusses the findings.

Chapter 5: Conclusion and Recommendations

This chapter presents the conclusions derived from the data analysed in Chapter 4 and includes recommendations for future research.

CHAPTER 2 : LITERATURE REVIEW

This chapter provides an overview of waste tyre application in concrete technology. Incorporating waste tyre aggregates in concrete normally affects the bond strength between the cement matrix and waste tyre particles, thus affecting concrete's durability and mechanical properties. This section further discusses the influence of cement extenders, FA, SF and GGBFS on conventional and rubberised concrete properties. Furthermore, the performance of modified cement extenders with alkali activation in conventional concrete is also reviewed.

2.1 Review of Waste Tyre Aggregates in Concrete

As reported by the South African Tyre Recycling Process Company, scrap tyres amounting to 160,000 tonnes are produced yearly in South Africa. Out of 160000 tons, 10000 tons of scrap tyres are recycled into different types and sizes for various applications. The rest of 150 000 tons of scrap tyres are burned and illegally dumped into the environment (SA Tyre Recyclers, 2020).

From the afore-mentioned postulations, it can be concluded that disposal management of waste tyres poses a significant challenge to the environment because these tyres are not prone to decay, and they yield toxic gasses when burned, which pollute air, land and water (Lesia, Gopinath and Kiliswa, 2019). Waste tyres were initially used in breakwaters, reefs, erosion control, playground equipment, highway crush barriers, noise barriers, guard rails posts, etc. (Hylands and Shulman, 2004). Hence, adopting waste tyres in concrete technology can assist in addressing disposal management challenges as it will decrease the burning and illegal dumping of waste tyres into the environment.

Applying waste tyres in concrete started around the 1980s (Toutanji, 1996). Waste tyres are ground through the milling process into small particles to form crumb rubber particles referred to as crumb rubber (CR) aggregates. CR aggregates are incorporated into concrete to form rubberised concrete. CR, on the one hand, improves concrete ductility and brittle failure and decreases concrete weight. As a result, waste tyre aggregates find their application in lightweight concrete, roadside

barrier walls, etc. On the other hand, using waste tyre aggregates in concrete reduces concrete strength and durability, deprecating its usage in load-bearing structural components due to decreased density, weight, and strength.

2.2 Production and Classification of Waste Tyre Aggregates

Scrap tyres can be recycled through mechanical or cryogenic milling. Mechanical milling is where the tyres are crushed using cracker grinding and then granulated and classified into other classes depending on the grading size. Cryogenic milling is where tyres go through temperature below the glass transition temperature by freezing into nitrogen liquid. They are cooled and crushed using a hammer mill and classified into different sizes depending on the application (Tsoana, 2015; Lesia, Gopinath and Kiliswa, 2019).

Mechanically milled waste tyre aggregates are preferred over cryogenic milled because they are cheap and easy to manufacture. The Cryogenic milling produces uniform, finely shaped particles that produce the required gradations. When cooled, the rubber becomes steel-like particles with free fabric content (Tsoana, 2015). As a result, cryogenic milling rubber products are preferred to mechanically milled tyres due to their physical properties. However, they are costly compared to mechanically milled ones. Different researchers classify CR aggregates into three distinct categories, viz;

- a) **Chipped rubber, Shredded, or fibre:** applied to replace coarse aggregates, with dimensions of 430–73mm length (see Figure 2.1a).
- b) **Fine or coarse Crumb rubber (FCR or CCR):** Used as coarse or fine aggregates or to replace the sand or coarse aggregates in concrete. Crumb rubber size ranges from 0.425–19mm. Aggregates are made with high irregularities to improve surface texture and can either be cryogenic or mechanically milled (see Figure 2.1 b and Figure 2.1c).
- c) **Grounded rubber or powder:** is applied to substitute cement or fine aggregates in concrete due to particles ranging from 0.075-0.475mm (Ganjian, Khorami and Maghsoudi, 2009).

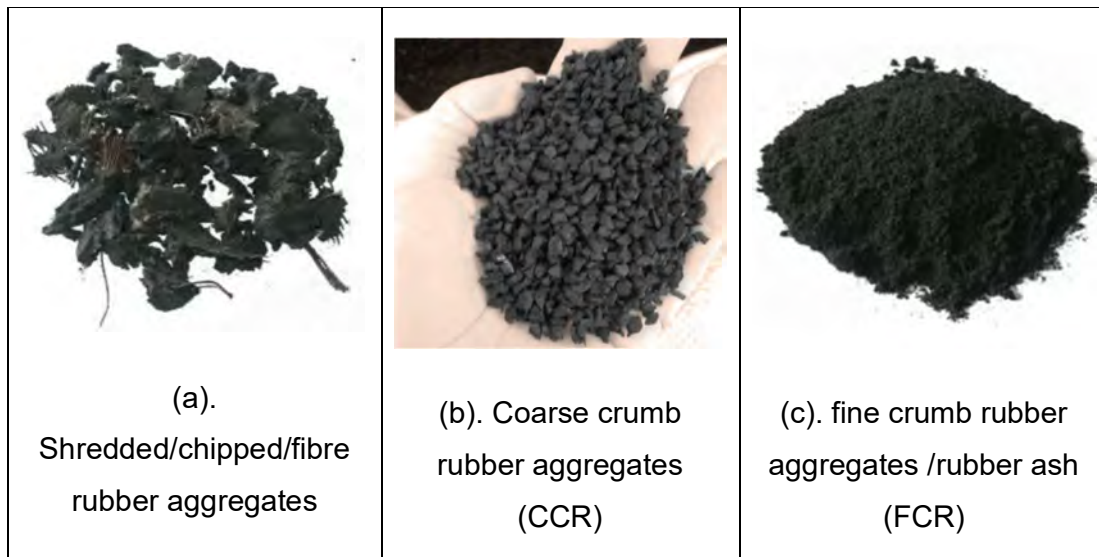


Figure 2.1. Different categories of CR aggregates: (a) shredded rubber aggregates, (b) coarse crumb rubber aggregates and (c) fine crumb rubber aggregates

In addition to the above classification, CR aggregates are classified by ASTM D-6270, which is the standard practice of using waste tyres in civil engineering applications (Liu, 2013). This is illustrated in Table 2.1 below.

Table 2.1. ASTM D-6270 terminology for recycled waste tyre aggregates (Liu, 2013)

Classification	Lower Limit (mm)	Upper Limit (mm)
Chopped tyre	Unspecified dimensions	
Rough Shred	1.97x1.97x1.97 (50x50x50)	30x1.97x3.94(762x50x100)
Tyre derived Aggregates	0.47 (12)	12 (305)
Tyre Shreds	1.97 (50)	1.96 (50)
Granulated rubber	0.017 (0.425)	0.47 (12)
Ground Rubber	-	<0.017 (0.425)
Powered rubber	-	<0.017 (0.425)

2.3 The Impact of Crumb Rubber Aggregates on Concrete Properties

This section reviews the literature on the impact of CR aggregates on flexural, compressive, and tensile strength, water permeability, sorptivity and porosity by

considering different water/cement ratios (w/c), different aggregate sizes and percentage replacements of sand and coarse aggregates with other classes of CR aggregates.

2.3.1 Crumb Rubber Aggregates Impact on Concrete Mechanical Properties

Concrete strength, a critical indicator of concrete quality, is influenced by various parameters, including the type and proportion of aggregates used. Ganjian, Khorami and Maghsoudi (2009) conducted a study examining the effect of incorporating more than 5% chipped rubber and rubber powder as coarse aggregates and cement, respectively, in concrete mixes. They used a water-to-cement (w/c) ratio of 0.5 and a superplasticiser content of 0.4% by cement weight. The results showed a decrease in both compressive and tensile strength due to a bonding deficiency between the cementitious matrix and the rubber aggregates. Since tensile strength is primarily dependent on bond strength, this deficiency leads to reduced mechanical performance.

Additionally, Ganjian, Khorami and Maghsoudi (2009) further investigated the impact of rubber aggregates on concrete by considering their physical properties. They found that the applied stress within concrete structures containing rubber aggregates was not uniformly distributed, leading to the formation of cracks under load, which ultimately caused concrete failure. Crumb rubber (CR) aggregates behave like pores within the concrete matrix, generating high stresses on their surfaces. This characteristic facilitates early breakdown of concrete specimens during testing, as cracks propagate more readily, resulting in reduced overall concrete strength (Lesia, Gopinath and Kiliswa, 2019).

Studies by Ganjian, Khorami and Maghsoudi (2009); Dumne (2013); Lesia, Gopinath and Kiliswa (2019) have shown that replacing less than 5% of traditional aggregates with CR aggregates results in mechanical properties that are nearly equivalent to those of conventional concrete. However, increasing the CR aggregate content beyond 5% leads to a decline in mechanical properties due to poor bonding and stress distribution. This observation highlights the need for further research to

enhance the properties of concrete containing higher percentages of CR aggregates.

El-Gammal *et al.* (2010) explored the replacement of sand and coarse aggregates with 50% fine crumb rubber and 100% chipped CR aggregates, respectively. Their results indicated a substantial reduction in compressive strength—by 90% in concrete containing 100% chipped CR aggregates and by 80% in concrete with 50% crumb rubber. The study suggests that crumb rubber aggregates perform better than chipped rubber aggregates due to more uniform particle distribution within the concrete matrix.

Boudaoud and Beddar (2012) replaced coarse crushed gravel aggregates with crumb rubber of specific sizes 8/16mm and 16/25mm with 10–12mm and 16–20mm and observed a 50% reduction in compressive and flexural strength. The decline in strength was further exacerbated by an increase in the percentage of CR aggregates, attributed to the non-homogeneous distribution of crumb rubber within the concrete mix.

Gupta, Chaudhary and Sharma (2014) examined the impact of varying water-to-cement ratios (0.55, 0.45, and 0.35) on the strength of rubberised concrete, with sand partially replaced by rubber fibre (up to 25%) and fly ash (up to 20%). Their findings revealed that concrete with a 0.35 w/c ratio achieved better density, compressive, and flexural strength compared to higher ratios. While the 0.55 w/c ratio increased concrete slump, improving CR aggregate distribution, it only marginally enhanced compressive strength. The presence of rubber fibres facilitated a stronger bond between aggregates and the cement matrix, limiting crack propagation under load.

Research by Deshpande *et al.* (2014); Wakchaure and Chavan (2014) further explored the use of shredded and crumb rubber aggregates in place of natural sand and coarse aggregates. They found that incorporating 1-10% of rubber aggregates led to a reduction in compressive strength, which was attributed to the formation of voids as rubber particles repelled water and attracted air. Surface treatment of rubber aggregates with Sodium Hydroxide (NaOH) improved their texture and bond

with the cement matrix, enhancing compressive strength. Wakchaure and Chavan (2014) reported that NaOH-treated rubber aggregates showed a 12.21% and 21.83% reduction in compressive strength at 1.5% and 2% replacement levels, respectively. However, the addition of fibreglass helped recover the lost strength by further reinforcing the concrete matrix.

These studies collectively demonstrate the complex interaction between rubber aggregates, cementitious materials, and concrete strength. While rubber aggregates can reduce concrete's mechanical properties due to poor bonding and stress distribution, careful optimisation of mix proportions, surface treatments, and the inclusion of additional reinforcing materials can mitigate these effects, highlighting the potential for sustainable and effective use of rubber aggregates in concrete.

2.3.2 Impact of Crumb Rubber Aggregates on Concrete Durability Properties

CR aggregate generally creates a bonding deficiency between the aggregates and the cement paste matrix, reducing the concrete mechanical characteristics. Hence, looking profoundly into the impacts of CR aggregates on concrete durability properties is essential. As a result, Bravo and De Brito (2012) investigated the impact of replacing sand and coarse aggregates with 15%, 10% and 5% of grounded and cryogenic aggregates. The results revealed that the absorption of water increased further with the percentage replacement increase of CR aggregates. This behaviour was due to the bonding deficiency between the aggregate interface and cement paste, which created water passage through the concrete structure. However, CR aggregates reduced shrinkage and chloride penetration.

Similarly, in their review study, Lesia, Gopinath and Kiliswa (2019) discovered that 10% of rubber fibres and rubber ash increased carbonation and absorption of water because of entrapped air and aggregated distribution, which created water and carbon dioxide passage. However, chloride-ion penetration decreased with increased rubber fibre and ash due to the non-reactive nature of CR aggregates. In consonance, Huda (2014) observed that water absorption and porosity increased

when coarse natural aggregates were replaced with 30–100% crumb rubber aggregates. Additionally, a 3.5% increase in water absorption was observed with 15%, 10%, and 5% substitution of sand and coarse aggregates with 1-4mm and 5-8mm of scrap tyre rubber aggregates (Adamu and Uche, 2014).

Water absorption decreased gradually with 0 to 20% sand replacement by CR aggregates in concrete made of 0.5, 0.45 and 0.4w/c ratios; however, at 5% replacement and 0.45 and 0.4 w/c, there was no change in the absorption of water results were similar to the reference specimen results (Thomas *et al.*, 2014). Furthermore, Thomas and Gupta (2015) also studied the impact of 12.5% of 0.8-2mm rubber powder and 2-4mm crumb rubber on concrete with crushed stone and river sand. Their results showed that porosity, carbonation, and water absorption decreased due to the w/c ratio, type, size, and gradation of rubber aggregates used in the concrete mix.

Moreover, Su *et al.* (2015) found that finer CR aggregates achieve better water permeability than coarser CR aggregates. Also, well-graded CR aggregates yield better water permeability resistance than single-sized rubber aggregates (Lesia, Gopinath and Kiliswa, 2019). Once more, 5% and 15% replacement of sand with rubber powder enhanced resistance to sulphate attack (Xu *et al.*, 2015).

Moreover, it was observed from the literature that water absorption, water penetration, and sorptivity increase with the increase in the replacement percentage of aggregates with CR aggregates (Ghosh and Bera, 2016; Thomas and Gupta, 2016). With more than 5% replacement of natural aggregate with rubber aggregates, water absorption, sorptivity and porosity are affected negatively due to high air content in rubberised concrete, compromised bond strength, aggregate gradation, and aggregate size. Hence, improving bond strength and CR aggregate gradation led to better concrete properties.

2.4 The Impact of FA on Rubberised Concrete Mechanical Properties

Blending cement with FA and GGBFS enhances concrete strength. It reduces permeability and chemical attack due to material fineness, which fills the air voids

between cement and aggregate matrix and increases concrete density and weight (Rasol, 2015; Samad, Shah and Limbachiya, 2017; Zulu, 2017). Therefore, this section reviews the literature on the impact of FA on rubberised concrete mechanical properties

2.4.1 Workability

Concrete slump assists in evaluating and measuring concrete consistency and how workable concrete can be. Therefore, this section covers the review of the effects of FA on rubberised concrete workability. As shown in Figure 2.2 (a) and (b) below, FA improved the workability of concrete incorporating crumb rubber aggregates. Slump increases because of the unvarying shape of the rubber aggregate and the w/c ratio (Bala, Sehgal and Saini, 2014). Porwal and Dwivedi (2016) also observed a similar pattern of concrete slump increasing with increasing coarse crumb rubber aggregate and FA content in concrete.

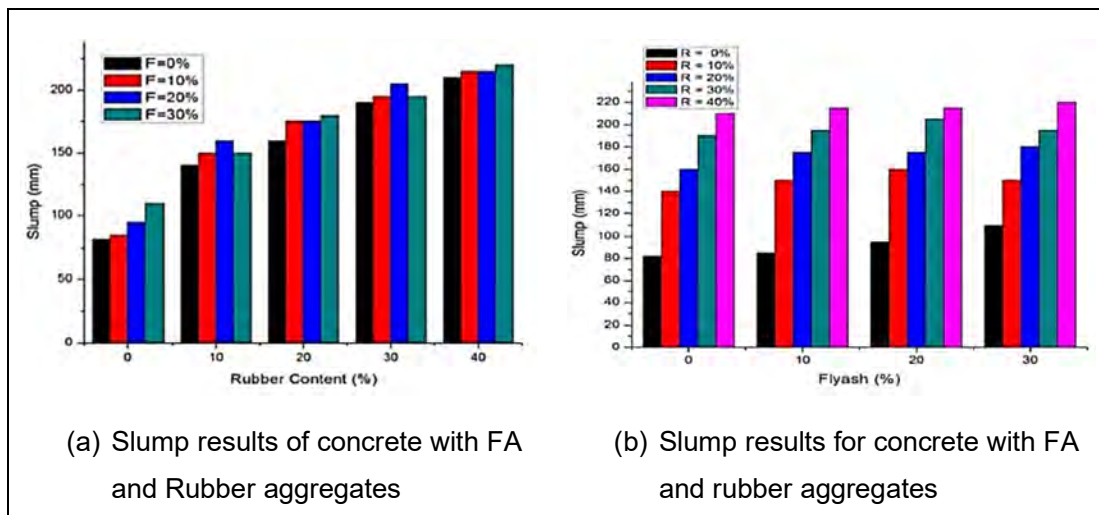


Figure 2.2: Variation of fly ash and rubber aggregate replacement in concrete (Bala, Sehgal and Saini, 2014)

2.4.2 Compressive Strength

This section discusses the impact of replacing PC with FA on the compressive strength of rubberised concrete. Increasing CR aggregates content, compressive strength decreased because the crumb rubbers are less stiff than cement paste.

However, as shown in Table 2.2 Below, different grading methods with different CR content were evaluated. Based on the results, a bigger fraction size of 0.51-1mm yielded high compressive strength on both 20% and 30% CR aggregate replacement. High compressive strength was due to particle size grading and distribution of 0.5-1mm FCR aggregates (Yilmaz and Degirmenci, 2009).

Table 2.2: Results of compressive strength of the specimen with FA on concrete with 20% and 30% of FCR aggregates (Yilmaz and Degirmenci, 2009)

FCR	Fraction size (mm)	FA %	28 days Compressive Strength (Mpa)
20%	0-0.25	70	4.63
	0.25-0.50		4.81
	0.50-1.0		4.84
30%	0-0.25	60	3.94
	0.25-0.50		4.37
	0.50-1.0		4.83

Furthermore, cement was replaced with 20, 40 and 60% of FA and sand with 0.25-4mm CR aggregates at 5, 15 and 25%. The results shown in Figure 2.3 below show that compressive strength declined with increased CR aggregates and FA percentage replacement. The compressive strength of concrete with 0% rubber decreased with FA increase; a similar pattern was observed with concrete with 5%, 15%, and 25% CR aggregates (Güneyisi, 2010). Comparing the strength results with other researchers' results, compressive strength reduction was attributed to percentage replacement and fraction size of FCR aggregates.

Similar trends to Güneyisi (2010) were observed by Azevedo *et al.* (2012), as shown in Figure 2.4. The increased percentage replacement of fine crumb rubber aggregates (RW) aggregates and FA (CV) also decreased compressive strength. However, because of the slow reaction of the hydration process, the compressive strength increased with time.

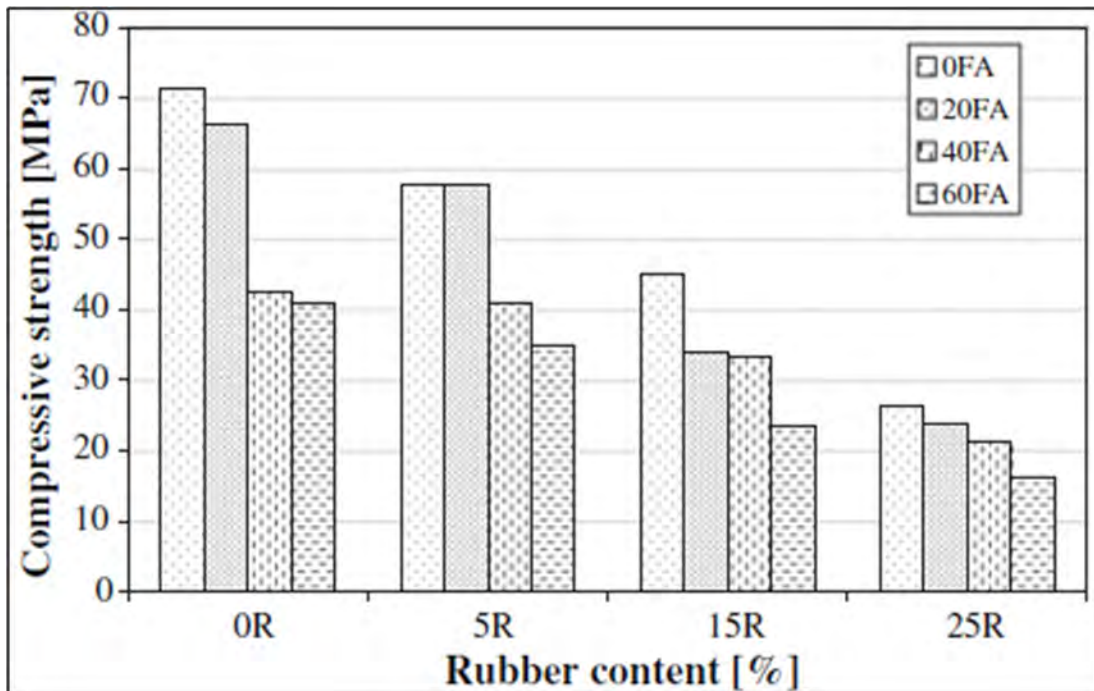


Figure 2.3: Compressive strength results of rubberised concrete with FA (Güneyisi, 2010)

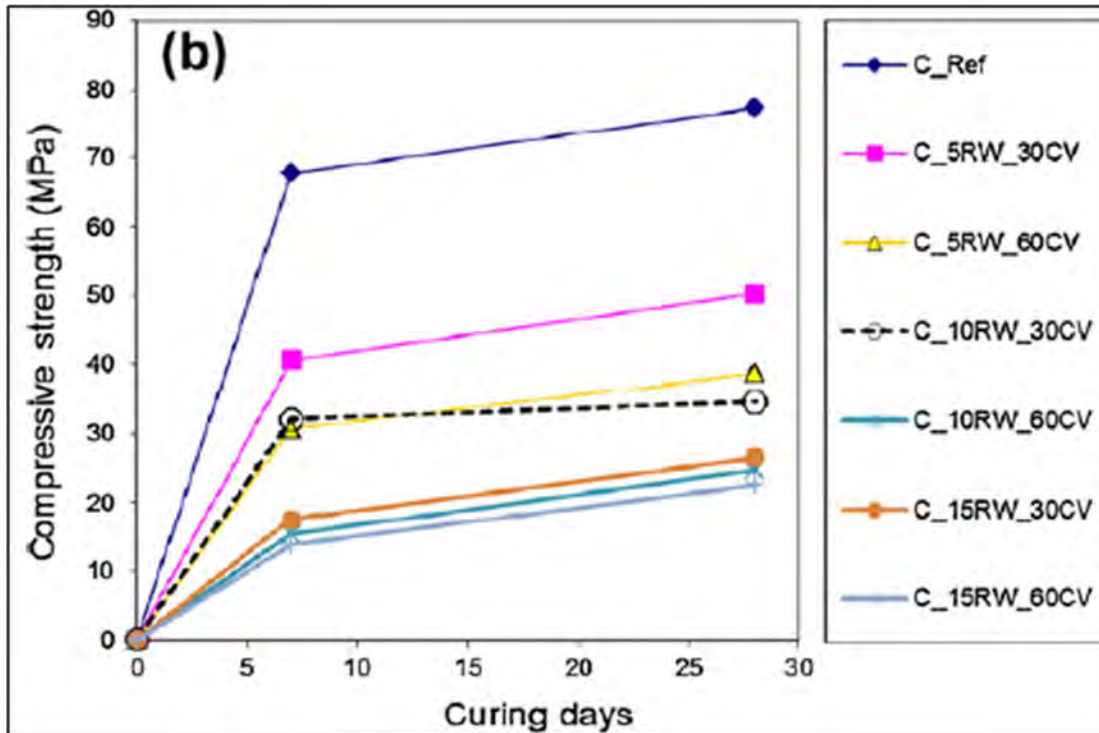


Figure 2.4: Compressive strength results on rubberised concrete with FA content (Azevedo *et al.*, 2012)

The effect of 10% and 20% of FA on concrete with 10% and 20% of 20mm CCR aggregates was studied by Porwal and Dwivedi (2016), comparing other specimens' results with that of TCA0FA0, it can be shown in the results in Table 2.3 that with an increase in CCR aggregates, compressive strength decreased. However, by introducing FA, compressive strength improved slightly; e.g. from 10% CCR and 0% FA, compressive strength was 21.83Mpa. By adding 10% FA, the strength increased to 22.66Mpa. Similar results were also observed in mixed notation TAC20FA0 and TAC20FA10, etc.

Table 2.3: Compressive strength results (Porwal and Dwivedi, 2016)

Notation	FA (%)	CCR aggregates (%)	Compressive strength (Mpa)
TCA0FA0	0	0	29.55
TCA10FA0	0	10	21.83
TAC20FA0	0	20	18.22
TAC30FA0	0	30	12.44
TCA0FA10	10	0	30.22
TCA10FA10	10	10	22.66
TAC20FA10	10	20	20.22
TAC30FA10	10	30	14.44
TCA0FA20	20	0	30.50
TCA10FA20	20	10	23.55

2.4.3 Flexural Strength

The impact of incorporating crumb rubber (CCR) aggregates and fly ash (FA) on the flexural strength of concrete has been the subject of several studies. Porwal and Dwivedi (2016) investigated the effects of varying fly ash content on concrete containing CCR aggregates. Their findings indicated that the flexural strength of concrete improved with increased FA content. Specifically, in their study, concrete with 10% CCR aggregates and no fly ash had a flexural strength of 4.80 MPa. When 10% fly ash was added to the mix, the flexural strength increased to 5.20 MPa. This enhancement was also observed with higher FA content; concrete with 20% and 30% CCR aggregates and 10% and 20% FA showed similar improvements in flexural strength. This suggests that fly ash contributes positively to the performance

of CCR aggregate concrete by improving the material's ability to resist bending stresses.

In addition, Reddy, Reddy and Krishnan (2017) reported that the inclusion of 5% shredded coarse rubber aggregates combined with 20% fly ash led to a slight increase in flexural strength, from 9.2 N/mm² to 9.4 N/mm². Their results corroborate the findings of Porwal and Dwivedi (2016) by demonstrating that the presence of fly ash in concrete with rubber aggregates can enhance the material's flexural performance, albeit to a lesser extent compared to other studies.

These studies collectively highlight the beneficial role of fly ash in improving the flexural strength of concrete containing CCR aggregates. The enhanced performance can be attributed to the improved bonding between the CCR aggregates and the cementitious matrix facilitated by the fly ash, which may lead to a more robust concrete structure capable of withstanding greater flexural stresses.

2.4.4 Bond Strength

The enhancement of bond strength is crucial for improving the overall strength of concrete, particularly when incorporating waste tyre rubber aggregates. An important aspect of this research involves understanding the role of fly ash (FA) in modifying the properties of concrete containing crumb rubber (CCR) aggregates.

Bala, Sehgal and Saini (2014) investigated the influence of fly ash on the bond strength of concrete with waste tyre rubber aggregates. Their study, detailed in Figure 2.5, revealed that concrete containing 10%, 20%, and 30% CCR aggregates of 4.75–20 mm size experienced substantial reductions in bond strength. Specifically, bond strength decreased by 62.5%, 58.3%, 75%, and 83.3% with increasing CCR content relative to a control mix with no CCR aggregates.

Despite these reductions, the study also highlighted that the incorporation of fly ash into concrete with 20% CCR aggregates led to an improvement in bond strength. This improvement is attributed to the fine particles of fly ash, which help to fill the air voids created by the rubber aggregates. Rubber aggregates tend to attract air and

repel water due to their polar nature, which can negatively impact bond strength. The fine properties of fly ash mitigate this issue by reducing the voids and enhancing the adhesion between the rubber aggregates and the cementitious matrix.

Lesia, Gopinath and Kiliswa (2019) also support these findings, noting that the presence of fly ash contributes positively to the bond strength of rubberised concrete. The fine particles of fly ash effectively address the challenges posed by the air pockets created by the rubber aggregates, thereby improving the overall bond strength and contributing to better concrete performance.

In summary, the integration of fly ash into concrete mixes containing rubber aggregates significantly enhances bond strength. This improvement is due to the ability of fly ash to fill voids and facilitate better adhesion between the aggregates and the cement matrix, ultimately leading to stronger and more durable concrete.

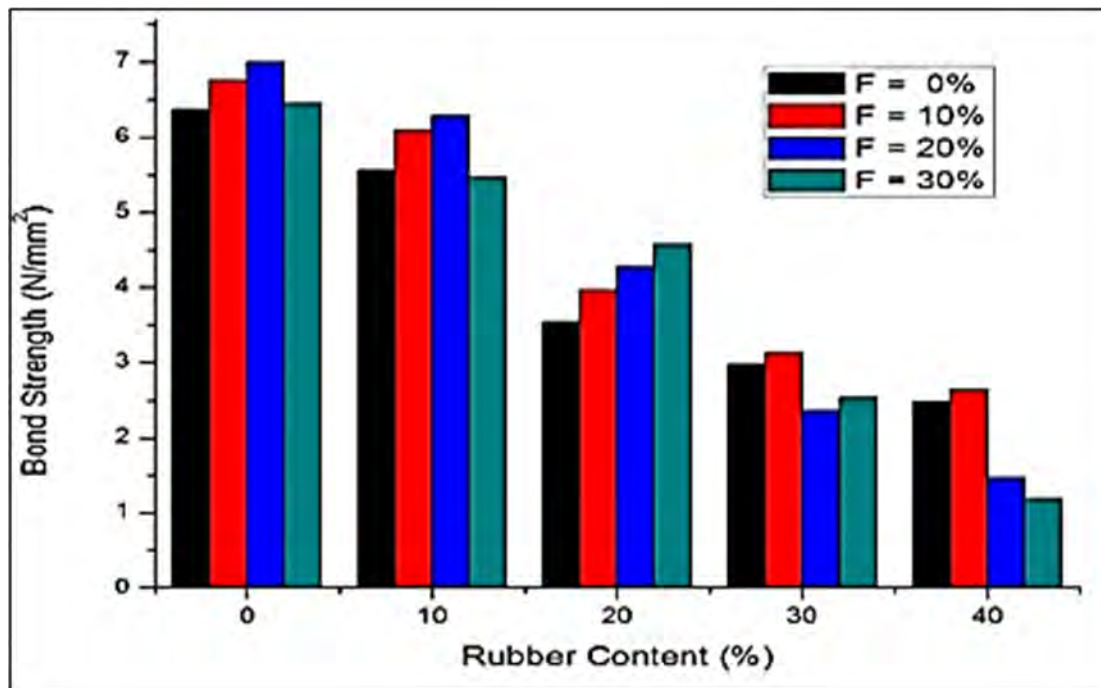


Figure 2.5: Bond strength results on rubberised concrete with 0-30% FA (Bala, Sehgal and Saini, 2014)

2.4.5 Split Tensile Strength

The split tensile strength of concrete is a critical parameter that can be significantly influenced by the incorporation of various aggregates and supplementary cementitious materials. Research by Porwal and Dwivedi (2016) demonstrated that the inclusion of CCR (crumb rubber) aggregates, when combined with varying percentages of fly ash (FA), can lead to noticeable improvements in the split tensile strength of concrete.

Specifically, their study found that a concrete mix containing 10% CCR aggregates without any fly ash content exhibited a split tensile strength of 1.95MPa. However, when the same mix was modified to include 10% fly ash, the split tensile strength increased to 2.0MPa. This suggests that the addition of fly ash can enhance the bonding between the CCR aggregates and the cement matrix, thereby improving the overall tensile strength of the concrete.

Further investigations by Reddy, Reddy and Krishnan (2017) support these findings, indicating that the strategic use of fly ash in combination with natural and rubber aggregates can optimise the mechanical properties of concrete. In their study, a concrete mix incorporating 20% fly ash and 80% Portland cement (PC), along with 95% natural coarse aggregates (NCA) and 5% coarse shredded rubber aggregates, was shown to attain the desired split tensile strength gradually. The results, as summarised in Table 2.4, indicate a progressive improvement in the tensile strength with the increase in fly ash content, highlighting the role of fly ash in enhancing the strength characteristics of concrete modified with rubber aggregates.

These studies collectively underscore the potential benefits of integrating CCR aggregates and fly ash into concrete mixes, not only as a means to improve mechanical performance but also to contribute to sustainable construction practices by utilising recycled materials. The incorporation of fly ash, a by-product of coal combustion, and crumb rubber from discarded tyres provides an effective approach to enhancing concrete properties while promoting environmental sustainability.

Table 2.4: Average Split Tensile Strength N/mm² of M35 Grade Results (Reddy, Reddy and Krishnan, 2017)

S. #	Mix proportion	7 days	14 days	28 days
1	100% NCA+ 100%PC+0%Scrap tyre+0%FA	1.64	2.23	2.61
2.	95% NCA+ 90%PC+5%Scrap tyre+10%FA	1.46	1.98	2.38
3.	95% NCA+ 85%PC+5%Scrap tyre+15%FA	1.56	2.12	2.43
4.	95% NCA+ 80%PC+5%Scrap tyre20%FA	1.63	2.21	2.60

2.5 Impact of FA on Rubberised Concrete Durability Properties

Durability measures the concrete ability to resist water permeability, chloride penetration, chemical attack, etc. From the literature, it is conclusive that bond strength is the major problem that affects rubberised concrete's mechanical properties. Hence, this section will review the impact of FA on rubberised concrete durability properties, focusing mainly on water absorption, water permeability and chloride penetration.

2.5.1 Water Absorption, Water Permeability and Chemical Attack

The water absorption characteristics and durability of concrete can be significantly influenced by the type and proportion of aggregates used, as well as the incorporation of supplementary cementitious materials such as fly ash (FA). This section reviews the effects of fine crumb rubber (FCR) aggregates and FA on water absorption, capillary absorption, and resistance to acid attack in concrete.

Gesoğlu and Güneyisi (2011) investigated the impact of FCR aggregates on water absorption in concrete. They observed that water absorption increased with the content of FCR aggregates, ranging from 2.73% to 4.25% and 2.56% to 4.03% at 28 and 90 days, respectively. This trend indicates that rubberised concrete becomes more absorbent as the FCR aggregate content increases. However, the substitution of Portland cement (PC) with FA was found to reduce water absorption. For instance, concrete with 15% FCR and 60% FA exhibited a water absorption rate of 3% at 90 days, compared to 3.35% in concrete with 15% FCR and no FA, representing a 12% reduction. This reduction is attributed to the finer particle size of FA, which helps to fill voids and improve the overall density of the concrete mix.

Bjegović, Baričević and Serdar (2011) reported similar findings, noting that replacing 10% of PC with FA in concrete containing 0%, 10%, and 15% finely shredded rubber and fine crumb rubber led to an average reduction in water absorption by 78% when rubber content ranged between 5% and 15%. They attributed this improvement to the ability of rubber aggregates to capture air in pores and repel water, which reduces capillary absorption. However, increased rubber content also led to a higher depth of water permeability due to bond deficiencies between the binder paste and rubber particles.

Azevedo *et al.* (2012) observed that the capillary water absorption increased with higher FA replacement levels. Their results in Figure 2.6(a) showed that concrete mixes with 30% and 60% FA (C_30CV & C_60CV) exhibited greater capillary water absorption compared to mixes containing FA and 5%, 10%, and 15% FCR aggregates in Figure 2.6(b). Notably, a significant reduction in capillary water absorption was achieved in the mix with 15% FCR and 30% FA (C_15RW_30CV), indicating that the incorporation of FCR aggregates was more effective in reducing water absorption than increasing FA content alone.

In addition to water absorption, the resistance of concrete to acid attack was also enhanced by high FA content. Azevedo *et al.* (2012) noted that the fineness of FA reduces air pockets in concrete, which otherwise create pathways for acid ingress, thus improving the concrete's resistance to acid attack. Furthermore, FCR aggregates were found to reduce chloride ion penetration more effectively than shredded rubber aggregates. This reduction is attributed to the role of FA in filling voids between FCR aggregates and natural aggregates and to the improved distribution of aggregates within the concrete mix (Bjegović, Baričević and Serdar, 2011).

In summary, the inclusion of FA in concrete containing FCR aggregates significantly affects water absorption, capillary absorption, and durability. FA improves the concrete's density and resistance to water absorption and acid attack, while FCR aggregates contribute to these properties by altering the pore structure and reducing chloride ion penetration. The combination of FA and FCR aggregates can enhance

the overall performance of concrete, making it a promising approach for improving the durability and sustainability of concrete materials.

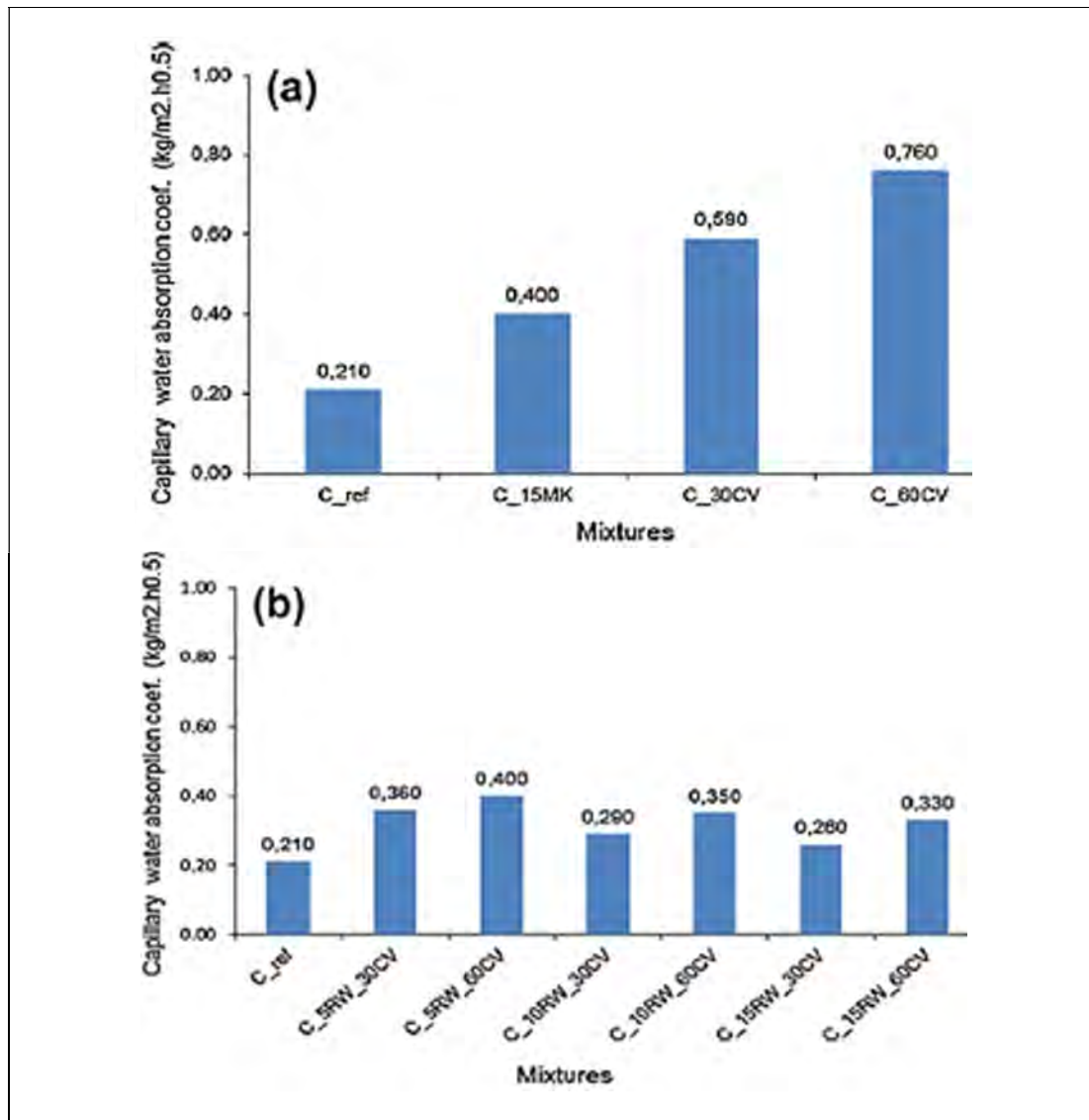


Figure 2.6: Water absorption coefficient results in (a) capillary water absorption for conventional concrete with cement extenders and (b) capillary water absorption for rubberised concrete with cement extenders (Azevedo *et al.*, 2012)

2.6 Cement Extender Modification Through Geopolymerisation

Research by Davidovits (1991); Panias and Giannopoulou (2004); Patankar, Ghugal and Sanjay S. Jamkar (2015) has focused on enhancing the performance of

pozzolanic materials rich in silica and alumina, such as fly ash (FA), ground granulated blast furnace slag (GGBFS), and silica fume (SF). These studies revealed that pozzolanic materials when activated by an alkaline solution, form an alumino-silicate polymer commonly referred to as an alkali-activated binder, geopolymer binder, or geopolymer cement. This process results in the formation of a three-dimensional polymeric network of silicon-oxygen-aluminium (Si-O-Al) bonds, which impart significant strength and durability to the concrete.

Materials rich in silica (SiO_2) and alumina (Al_2O_3), such as fly ash, rice husk ash, slag, silica fume and metakaolin, are typically used to create geopolymer cement due to their high pozzolanic reactivity (Kothari, 2017; Lesia, Gopinath and Kiliswa, 2019). Among these materials, fly ash is particularly favoured as a cement extender in geopolymer concrete. This preference is primarily because the production of FA emits significantly less carbon dioxide compared to traditional Portland cement, making it an environmentally friendly alternative. Additionally, fly ash is economical and widely available, further supporting its use in sustainable concrete production.

The suitability of fly ash in geopolymer binders is also attributed to its high concentration of amorphous aluminosilicates and low levels of calcium oxide (CaO). Low-calcium fly ash is generally preferred over high-calcium varieties because high CaO content can lead to rapid heat generation, which may cause premature setting of the concrete, adversely affecting workability and performance (Wardhono, 2015). Wardhono (2015) suggests that for optimal performance in geopolymer concrete, the calcium oxide content in fly ash should be less than 20%. This restriction ensures a controlled setting time and enhances the durability of the resulting geopolymer concrete.

In conclusion, the development of geopolymer cement utilising pozzolanic materials like fly ash offers a sustainable and effective solution for concrete production. The alkaline activation of these materials forms a robust alumino-silicate network, enhancing the mechanical properties and durability of the concrete while reducing the environmental impact associated with conventional Portland cement production.

2.6.1 Geopolymerisation (alkali-activation) of Cement Extenders

The geopolymerisation process, analogous to the hydration process in conventional Ordinary Portland Cement (OPC) concrete, is a chemical reaction that occurs when aluminium-silicate materials react with alkaline activators. This process is essential for the formation of geopolymer concrete, as it transforms the raw materials into a solid, durable binder (Wardhono, 2015; Kothari, 2017).

Geopolymerisation is characterised as an exothermic and amorphous reaction that forms a three-dimensional network of silicate structures. These structures are composed of shared oxygen atoms between tetrahedrally coordinated silica (Si) and aluminate (Al) units, creating a polymeric chain or network. The presence of positive ions, such as sodium (Na^+), potassium (K^+), lithium (Li^+), or calcium (Ca^{2+}), is necessary to balance the negative charges of the aluminium ions in four-fold (IV) coordination (Ng *et al.*, 2018).

Figure 2.7 categorises the geopolymerisation process into three types based on the silica-to-alumina (Si/Al) ratios: poly(sialate), poly(sialate-siloxo), and poly(sialate-disiloxo) (Singh, 2018). Each type of geopolymer structure depends on the proportion of silicon to aluminium within the starting materials, which influences the final properties of the geopolymer concrete;

- a) Poly(sialate): This structure has a low Si/Al ratio, typically resulting in a highly cross-linked network that offers substantial mechanical strength.
- b) Poly(sialate-siloxo): With a moderate Si/Al ratio, this type of geopolymer provides a balance between strength and flexibility, making it suitable for various structural applications.
- c) Poly(sialate-disiloxo): A higher Si/Al ratio characterises this type, resulting in a structure that may have enhanced durability and resistance to chemical attacks.

The type of alkali metal used (e.g., sodium, potassium) can further influence the characteristics of the geopolymer. These ions help stabilise the negative charges on the aluminium ions and play a crucial role in determining the setting time, strength, and durability of the geopolymer concrete (Wardhono, 2015).

In conclusion, the geopolymerisation process is fundamental to the development of geopolymer concrete, providing a sustainable alternative to conventional OPC concrete. By carefully selecting the type and ratio of silica to alumina, as well as the choice of alkaline activators, it is possible to tailor the properties of geopolymer concrete to meet specific engineering and environmental requirements.

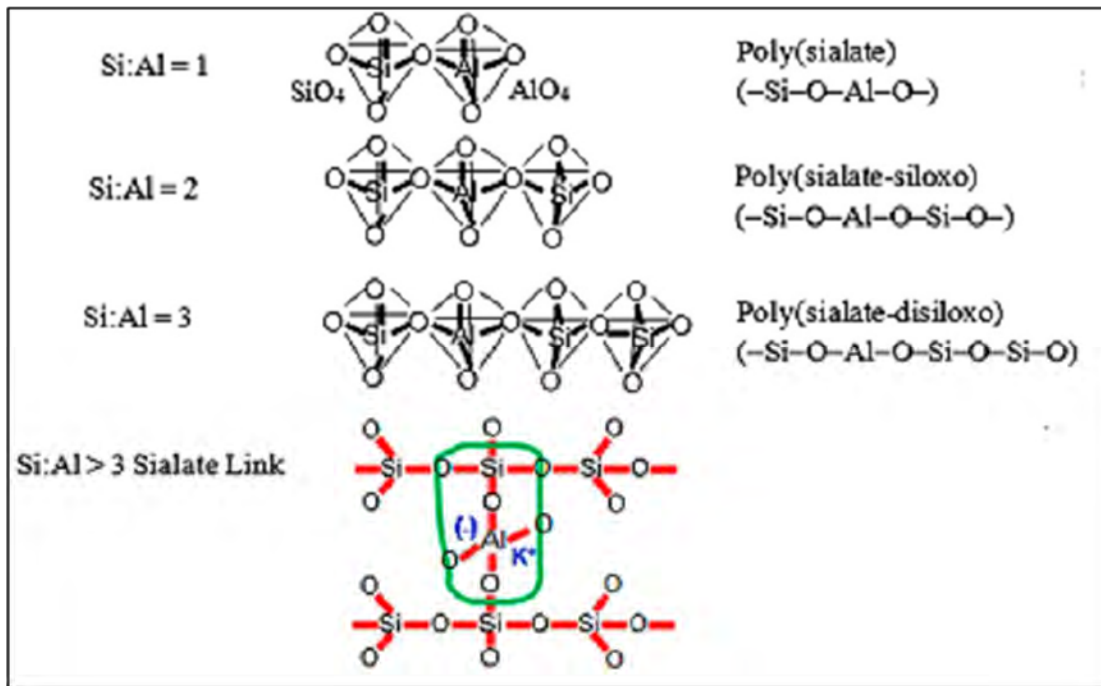


Figure 2.7: Three forms of geopolymerisation reaction structure (Singh, 2018)

The Si-Al material reaction produces a Si-O-Al-O bond with a three-dimensional chain structure as (Sharma and Ahmad, 2017) stated. The chemical structure equation is expressed in equation 2.1 below;

$$M_n [-(SiO_2)_z - AlO_2]_n \cdot wH_2O \quad (2.1)$$

Where;

M – alkaline elements or cations, e.g. Potassium, sodium, calcium, etc.

n – degree of polymerisation

z – Si/Al ratios; 1,2,3 or higher

During the geopolymerisation reaction, cement extenders go through the process shown in Figure 2.8 and Figure 2.9 (Singh, 2018). This process can be presented by the chemical reaction equation 2.2. The geopolymerisation reaction takes place in three stages (Kothari, 2017), as shown in Equation 2.2, Figure 2.8, and Figure 2.9;

- Dissolution/hydrolysis:** First, H^+ ions are exchanged in alkali earth metal or alkali metal cations, and solid aluminium silicate material liquefies and produces a concentrated alumina silicate solution (Naghizadeh and Ekulo, 2017).
- Gelation and Nucleation:** Water and hydroxide ions break down the network, and aluminium silicate gel precipitates from the solution by releasing the water used during the dissolution. Lastly, aluminosilicate gels (zeolite precursors) are formed (Naghizadeh and Ekulo, 2017).
- Oligomerisation, polymerisation and Hardening** form a 3D network of silicon–aluminates (geopolymer backbones), which result in a three-dimensional polymeric chain and ring structure consisting of Si-O-Al-O bonds (Patil and Manojkumar, 2013). Lastly, water, which is added during the process to maintain concrete workability and dissolving of solutes ($NaOH$ and Na_2SiO_3), is ejected from the matrix during the curing of the concrete (Rangan, 2008).

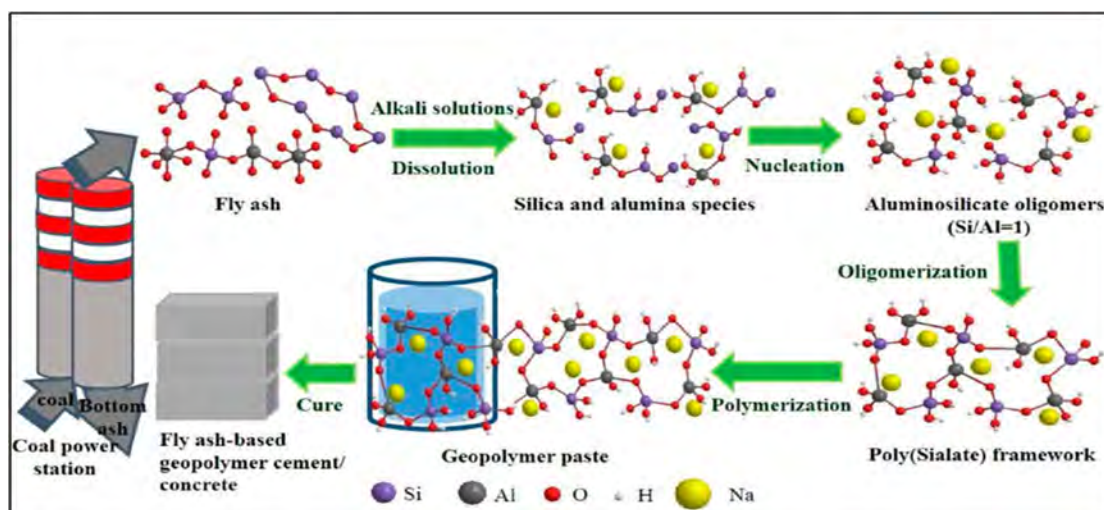


Figure 2.8: Geopolymerisation process from FA to FA-based geopolymer concrete (Singh, 2018)

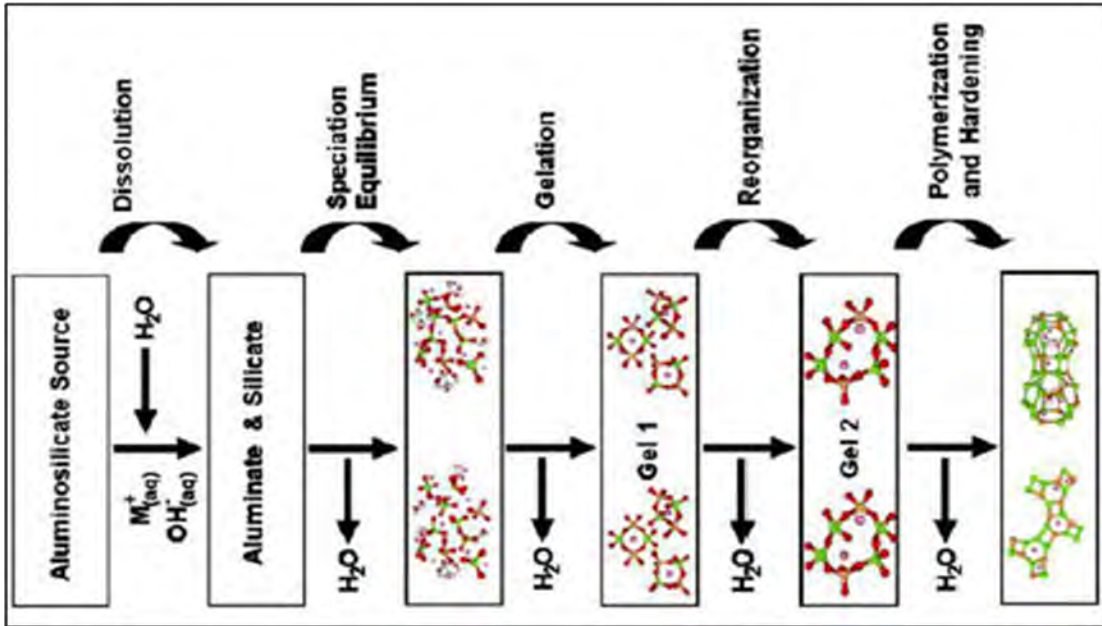
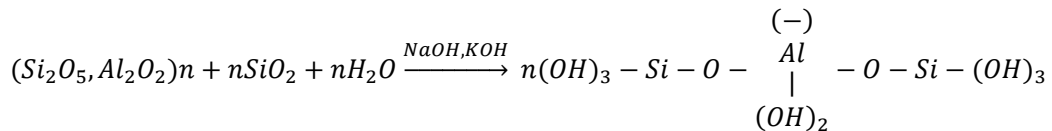


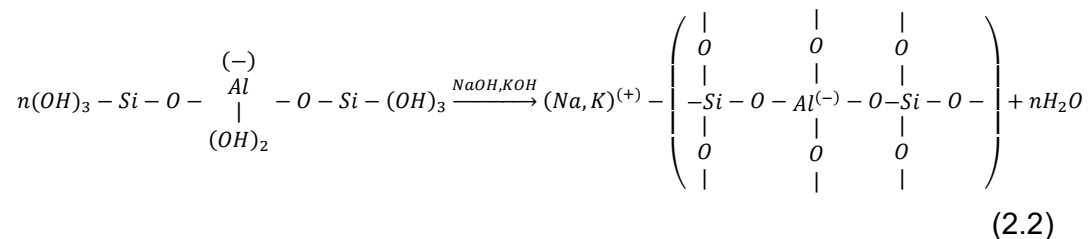
Figure 2.9: Model for geopolymer (Ling, 2018)

Furthermore, presented in Equation 2.2 below is the fundamental reaction inherent in the geopolymerisation process. It delineates the chemical transformation that transpires when cement extenders intertwine with silicates, water, and alkaline liquids to generate the geopolymer precursor. This precursor subsequently engages with alkaline ions, culminating in creating the geopolymer backbone—a pivotal element that fosters the development of strength within concrete structures (Kothari, 2017).

Si – Al Sources + Silicates + Water + Alkaline liquid → Geopolymer precursor



Geopolymer precursor + Alkaline ions → Geopolymer backbone



2.7 Factors Affecting Geopolymerisation

Naghizadeh and Ekulo (2017) identify various types of alkaline solutions capable of reacting with aluminosilicates to initiate the geopolymerisation process. These solutions include alkaline-earth metal hydroxides, alkaline hydroxides, weak acid salts, and strong acid salts. Among these, sodium hydroxide (NaOH), potassium hydroxide (KOH), sodium silicate, and potassium silicate are commonly employed as activators in geopolymer concrete. Specifically, sodium hydroxide and sodium silicate are the most preferred activators due to their widespread availability, safety, and cost-effectiveness.

For geopolymer concrete to achieve optimal mechanical properties and durability, the formation of a robust gel phase and a high gel-to-non-polymeric ratio is crucial. The use of alkaline solutions, in conjunction with thermal curing, facilitates the rapid development of high-strength geopolymer concrete. This combination helps achieve substantial mechanical strength in a relatively short curing period (Živica, Palou and Križma, 2015).

The effectiveness of the geopolymerisation process is influenced by various factors, including the type of alkali activators used, the characteristics of the raw materials, and the mix design parameters (Kothari, 2017). Key factors that impact the hardening and overall properties of geopolymer concrete include:

- a) Aluminosilicate raw material
- b) Raw material surface area
- c) glassy phase raw material content
- d) Reactive silicon and aluminium content amount
- e) Inert aggregates in FA, Calcium and iron presence
- f) Curing pressure and temperature
- g) Curing time
- h) Curing methods (conventional heating or microwave heating)
- i) Alkalis concentration and type
- j) Raw material/alkaline solution ratio
- k) Sodium oxide/water molar ratio

- l) Geopolymer solids/water ratio
- m) Silica Oxide/Sodium Oxide ratio
- n) Aluminium Oxide/Sodium oxide ratio

In conclusion, the successful development of geopolymer concrete requires careful consideration of these factors, as they collectively influence the geopolymerisation process and the performance characteristics of the final product. The choice of raw materials, alkaline activators, and curing conditions must be optimised to achieve the desired mechanical strength, durability, and sustainability of geopolymer concrete.

2.8 Impact of Geopolymerisation on Fresh Concrete Properties

In this section, an in-depth examination is undertaken to explore and elucidate the effects of geopolymerisation on the workability, mechanical characteristics, and durability aspects exhibited in both standard and rubberised concrete. This investigation meticulously considers all the factors previously outlined in section 2.7.2, aiming to provide comprehensive insights into the ramifications of geopolymerisation across these crucial facets of concrete performance.

2.8.1 Workability

Workability refers to the ease with which concrete can be mixed, placed, and compacted while remaining homogeneous. Understanding the impact of geopolymerisation on the workability of concrete is essential for optimising its use in construction. Ghosh and Ghosh (2012) investigated the workability of geopolymer concrete and found that the flow diameter of the concrete mixture linearly decreases with an increase in sodium oxide (Na_2O) and silicon dioxide (SiO_2) content.

This decrease in flow diameter is attributed to the increased viscosity of the concrete mix caused by higher concentrations of Na_2O . The researchers also noted that workability improved with a higher water-to-fly ash (w/FA) ratio. The addition of water reduces the molarity of the alkali activator concentration, which in turn lowers the viscosity of the mix and slows down the geopolymerisation rate, resulting in enhanced workability.

Further studies by Kothari (2017) indicated that the workability of geopolymer concrete is influenced by the composition of alkaline activators. Workability improved with higher sodium hydroxide (NaOH) content and lower sodium silicate content. This is because NaOH reacts more quickly, leading to less deformation of the concrete mix, thus making it easier to handle.

Blash and Lakshmi (2016) found similar results with slag-based geopolymer concrete, particularly when silica fume (SF) was used as a replacement for ground granulated blast-furnace slag (GGBFS). As shown in Table 2.5, the workability improved with an increase in silica fume content because SF is finer than GGBFS. The finer particles of SF enhance the packing density and reduce the viscosity of the mix, facilitating better flow and workability.

In conclusion, the workability of geopolymer concrete is significantly influenced by the type and concentration of alkaline activators, the water-to-fly ash ratio, and the particle size of the supplementary cementitious materials used. A careful balance of these factors is crucial for achieving the desired workability without compromising the mechanical strength and durability of the geopolymer concrete.

Table 2.5: Slump test results (Blash and Lakshmi, 2016)

Material %		Slump	Date of Product
GGBFS	SF		
100	0	89	18/05/2016
80	20	95	14/06/2016
60	40	97	16/06/2016
40	60	100	16/06/2016
20	80	103	16/06/2016
0	100	112	18/06/2016

2.8.2 Setting Time

Temperature is a critical factor influencing the behaviour of geopolymer concrete, particularly its setting time. Hardjito, Cheak and Ing (2008) observed that higher temperatures were associated with shorter setting times, suggesting that

temperature plays a vital role in the hardening process of geopolymer concrete. This correlation was further explored by Ghosh and Ghosh (2012), who identified that increased levels of silicon dioxide (SiO_2) within the concrete mix led to reduced initial and final setting times. The reduction in setting times was attributed to the enhanced liquefaction of silicon (Si) and aluminium (Al) during the initial dissolution phase, which subsequently accelerated the rate of polycondensation—a key reaction in the geopolymerisation process.

Risdanareni *et al.* (2016) expanded on these observations by highlighting the impact of the chemical composition of alumino-silicate materials on setting times. Their research demonstrated that mixes with lower calcium oxide (CaO) content, such as those containing fly ash with 7.99% CaO (denoted as FA Ps), exhibited longer setting times. In contrast, mixes with higher CaO contents—such as those with 8.54% CaO (FA Pt) and 14.43% CaO (FA Gr)—showed shorter setting times. This evidence underscores the significant role of CaO content in influencing the setting behaviour of geopolymer concrete, as depicted in Figure 2.10.

In addition to chemical composition, activator dosage and the proportion of fly ash (FA) to slag in the mix also significantly affect setting times. Kothari (2017) noted that higher activator dosages tend to result in shorter setting times due to the rapid formation of geopolymer gel. Similarly, increasing the fly ash content in slag-fly ash-based geopolymers led to faster initial and final setting times. Conversely, reducing the FA content led to a noticeable increase in setting time, attributed to less gel formation and the presence of larger pores within the concrete matrix.

In summary, the setting time of geopolymer concrete is influenced by multiple factors, including temperature, the chemical composition of alumino-silicate materials (particularly CaO content), the dosage of alkaline activators, and the proportion of fly ash in the mix. These parameters must be carefully controlled to achieve optimal set behaviour and mechanical performance in geopolymer concrete.

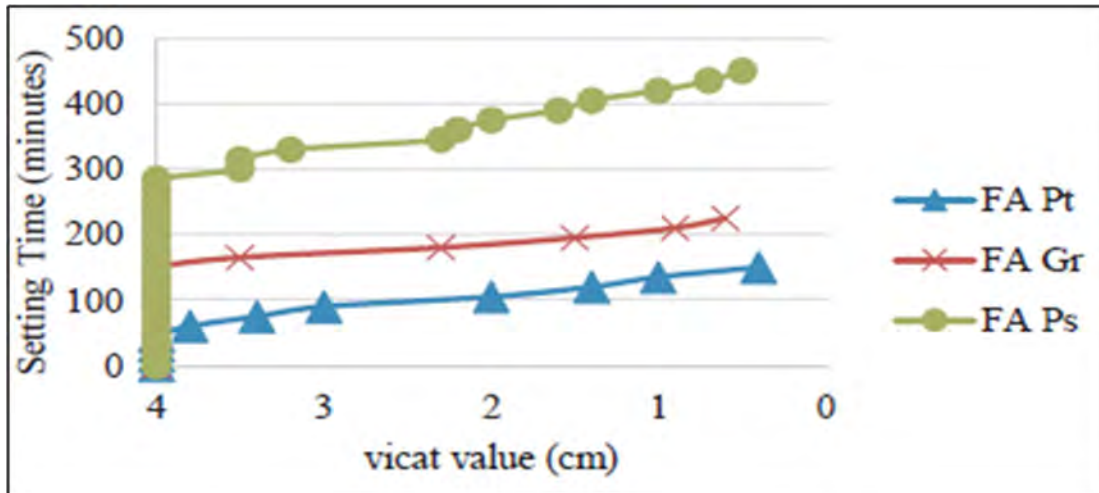


Figure 2.10: Setting time of geopolymer (Risdanareni *et al.*, 2016)

2.9 Geopolymerisation on Mechanical Properties of Concrete

Commonly employed geopolymer binders encompass a spectrum of materials such as fly ash, silica fume, GGBFS, and various binary combinations like fly ash-silica fume, silica fume-GGBFS, GGBFS-PC and fly ash-GGBFS. This section explores diverse geopolymer binders (alkali-activated binders), elucidating the multifaceted factors influencing geopolymerisation within geopolymer concrete.

2.9.1 Fly Ash-Based Geopolymer Concrete

Fly ash (FA), a common aluminosilicate source material plays a significant role in the development of geopolymer concrete. However, not all fly ashes are suitable for this purpose. According to Rangan (2008), low-calcium fly ash is preferred over high-calcium fly ash because the latter can alter the microstructure of the concrete and hinder the geopolymerisation process. Temperature is another critical factor in the polymerisation process.

Research by Hardjito, Cheak and Ing (2008) demonstrated that curing concrete at elevated temperatures (65°C, 70°C, and 80°C for 24 hours, followed by room temperature until testing) accelerates the geopolymerisation reaction, leading to early strength development within the first 24 hours of heat curing. However, they noted that high curing temperatures do not necessarily guarantee high compressive

strength at 28 days; instead, they primarily expedite the early stages of strength gain.

The concentration of sodium hydroxide (NaOH) also influences the compressive strength of geopolymer concrete. Hardjito, Cheak and Ing (2008) found that increasing the concentration of NaOH enhances compressive strength, whereas an increase in the alkaline-to-fly ash ratio reduces strength due to the excessive formation of sodium carbonate, which results from the reaction of sodium with atmospheric carbon dioxide.

The optimal alkaline solution-to-fly ash ratio was determined to be 0.4. Patankar, Jamkar and Ghugal (2013) also observed that higher water-to-geopolymer solids ratios reduce compressive strength, suggesting an optimal ratio of 0.25. This ratio is comparable to the water-to-cement ratio used in traditional Portland cement concrete, where water represents the total water content in the mix, and alkalis serve as the mixing agent, analogous to water in geopolymer concrete (Rangan, 2008; Živica, Palou and Križma, 2015).

Sodium oxide (Na_2O) is another crucial component in geopolymerisation. Thokchom, Ghosh and Ghosh (2009) studied the effects of Na_2O content on mortar cured at 85°C for 24 hours, followed by ambient temperature conditions. They found that higher Na_2O content led to increased compressive strength. Similarly, Ryu et al. (2013) reported optimal strength development at a $\text{SiO}_2/\text{Na}_2\text{O}$ ratio of 8.01 and an $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$ ratio of 1.94 when specimens were cured at 60°C for 24 hours. Increased NaOH molarity was also found to improve concrete strength, a trend attributed to the enhanced breakdown of the fly ash glassy phase and subsequent activation of Si and Al reactions due to higher temperatures and NaOH molarity.

Patil and Manojkumar (2013) further examined the effects of varying $\text{NaOH}/\text{Na}_2\text{SiO}_3$ ratios (1, 1.5, 2, and 2.5), NaOH molarity, and alkaline solution-to-fly ash ratios (0.4 and 0.35). The highest compressive strength was achieved at a $\text{NaOH}/\text{Na}_2\text{SiO}_3$ ratio of 2.5, with 16M NaOH concentration and an alkaline solution-to-fly ash ratio of 0.35. Heniegal *et al.* (2015) supported these findings, observing optimal properties at 16M

NaOH concentration, 60°C curing for 24 hours, followed by exposure to direct sunlight until the testing day.

These observations are consistent with findings by Nit Srinagar, Sofi and Gull (2015) as depicted in Figure 2.11, who identified an optimal NaOH concentration of 16M, a Na_2SiO_3 to NaOH ratio of 2.5, and an alkaline-to-fly ash ratio of 0.35, aligning with the results of (Patankar, Jamkar and Ghugal, 2013; Patil and Manojkumar, 2013).

Karuppuchamy, Ananthkumar and Raghavapriya (2018) investigated the use of Class F fly ash in mortar mixes under varying molarity and thermal curing conditions. Their findings indicated that a 12M NaOH concentration was optimal and that compressive strength increased with higher curing temperatures, demonstrating the dependence of strength enhancement on temperature.

This body of research highlights the importance of selecting suitable fly ash, controlling curing temperatures, and optimising chemical compositions to enhance the mechanical properties of geopolymer concrete. Understanding these parameters is crucial for achieving desired performance characteristics in geopolymer-based materials.

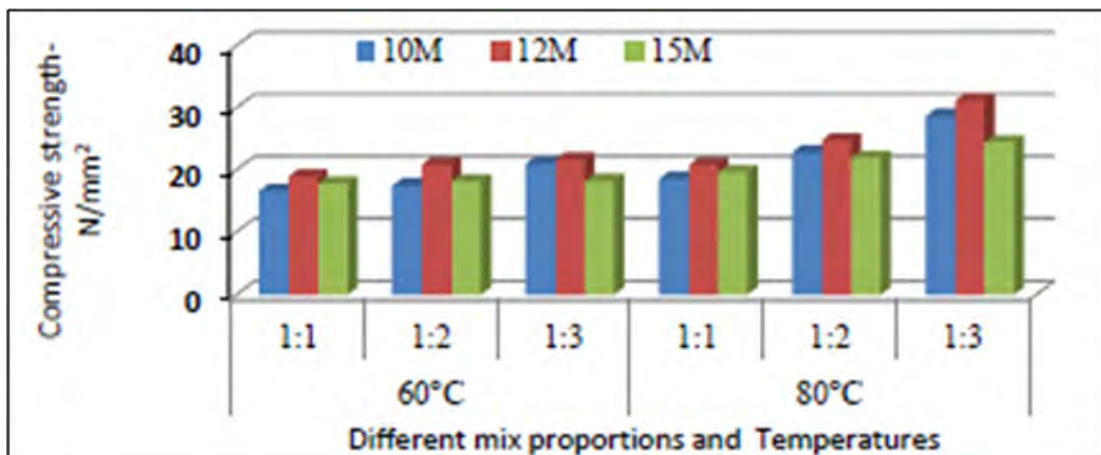


Figure 2.11: Compressive strength against different Molarity, ratios and temperature (Karuppuchamy, Ananthkumar and Raghavapriya, 2018)

In addition, Lăzărescu *et al.* (2017) compared different sodium silicate and sodium hydroxide ratios with a constant alkaline solution/fly ash ratio. All specimens were oven-cured for 24 hours at 70°C temperature. They observed that increasing the sodium silicate to sodium hydroxide ratio increased the compressive strength because of the increased content of SiO₂. In turn, more bonds of Si-O-Si were formed, developing a tougher material. In addition, the highest compressive strength was gained at a 2.5 ratio of sodium silicate/sodium hydroxide, and mechanical properties increased with a decrease in Na₂O/SiO₂ ratio.

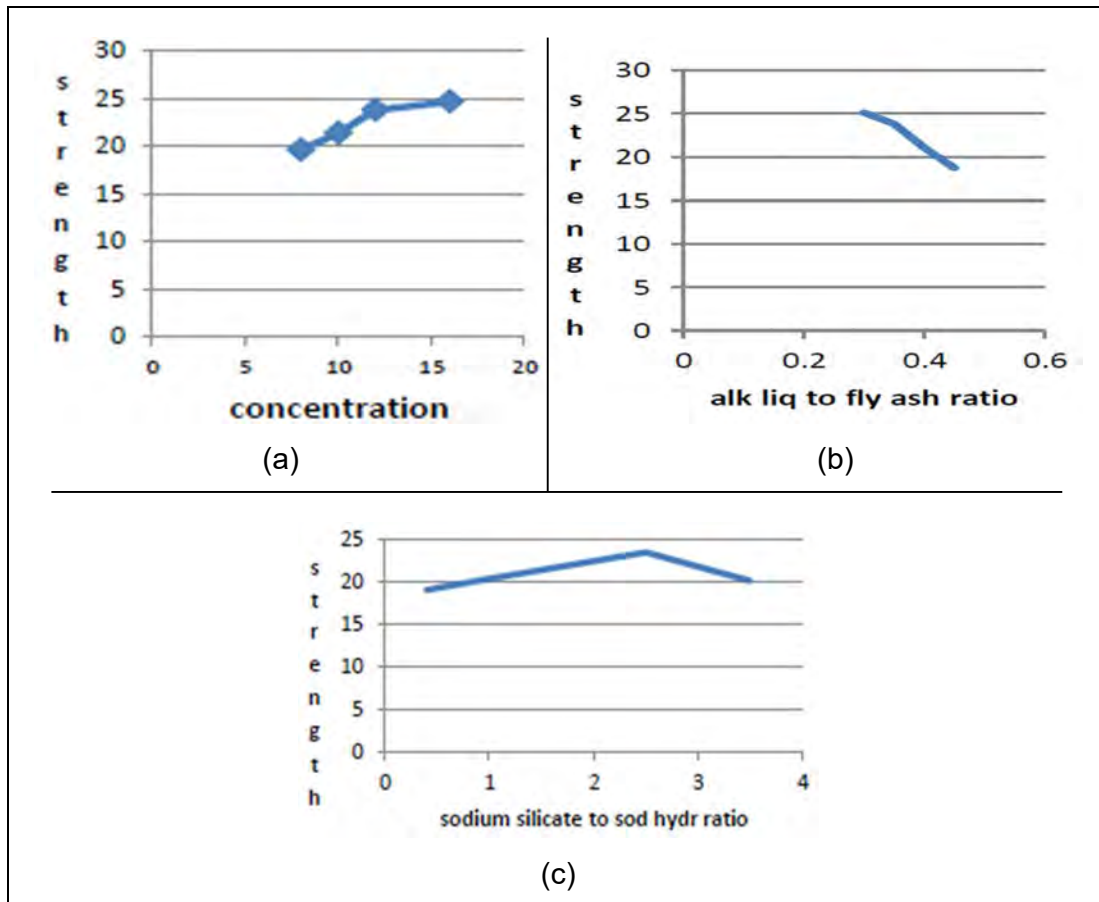


Figure 2.12: (a) Strength variation with NaOH concentration, (b) strength variation with Na₂SiO₃/NaOH Ratio, and (c) strength variation with alkaline to fly ash ratio (Nit Srinagar, Sofi and Gull, 2015)

2.9.2 Silica Fume (SF) Based Geopolymer Concrete

The use of silica fume (SF) as a geopolymer binder has been shown to influence the compressive strength of concrete significantly. Kockal, Beycan and Gulmez (2018) found that in SF-based geopolymer concrete with a sodium hydroxide (NaOH) concentration of 6 molarity, the compressive strength increased as the calcium hydroxide content was elevated. This enhancement in strength was attributed to the modification of pore structure induced by the addition of silica fume.

The fine particles of silica fume effectively filled the pores, and the formation of calcium-based high-strength hydrate gels contributed to increased compressive strength (Xie *et al.*, 2019). Further research by Aysha Banu *et al.* (2018) explored the effects of replacing traditional cement with silica fume and river sand with foundry sand. In their study, the concrete was designed with a sodium silicate-to-sodium hydroxide ($\text{Na}_2\text{SiO}_3/\text{NaOH}$) ratio of 3 and a NaOH concentration of 8M, with samples cured for 24 hours at a temperature of 60°C.

The results, depicted in Figure 2.13, showed that the compressive strength of geopolymer concrete exceeded that of conventional concrete. This was attributed to the modified microstructure of the geopolymer concrete, which enhanced the bonding between the alkaline solution, silica fume, and aggregates, ultimately providing superior strength.

These findings underscore the potential benefits of using silica fume in geopolymer concrete formulations, particularly in terms of enhancing mechanical properties and achieving high compressive strength through microstructural modifications. The role of silica fume in improving the pore structure and bonding interactions within the concrete matrix is crucial for developing high-performance geopolymer concrete.

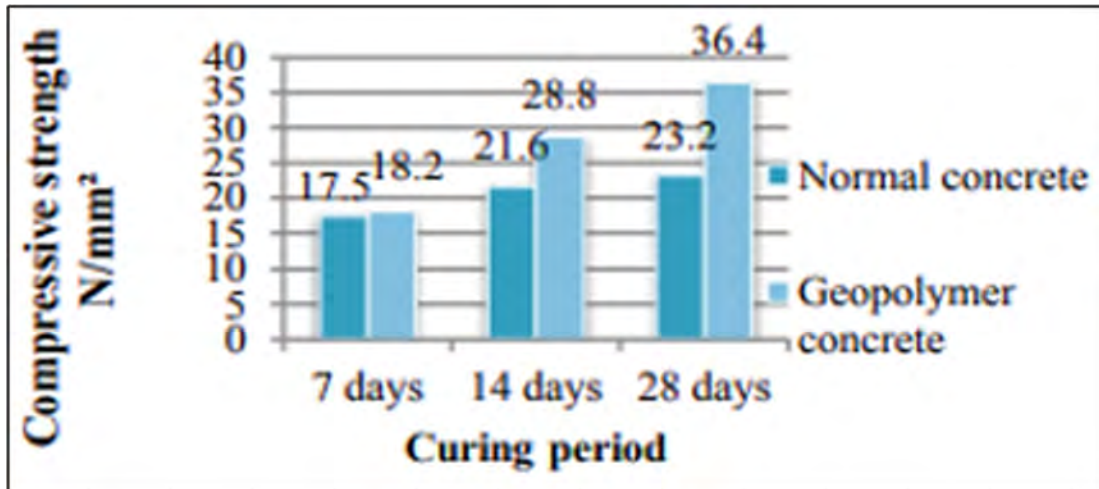


Figure 2.13: Strength results (Aysha Banu *et al.*, 2018)

2.9.3 Binary Mixes of Geopolymer Concrete

Besides fly ash and silica fume-based geopolymer concrete (GPC), various binary geopolymer mixes perform differently when compared to the two discussed geopolymer binders. Henceforth, this section discusses the impact of different binary blends in geopolymer concrete, considering various factors that affect geopolymerisation reaction.

2.9.4 Fly Ash-Based Geopolymer with Silica Fume

The substitution or blending of Portland cement (PC) with silica fume (SF) or fly ash (FA) in geopolymer concrete can significantly affect its properties. In particular, FA can be replaced or mixed with SF, ground granulated blast-furnace slag (GGBFS), and PC to form binary binders, impacting the mechanical performance of the concrete.

Dutta *et al.* (2010) investigated the effects of incorporating silica fume into low calcium fly ash-based geopolymer mortar and paste, with a water-to-fly ash ratio of 0.33, a $\text{SiO}_2/\text{Na}_2\text{O}$ ratio of 1, and sodium silicate and hydroxide with Na_2O content of 8%. Their study revealed that the addition of 2.5% silica fume to the geopolymer paste resulted in a decrease in compressive strength from 37 MPa to 34 MPa. Increasing the silica fume content further reduced the compressive strength to 30 MPa. In contrast, the compressive strength of the geopolymer mortar increased with

the addition of silica fume, rising from 26 MPa to 31 MPa with 2.5% SF and to 36 MPa with 5% SF. This increase in strength was attributed to the decrease in the Si/Al ratio, which positively affected the mortar strength while adversely impacting the paste strength.

Gopalakrishnan and Chinnaraju (2012) explored the substitution of FA with 20% and 40% SF, using sodium hydroxide concentrations of 8M and 12M and hot air curing at 100°C for 24 hours. Their results showed that a 12M NaOH concentration combined with 40% SF produced higher tensile and compressive strength compared to the 8M NaOH concentration. This indicates that both the concentration of NaOH and the percentage of SF play critical roles in enhancing the mechanical properties of geopolymer concrete.

Further research by Okoye, Durgaprasad and Singh (2016) investigated the blending of FA with 5% to 40% SF, using 14M NaOH and a $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio of 2.5, with curing at 100°C. The results, compared with ordinary Portland cement concrete (OPCC), demonstrated that geopolymer concrete (GPC) containing 40% silica fume and a water-to-solid ratio of 0.3 exhibited superior compressive, tensile, and flexural strength compared to other GPC mixes and OPCC. This improvement was attributed to the fine particles of silica fume, which effectively filled the pores in the concrete mix, enhancing its compactness. However, it was also noted that increased SF content led to reduced workability in the GPC.

These studies highlight the significant impact of silica fume on the mechanical properties and workability of geopolymer concrete. The addition of SF can improve concrete strength by filling pores and enhancing the matrix, although it may reduce workability at higher concentrations.

2.9.5 Fly Ash-Cement-Based Geopolymer Concrete

The incorporation of fly ash (FA) with Portland cement (PC) in geopolymer concrete (GPC) has been explored to assess its impact on concrete properties. Nath and Sarker (2015) conducted a study on the effects of blending 5% fly ash with Portland cement in GPC. The concrete specimens were cured at ambient temperature, with

a sodium hydroxide (NaOH) molarity of 14M and a sodium silicate to sodium hydroxide ratio of 2.5.

Their findings, illustrated in Figure 2.14, indicated that increasing the proportion of fly ash beyond 5% in the Portland cement mix led to an improvement in compressive strength. This enhancement was attributed to the presence of Portland cement, which accelerates the geopolymerisation process and contributes to higher strength. The increase in compressive strength was further supported by the calcium ion (Ca^{2+}) content in the Portland cement, which plays a crucial role in facilitating the geopolymerisation reaction and improving the overall concrete strength.

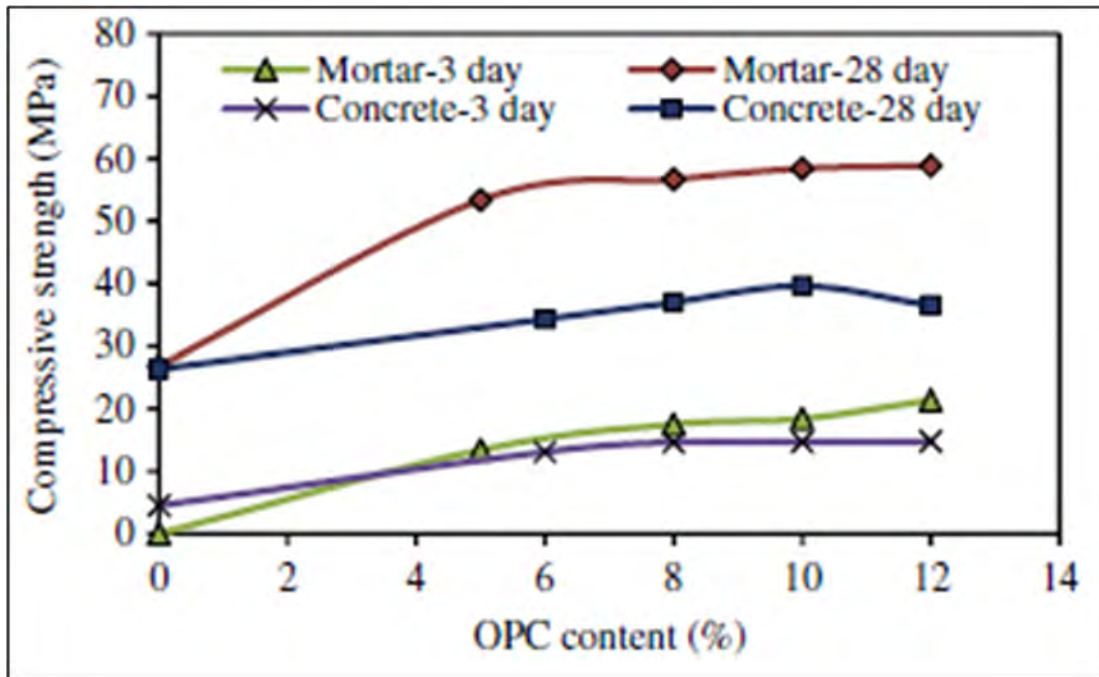


Figure 2.14: Compressive strength with different content of OPC in FA-based geopolymer concrete (Nath and Sarker, 2015)

Similarly, Noushini *et al.* (2016) investigated the impact of low calcium FA blended with 20% kaolite and 10% OPC and GGBFS, cured at 60 °C, 75 °C and 90 °C for 12 hours, 24 hours, and 8 hours, and other specimens cured under sealed ambient conditions (SAC) at controlled room temperature of 23 °C and other with lime water curing (LWC), activated by sodium silicate and 14M concentration of Sodium

Hydroxide. 28 days compressive strength of 64.5Mpa was noted in OPC cured in lime water, while 62.3Mpa was obtained in GPC cured at 75 °C for 24hours.

Furthermore, Aliabdo, Abd Elmoaty and Salem (2016) studied the impact of 5%, 10% and 15% of OPC on low calcium fly ash of 350, 400 and 450Kg/m³ and also the impact of alkaline solution resting time of 30min and 24 hours, considering 16M of NaOH and cured under 28°C, 50°C, 70°C and 90°C temperature. The tensile and compressive strength increased with temperature, and FA and PC percentage replacement increased.

Also, 30 minutes yield high strength compared to 24 hours, and maximum strength was obtained at 70°C curing temperature. In addition, cement replaced 20%, 15%, 10% and 5% of low calcium FA with NaOH molarity of 5, 10, 15 and 20, cured under 90°C, 80 °C, 70 °C, and 60 °C temperatures for 24 hours. High compressive strength was observed at 20% replacement and 15M concentration of NaOH at a curing temperature of 70°C compared with other GPC's mix (Mehta *et al.*, 2017).

Similarly, Mehta and Siddique (2017) studied the replacement of 20% of cement with FA and noted 20% to be the optimum percentage replacement of fly ash in concrete with a 10M concentration of NaOH, alkaline content of 171 Kg and subjected to 80°C temperature curing for 24 hours. Therefore, it can be deduced that cement content positively influences GPC, and there is a direct relationship between geopolymerisation and heat hydration, which consequently impacts compressive strength (Mehta *et al.*, 2017).

2.9.6 Fly Ash-GGBFS-Based Geopolymer Concrete

Kumaravel, Thirugnanasambandam and Antony (2014) investigated the effects of incorporating ground granulated blast furnace slag (GGBFS) into low calcium fly ash (FA)-based geopolymer concrete (GPC). In their study, 25% of low calcium FA was replaced with GGBFS, and the mix was activated with a sodium silicate to sodium hydroxide (Na₂SiO₃/NaOH) ratio of 2.5. The specimens were cured under hot air at 60°C for 24 hours and then allowed to cure at ambient temperature. The results showed that the GPC achieved a compressive strength of 48 N/mm², outperforming

conventional cement concrete, which achieved a compressive strength of 46.5 N/mm². This indicates that the inclusion of GGBFS in low calcium FA-based geopolymer can enhance compressive strength compared to traditional cement.

On the other hand, Neupane (2016) explored the effects of different activator mixtures in geopolymer concrete. In this study, pozzolanic materials were unified to form a one-part binder, which was then cured under ambient temperature (23°C) before de-moulding. After de-moulding, the specimens were sprayed and sealed with plastic until the testing period.

The activators used included sodium hydroxide (NaOH) at concentrations of 8M for an activator/binder ratio of 0.3 and 13M for a water/binder ratio of 0.45. Figure 2.15 illustrates two types of geopolymer mixes: Geopolymer 1, containing 70% FA and 30% GGBFS, and Geopolymer 2, consisting of 40% FA and 60% GGBFS. The results from this study underscore the significance of binder composition and curing conditions on the performance of geopolymer concrete.

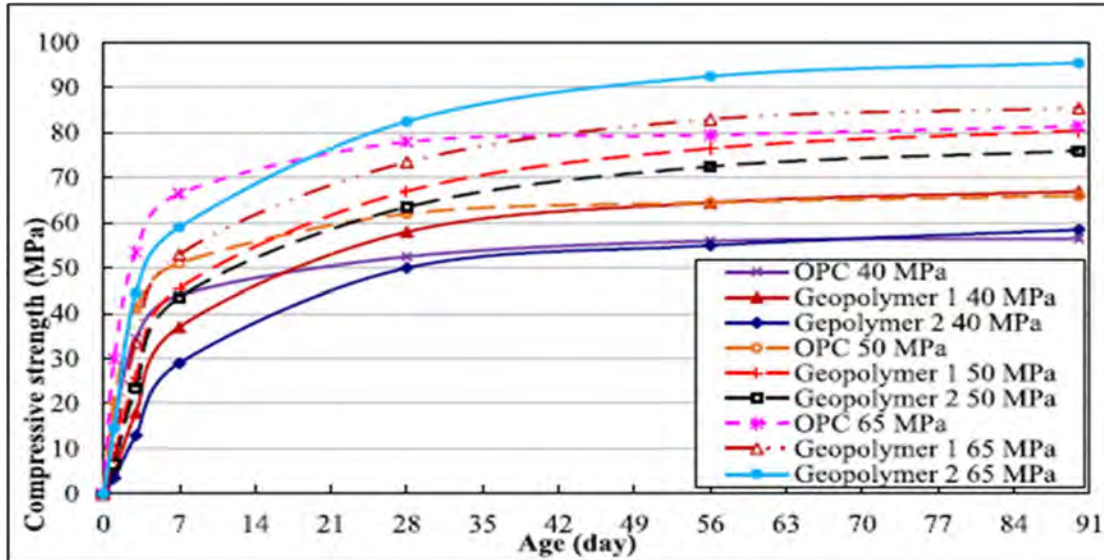


Figure 2.15: Compressive strength of OPC and FA-GGBFS-based geopolymer concrete (Neupane, 2016)

As illustrated in Figure 2.15, Geopolymer 2 exhibited superior compressive and flexural strength compared to Ordinary Portland Cement (OPC), reaching a strength

of 65 MPa. This enhancement in strength has been attributed to the presence of calcium, which is believed to accelerate the geopolymerisation process. The study highlights that geopolymer concrete, particularly fly ash-slag-based variants, not only develops strength due to the formation of geopolymeric gel but also benefits from the presence of calcium-silicate hydrate (C-S-H) gel. The C-S-H gel contributes to strength development over time, paralleling observations from similar studies on fly ash-cement-based geopolymers.

Further analysis, shown in Figure 2.16, compares the performance of concrete specimens with different fly ash and slag ratios cured at 23°C. Concrete mixtures containing 70% fly ash and 30% slag (GP) and 60% slag with 40% fly ash (HE) were evaluated. The results indicate that these geopolymer concretes achieved higher strength compared to conventional OPC concrete. Notably, the strength of the GP mix reached 80 MPa, surpassing both the OPC and the HE mixes with an 80 MPa target strength. Conversely, for a target strength of 65 MPa, the HE geopolymer mix demonstrated superior performance. These findings, supported by Neupane, Chalmers and Kidd (2018) underscore the effectiveness of fly ash-slag-based geopolymers in achieving higher strengths and improved performance over time compared to traditional OPC concrete.

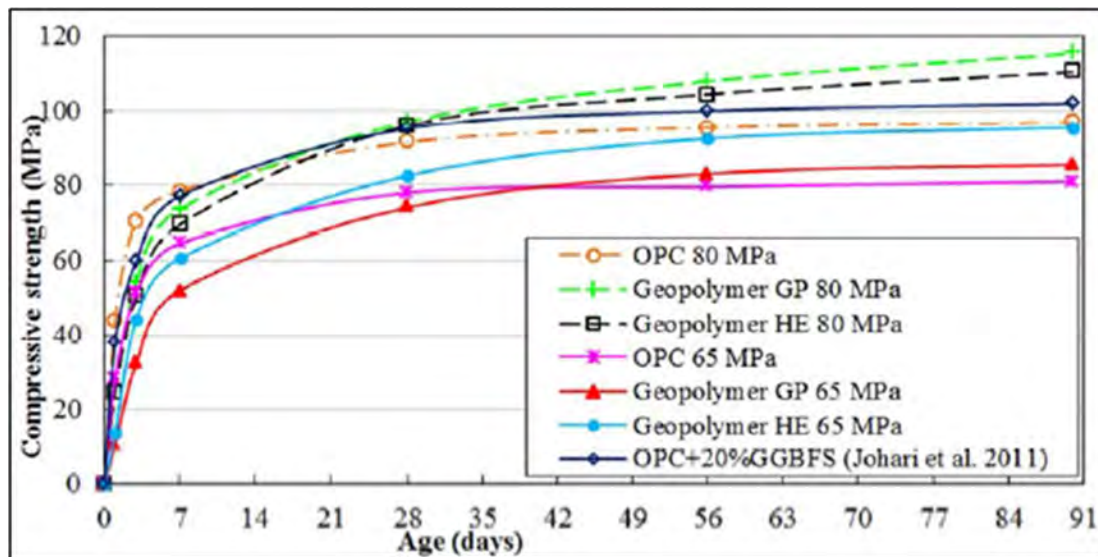


Figure 2.16: Compressive strength results for geopolymer and OPC concrete (Neupane, Chalmers and Kidd, 2018)

Furthermore, Xie *et al.* (2019) Produced geopolymer concrete of 50% FA and 50% GGBFS with 0.5 Water/Binder ratio, $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio of 2.5, with a temperature of 80°C for 24 hours, and provided good compressive and flexural strength and workability. The good behaviour was ascribed to a reduced Ca^{2+} content in fly ash compared to OPC and GGBFS. As a result, compared to OPC or GGBFS, a high content of fly ash may not be able to create more Ca high-strength hydrate gels to improve compressive strength early.

2.9.7 GGBFS-Based Geopolymer with Fly Ash and Silica Fume

Hadi, Farhan and Sheikh (2017) investigated the effects of SF, FA, and metakaolin on GGBFS geopolymer concrete cured at 25°C temperature. Their findings revealed a tensile strength of 61.15Mpa at a binder concentration of 450kg/m^3 . It was noted to be optimum binder content because the mix with 500kg/m^3 had the same Alkaline/binder ratio of 0.35 and showed a lower strength of 59.50kg/m^3 . Also, concrete compressive strength is highly influenced by the alkaline/binder ratio because it decreases with increased alkaline/binder ratio and increases with increased sodium hydroxide, which agrees with most researchers' studies in this chapter.

Blash and Lakshmi (2016) investigated the impact of SF and GGBFS on geopolymer concrete with NaOH of 8M concentration. From their results, with 100% replacement of SF with GGBFS, 28-day compressive strength was observed to be 81Mpa. Conversely, with 0% GGBFS, compressive strength declined significantly to 2Mpa. The reduction indicates that GGBFS-based geopolymer is better compared to SF. Also, GGBFS enhances the binding between aggregates and cement paste compared to SF-based geopolymers.

Similarly, as shown in Figure 2.17, as molarity rises on GGBFS-based geopolymer concrete cured at room temperature, split tensile strength, compressive strength, and flexural strength improve. As a result, molarity benefits the mechanical characteristics of GGBFS-based geopolymer concrete (Babu, Rahul and Kumar, 2017).

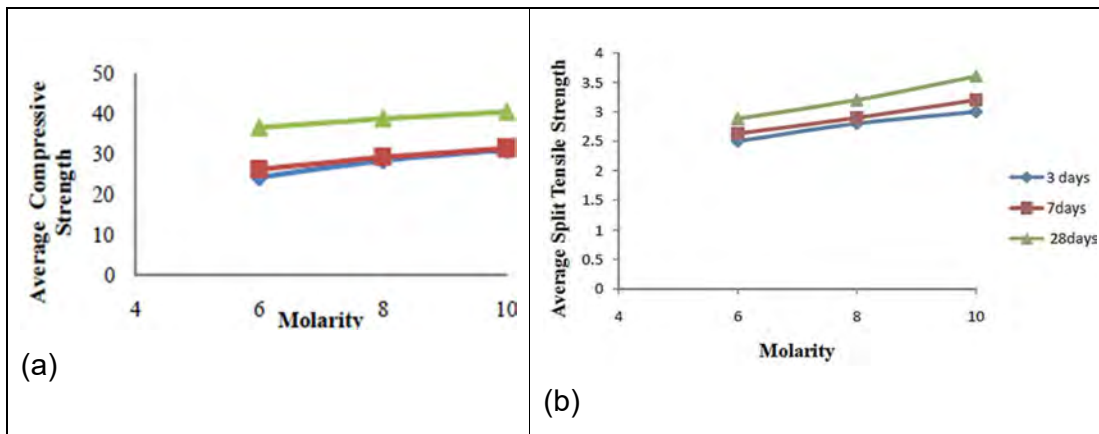


Figure 2.17: (a) Average compressive and (b) splitting tensile strength results (Babu, Rahul and Kumar, 2017)

2.10 Effect of Geopolymerisation on Concrete Durability

The durability of concrete is significantly influenced by factors such as the calcium oxide (CaO) content, material composition, and curing temperature. Singh (2018) and Živica, Palou and Križma (2015) highlight these factors' substantial effects on the mechanical properties of conventional concrete, suggesting that these same variables must be carefully evaluated to understand their impact on geopolymer concrete's durability.

Rangan (2008) demonstrated that thermally cured fly ash-based geopolymer concrete exhibits excellent resistance to sulfate attacks, acid resistance, and minimal creep. This highlights the potential of geopolymer concrete to outperform traditional concrete in various aggressive environments. Further, Thokchom, Dutta and Ghosh (2011) investigated the effects of silica fume (SF) on fly ash-based geopolymers, finding that SF inclusion reduces porosity and water absorption, thereby enhancing the mortar's overall characteristics.

Luhar and Khandelwal (2015) observed that class F (low calcium) fly ash-based geopolymer concrete exhibits lower sorptivity and water absorption compared to conventional concrete. Conversely, Lavanya and Jegan (2015) reported that high calcium fly ash-based geopolymer concrete still shows lower sorptivity and water

absorption than ordinary Portland cement (OPC) concrete. This suggests that while high calcium fly ash may be less effective than low calcium types in some respects, geopolymer concrete generally has reduced permeability compared to traditional concrete.

Nit Srinagar, Sofi and Gull (2015) noted that an increased alkaline liquid-to-fly ash ratio can lead to higher porosity, as the additional water content creates more cavities within the concrete. This increase in porosity can compromise the durability of geopolymer concrete, underscoring the importance of optimising the alkaline liquid ratio.

Wardhono (2015) explored the durability characteristics of geopolymer concrete made from fly ash and alkali-activated slag (AAS). The study found that fly ash has higher water absorption, permeability, and porosity compared to AAS. This is attributed to the fineness and spherical shape of the fly ash particles, which influence the pore structure. Additionally, Kockal, Beycan and Gulmez (2018) found that higher alkali content increases water absorption and porosity, emphasising the need for careful control of alkali dosages in geopolymer concrete formulations.

This comprehensive review underscores the complex interplay between material composition, curing conditions, and the resultant durability characteristics of geopolymer concrete. Understanding these factors is crucial for optimising the performance and longevity of geopolymer concrete in various applications.

2.10.1 Impact of Geopolymerisation on Mechanical Properties of Rubberised Concrete.

As it has been stipulated in section 2.6, cement extenders have a positive trend in improving concrete by incorporating waste tyre aggregates. Furthermore, when alkali solutions activate cement extenders, concrete's durability and mechanical properties improve. However, there are limited studies on how different geopolymer binary mixes impact the performance of different geopolymer parameters.

2.10.2 Impact of Fly Ash-Based Geopolymer Binder on Rubberised Concrete

The influence of alkali activation on concrete properties has been extensively studied, with various findings illustrating the complex interactions between aggregate types, alkali activators, and curing conditions.

Park *et al.* (2015) examined the impact of alkali-activated class C fly ash (FA) on concrete incorporating 1-2 mm recycled rubber aggregates (FCR). Their research, summarised in Table 2.6, indicated that compressive strength decreased with higher rubber aggregate content. Conversely, increasing the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio from 0.5 to 2 resulted in extended setting times and enhanced compressive strength. These findings suggest that the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio plays a critical role in the development of compressive strength in geopolymer concrete.

Luhar, Chaudhary and Luhar (2019) compared the effects of adding fibre and shredded rubber aggregates to Ordinary Portland Cement (OPC) and geopolymer concrete (GPC). Their results showed that the compressive strength of OPC decreased with increasing rubber aggregate content. For instance, the 28-day compressive strength of OPC with 10% rubber aggregates dropped from 53.2 MPa to 42.5 MPa, while GPC with the same rubber content showed a decrease from 54 MPa to 48.33 MPa.

This reduction in OPC strength is attributed to the lower stiffness of rubber aggregates compared to sand, which creates voids and weakens the bond between particles. In contrast, for GPC, the addition of rubber aggregates resulted in a less pronounced strength reduction, highlighting the potential of geopolymer concrete to maintain better performance with alternative aggregates.

A comparative analysis of OPC and GPC reveals that different geopolymerisation parameters significantly affect compressive strength. For instance, Park *et al.* (2016) studied geopolymer concrete with a $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio of 2, an alkaline/binder ratio of 0.4, and a NaOH molarity of 14M. Concrete specimens were cured at 90°C for 48 hours before being maintained at room temperature until testing.

Their results demonstrated that high CaO content in the concrete led to increased compressive strength, with concrete containing 14.14% CaO showing superior performance compared to those with 9.42% and 1.29% CaO. This finding suggests that calcium oxide content is a critical factor in achieving high compressive strength in geopolymer concrete.

Furthermore, Azmi *et al.* (2016) observed similar trends, where increased replacement of sand with FCR aggregates led to a decline in compressive strength. This underscores the need for careful consideration of aggregate types and geopolymerisation parameters to optimise concrete performance.

In summary, the reviewed studies highlight that while alkali activation and aggregate replacement significantly influence concrete properties, careful optimisation of these factors is crucial to achieving the desired strength and durability in both geopolymer and conventional concrete.

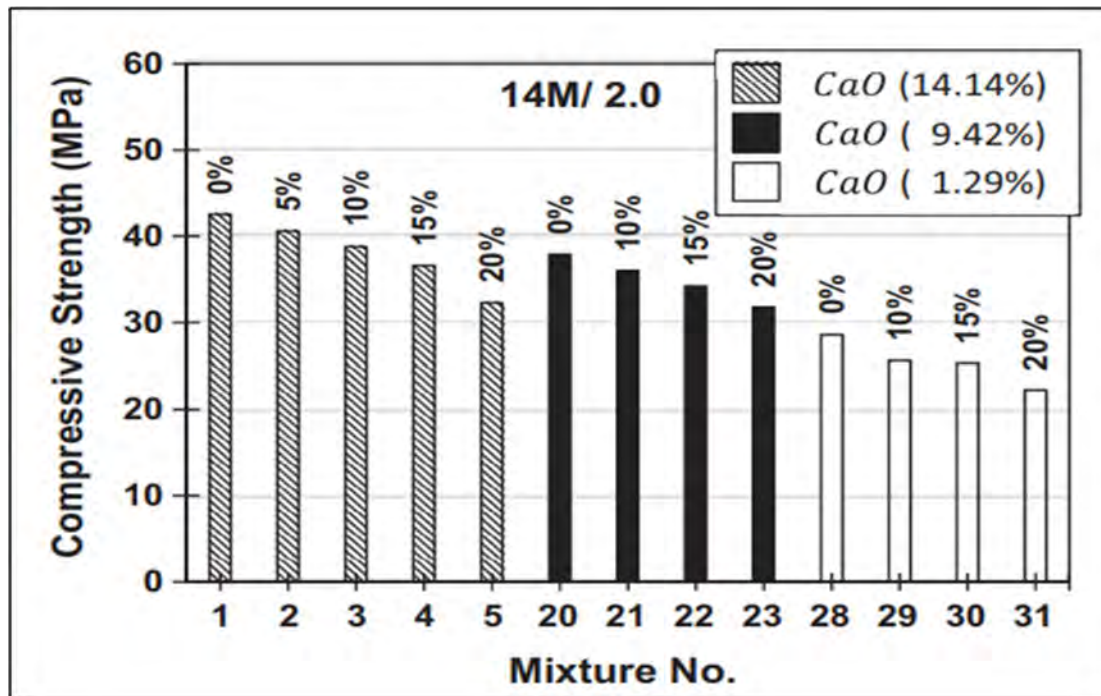


Figure 2.18: Compressive strength of rubberised FA-based geopolymer concrete (Park *et al.*, 2016)

Table 2.6: Setting time and compressive strength results (Park *et al.*, 2015)

Mixture	Rubber % (Vol.)	Na ₂ SiO ₃ kg/m ³	NaOH kg/m ³	Na ₂ SiO ₃ /NaOH	Comp. strength Mpa	Setting time (min)
Mix-1	0	42	84	0.5	30.8	4
Mix-2	20	42	84	0.5	25.9	4
Mix-11	0	84	42	2.0	38.2	10
Mix-12	20	84	42	2.0	33.5	9

2.10.3 Impact of GGBFS-Based Geopolymer Binder on Rubberised Concrete

Aly *et al.* (2019) investigated the effects of using ground granulated blast furnace slag (GGBFS) as a geopolymer binder in concrete. Their study involved partial replacement of both fine and coarse aggregates with crumb rubber at varying replacement levels of 0%, 10%, 20%, and 30%. The crumb rubber used had sizes of 0-0.420 mm for fine aggregates and 1-4 mm for coarse aggregates. The binder was activated with a sodium silicate (Na₂SiO₃) and sodium hydroxide (NaOH) solution at a ratio of 0.39, and curing was conducted in water at room temperature until the testing date.

The results of this study, as illustrated in Figure 2.19, demonstrated that a 10% replacement of aggregates with crumb rubber resulted in a 7% increase in compressive strength compared to the control mix. However, higher replacement levels of 20% and 30% led to reductions in compressive strength by 24% and 34%, respectively.

A similar reduction trend was observed in splitting tensile strength. The observed increase in strength at the 10% replacement level is attributed to improved bond strength between the binder paste and the aggregate matrix. This improvement is likely due to the reaction of NaOH with the crumb rubber aggregate surfaces, which enhances their texture and the overall interfacial bond, thereby contributing to better performance of the geopolymer concrete.

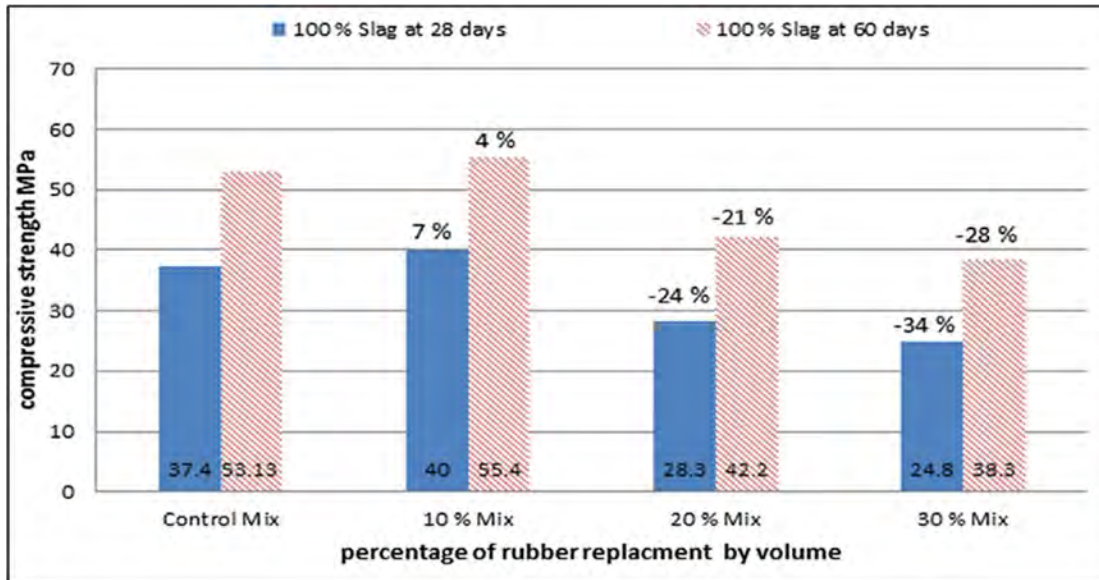


Figure 2.19: 28 and 60day Compressive strength of rubberised GGBFS-based geopolymer concrete (Aly *et al.*, 2019)

This investigation highlights the significant role of aggregate replacement levels and the interaction between the binder and aggregates in influencing the mechanical properties of geopolymer concrete. The findings underscore the potential benefits of moderate crumb rubber incorporation in enhancing concrete strength and durability.

2.10.4 Impact of FA-GGBFS-Based Geopolymer Binder on Rubberised Concrete

The influence of fly ash (FA) and ground granulated blast furnace slag (GGBFS) on geopolymer concrete incorporating crumb rubber (CR) aggregates has been explored in several studies. Pham *et al.* (2020) examined concrete made with a binder comprising 60% FA and 40% GGBFS, using a sodium silicate/sodium hydroxide ratio of 2.5 and a molarity of 12. Their study focused on concrete mixes containing 0%, 15%, and 30% small CR particles. The findings indicated that compressive strength decreased as the rubber aggregate content increased. This reduction was attributed to the lower stiffness of CR, which could not effectively support compression forces within the concrete matrix, and a lack of bonding between the cementitious paste and the rubber aggregates.

Similarly, Dong *et al.* (2021) investigated concrete with an 80% FA and 20% GGBFS binder, using a sodium hydroxide molarity of 12 and a sodium silicate/sodium hydroxide ratio of 1.6. The study assessed the performance of concrete containing 15% (M15) and 30% (M30) rubber aggregates. According to their results, as shown in Figure 2.20, compressive strength declined with increasing rubber content. However, when the GGBFS content was increased to 40% (M15-40S), both the three-day and 28-day compressive strengths improved relative to those with 15% and 30% rubber replacement. A similar improvement was observed in the 28-day splitting tensile strength, with values of 1.2 MPa for M15, 0.7 MPa for M30, and 1.4 MPa for M15-40S.

These studies highlight that while incorporating crumb rubber into FA and GGBFS-based geopolymer concrete generally leads to reduced strength, optimising the GGBFS content can mitigate some of these negative effects. The findings suggest that increasing GGBFS content enhances the overall performance of geopolymer concrete with CR aggregates, potentially due to improved interaction between the binder and the aggregates.

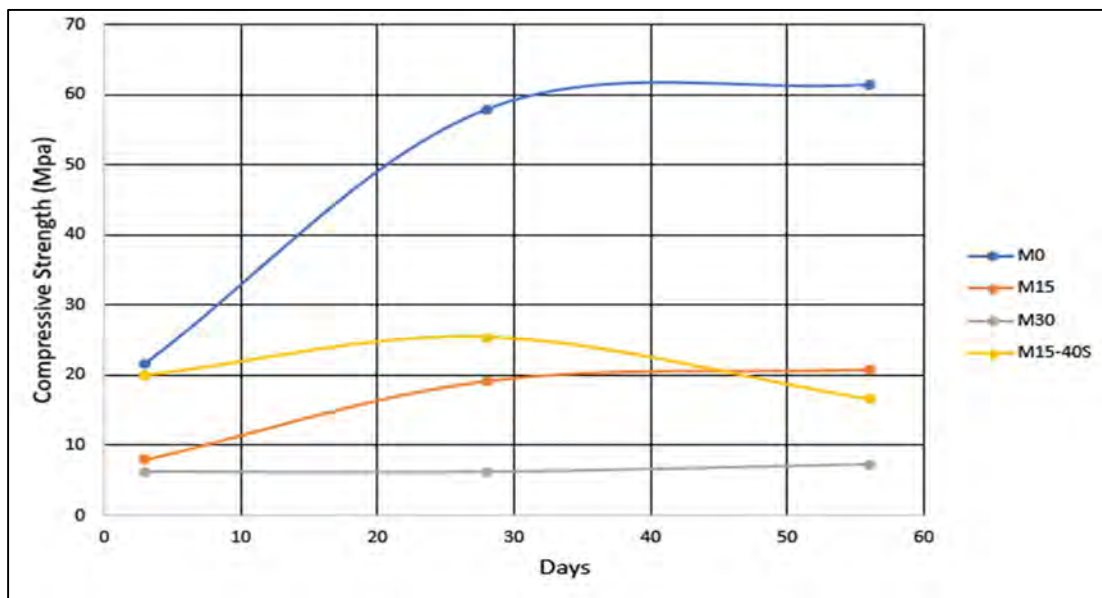


Figure 2.20: Compressive strength for rubberised FA and GGBFS-based geopolymer concrete (Dong *et al.*, 2021)

2.10.5 Impact of FA-OPC-Based Geopolymer Binder on Rubberised Concrete

This section reviews the impact of fly ash (FA) and ordinary Portland cement (OPC)-based geopolymer binders on concrete containing small crumb rubber (CR) aggregates. Charkhtab Moghaddam *et al.* (2021) explored the effects of substituting FA with 10% and 20% OPC in concrete containing 10% fine CR particles. Their study utilised a sodium hydroxide (NaOH) concentration of M12 and a sodium silicate to sodium hydroxide ratio of 2.5.

As shown in Table 2.7, replacing 10% of FA with OPC improved the compressive strength of the concrete from 37 MPa to 39 MPa. Further increasing the OPC content to 20% raised the compressive strength to 40 MPa, which was comparable to the control mix. This improvement was attributed to the reduction of pores and non-reactive FA particles within the mix. However, there was no significant change in splitting tensile strength, with values of 11.1 MPa for the control mix and 11.6 MPa, 11 MPa, and 10.6 MPa for the mixes with 10% and 20% OPC, respectively.

Table 2.7: 28-day compressive strength of rubberised FA and OPC-based geopolymer concrete (Charkhtab Moghaddam *et al.*, 2021)

Mix ID	Percentage replacement	Compressive strength (Mpa)
A	100% FA	40
B	100%FA + 10% CR	37
C	90%FA + 10% OPC + 10% CR	39
D	80%FA + 20% OPC + 10% CR	40

In another study, Zhang *et al.* (2021) investigated the effects of OPC, FA, and GGBFS on pre-treated pulverised rubber aggregates. The aggregates were treated with a 1% NaOH solution for one hour to dissolve zinc stearate and roughen the surface. According to Table 2.8, compressive strength increased with higher percentages of rubber substitution due to the enhanced surface roughness and adhesion of the rubber aggregates.

Specifically, the compressive strength of standard OPC concrete (CFS0) was 46.2 MPa. With 25% FA and 25% GGBFS substitution, the strength dropped to 23.2 MPa

but increased to 44.6 MPa with 35% FA and 35% GGBFS replacement. This was attributed to the formation of N-A-S-H gels from the geopolymer binder and C-(A)-S-H gels from the OPC binder, both contributing to enhanced mechanical properties.

Table 2.8: Compressive strength of rubberised GGBFS, OPC and FA-based geopolymer concrete (Zhang *et al.*, 2021)

Mix ID	Percentage replacement	Na ₂ SiO ₃	NaOH	Compressive strength (Mpa)	Splitting Tensile strength (Mpa)
RGC0	50% GGBFS + 50% FA	194	78	39.4	3.2
RGC5	50% GGBFS + 50% FA + 5%CR	194	78	43.8	4
RGC10	50% GGBFS + 50% FA + 10%CR	194	78	46.9	4.3
RGC15	50% GGBFS + 50% FA + 15%CR	194	78	42.3	3.8
RGC20	50% GGBFS + 50% FA + 20%CR	194	78	38	3.5
CFS0	100% OPC + 10%CR (conventional concrete)	N/A	N/A	46.2	4.4
CFS50	25% GGBFS + 25% FA+ 50% OPC + 10%CR	39	97	23.2	2.7
CFS70	35% GGBFS + 35% FA+ 30% OPC + 10%CR	54.6	135.8	44.6	3.7

Yousf *et al.* (2022) examined the effects of GGBFS and FA on rubberised concrete with 12M NaOH and sodium hydroxide to sodium silicate ratio of 1.7, using 7% fine CR aggregates. The study found that with 50% FA and 50% GGBFS, the 28-day compressive strength was 15.8 MPa at ambient curing conditions. The compressive strength decreased to 10.1 MPa with 75% FA and 25% GGBFS and increased to 22 MPa with 25% FA and 75% GGBFS. This indicates that higher GGBFS content generally improves compressive strength.

These studies illustrate that incorporating CR aggregates into FA and OPC-based geopolymer concrete can influence mechanical properties significantly. While the inclusion of CR can reduce compressive strength, optimising the proportion of

GGBFS and pre-treating rubber aggregates can mitigate some of these negative effects and enhance the overall performance of the concrete.

2.10.6 Impact of Geopolymerisation on Durability Properties of Rubberised Concrete

Dong *et al.* (2021) investigated the durability properties of concrete containing 80% fly ash (FA) and 20% ground granulated blast furnace slag (GGBFS), activated with a sodium silicate/sodium hydroxide ratio of 1.6 and a sodium hydroxide (NaOH) molarity of 12. They examined the impact of incorporating 15% and 30% fine crumb rubber aggregates on water absorption.

The control mix, which contained no rubber aggregates, exhibited the lowest water absorption percentage of 2.7%. In contrast, concrete specimens with 15% and 30% crumb rubber aggregates recorded water absorption rates of 3.8% and 4.7%, respectively. An increase in GGBFS content to 40% reduced the water absorption percentage to 4.2%, suggesting that higher GGBFS content can mitigate some of the negative effects of rubber aggregate incorporation.

Youssef *et al.* (2022) explored the effects of GGBFS and FA-based geopolymer binders on water absorption in rubberised concrete. Using a binder with a NaOH molarity of 12 and a sodium silicate to sodium hydroxide ratio of 1.7, they studied concrete with 7% fine crumb rubber aggregates. Their findings indicated that water absorption increased by 43% in concrete with 75% FA and 25% GGBFS compared to a mix with 50% FA and 50% GGBFS. Conversely, water absorption decreased by 4% in a mix containing 25% FA and 75% GGBFS.

Youssef *et al.* (2022) attributed the higher water absorption in certain mixes to the reduced reaction between binder products, leading to more voids in the aggregate and cementitious matrix. This phenomenon also resulted in increased shrinkage and the formation of micro-cracks, which contributed to higher water absorption and storage.

These studies highlight the significant impact of FA and GGBFS-based geopolymer binders on the durability properties of concrete containing crumb rubber aggregates.

While higher rubber content generally increases water absorption, the inclusion of GGBFS can help reduce this effect and improve overall durability.

2.10.7 Chapter Summary

Cement extenders like FA and GGBFS demonstrate significant potential in augmenting the durability and mechanical resilience of concrete containing discarded tyre rubber aggregates. However, challenges persist in establishing a robust bond between these aggregates thus hindering their seamless substitution for conventional coarse and fine aggregates in concrete.

Nevertheless, geopolymerisation stands out for enhancing the durability and mechanical traits of geopolymer concrete compared to its cement-based counterpart. Synthesising insights from the literature, it becomes evident that the beneficial impact of pozzolanic material, especially through alkali activation or geopolymerisation, holds promise in mitigating the adverse effects of rubber aggregates in concrete. This research will thus explore the impact of cement and alkali-activated cement extenders on rubberised concrete to elevate its durability and mechanical properties significantly.

CHAPTER 3 : EXPERIMENTAL PROGRAMME

The literature review in the second chapter explored the use of crumb rubber aggregates (CR) in concrete. It delves into the impact of cement extenders and geopolymerisation on conventional concrete and concrete incorporating CR aggregates (rubberised concrete). Despite this exploration, there remains a gap in research concerning how cement extenders and geopolymerisation affect the durability and mechanical properties of concrete incorporating fine crumb rubber aggregates (FCR aggregates).

This chapter outlines the methodology adopted to address these research gaps. It provides a comprehensive overview of the experimental procedures, materials employed, conducted tests, equipment utilised, mix design, blending ratios, and curing protocols. All concrete and material testing adhered to the South African National Standards (SANS) guidelines. The control mix followed the mix design protocol established by the Cement and Concrete Institute (C&CI).

The experiment was structured into three stages: A, B, and C, each involving varying replacement ratios. In stages A and B, gradual substitution of Portland cement (PC) was carried out with FA. Stage C involved using FA and cement extenders, comprising 60% GGBFS and 40% FA, as well as 60% GGBFS and 40% PC. The extenders underwent a geopolymerisation reaction by alkali activating extenders with sodium hydroxide and sodium silicate solution. Concurrently, throughout all three stages, sand was replaced with fine crumb rubber aggregates (FCR), ranging from 10% to 20%.

The study encompassed the testing of concrete specimens at 7 and 28 days to evaluate their splitting tensile and compressive strength. These tests aimed to explore how FCR aggregates, FA, and alkali-activated cement extenders influence the mechanical traits of concrete. Durability assessments of concrete specimens were conducted using tests to measure oxygen permeability, water sorptivity, porosity, and chloride conductivity.

3.1 Binders, Extenders, Aggregates and Chemicals

This section provides a comprehensive overview of the materials employed in the present investigation, including cement, binders, and other relevant components. This section examines material characteristics, chemical compositions, and grading of various materials.

3.1.1 Portland Cement

AfriSam produces diverse cement types, such as Portland cement (CEM I 52.5R) and various composite types of cement. To assess the effects of substituting PC with FA and GGBFS in concrete, Portland cement (CEM-I 52.5R) without additives was used. The cement was sourced from the AfriSam facility in Rooderport, Gauteng Region, and had a relative density of 3.12 g/ml as provided by AfriSam. The chemical composition of CEM I 52R is outlined in Table 3.1.

3.1.2 Fly Ash

This study utilised waste paper mill boiler ash (FA) sourced from the Mondi Paper manufacturing firm in Merebank, KwaZulu Natal. The FA replaced PC and was used as an FA-based geopolymer binder in conventional and rubberised concrete for stage C. The FA was chosen due to its local availability and chemical composition, boasting SiO_2 (35.29%) and Al_2O_3 (16.16%). Mixed with an alkaline solution, FA forms a robust three-dimensional polymeric alumina-silicate structure (Si-O-Al-O). This structure significantly enhances the bond strength between the aggregate and the binder matrix. This FA used in this study was also used by Anganoo, Kiliswa and Trois (2021) who found a relative density of 2.45g/ml, and a detailed chemical composition is shown in Table 3.1.

3.1.3 Ground Granulated Blast Furnace Slag

Ground Granulated Blast Furnace Slag (GGBFS), also referred to as Slagment, emerges as a residual product from blast furnaces during the iron-making process, which is created by rapidly cooling the molten slag with water or steam, followed by drying and grinding. This process yields a fine powder that demonstrates cement-like properties upon hydration.

In this research, akin to FCR aggregates, Ground Granulated Blast Furnace Slag (GGBFS) was employed as an alternative to FA and PC in the development of geopolymer concrete. GGBFS, chosen due to its composition of CaO (37.2%) and SiO₂(39.2%), prompts the formation of Ca-Al-Si gel when combined with an alkaline solution. This gel accelerates the setting time and effectively reinforces the bond between the binder matrix and aggregates (Hadi, Farhan and Sheikh, 2017). The GGBFS utilised in this study was obtained from the AfriSam facility in Rooderport, Gauteng Region. As per AfriSam specifications, the relative density of the GGBFS was measured at 2.89g/ml. A comprehensive breakdown of GGBFS's chemical composition can be found in Table 3.1.

Table 3.1: Chemical composition binders used in the study

Chemical compound (% by mass, ignited basis)	CEM I, 52R (AfriSam, 2017)	GGBFS (AfriSam, 2017)	FA (Anganoo, 2021)
Loss on ignition	2.9	Nil	4.8
SiO ₂	20.7	39.2	35.29
P ₂ O ₅	0	0.01	Nil
Al ₂ O ₃	4.6	13.2	16.16
Fe ₂ O ₃	2.6	Nil	3.21
CaO	65	37.2	21.52
MgO	1.7	7.8	5.15
K ₂ O	0.4	0.9	6.36
TiO ₂	0.3	Nil	0.84
Na ₂ O	0.1	Nil	Nil
SO ₃	2.9	0.3	4.13
Mn ₂ O ₃	0.1	Nil	Nil
S	Nil	1.1	Nil
MnO	Nil	0.8	Nil
FeO	Nil	0.5	Nil

3.1.4 Coarse Crushed Aggregates

The coarse crushed aggregates were obtained from the Durban facility of Coedmore Quartz. The aggregates utilised in the study had a maximum size of 19 mm. These aggregates had a relative density of 2.65g/ml, with compacted and loose bulk densities of 1446 kg/m³ and 1360 kg/m³, respectively, as the University of KwaZulu Natal Civil Laboratory provided. The aggregates exhibited a uniform grading, as

seen in Figure 3.1, and the grading test was carried out following the guidelines outlined in SANS 3001 – GR2:2011.

3.1.5 Natural Rough River Sand

The fine aggregates used in this study were river sand sourced from the Umgeni River. As depicted in Figure 3.1, the grading curve displayed a well-distributed pattern, reflecting a fineness modulus of 3.4, and the gradation test aligned with SANS 3001 - GR2:2011 (see *Appendix A, Table A.1*). Additionally, the University of KwaZulu Natal Civil Laboratory provided measurements indicating a compacted bulk density of 1320 kg/m³, a relative density of 2.65, and a loose bulk density of 1400 kg/m³ for these aggregates.

3.1.6 Fine Crumb Rubber Aggregates

The FCR aggregates were procured from Mathe Group, located at Hammarsdale in KwaZulu Natal, South Africa. The FCR aggregates had a maximum size of 1 mm and a fineness modulus of 2.25 (see *Appendix A, Table A.2*). The experiment was conducted following the guidelines outlined in SANS 3001 - GR2:2011. As shown in Figure 3.1, the FCR aggregates were well-graded.

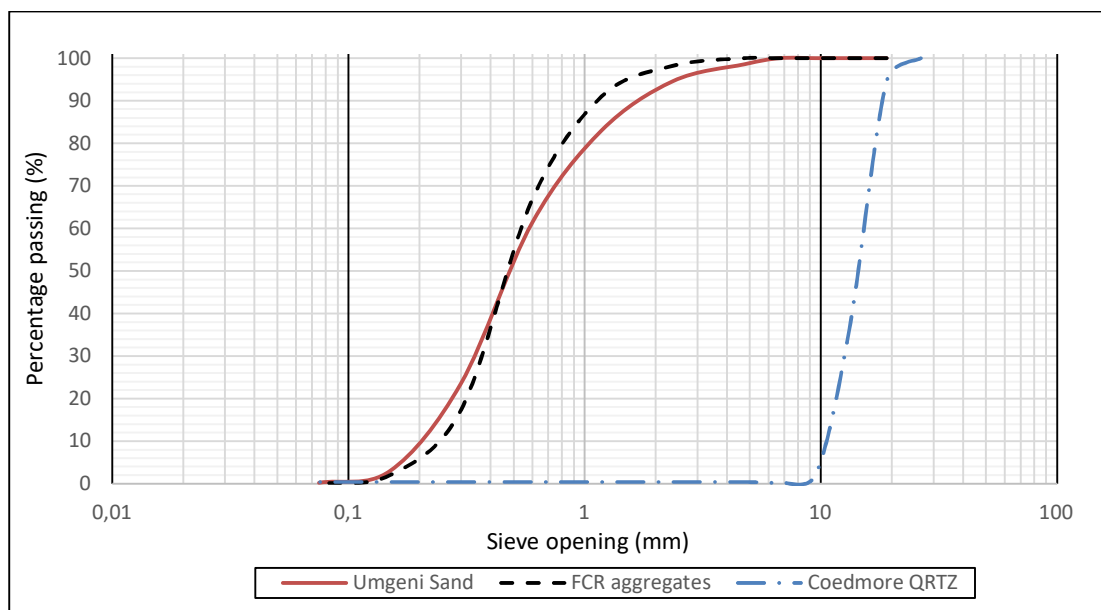


Figure 3.1: Grading curves for sand, FCR and 19 mm crushed aggregates

3.1.7 Alkaline Solution

Activators, known as alkaline hydroxides, initiate a reaction with alumina-silicates present in cement extenders like fly ash and GGBFS, forming an aluminosilicate gel that serves as the binding agent in concrete. Commonly used activators include Sodium Hydroxide, Potassium Hydroxide, Sodium Silicate and Potassium Silicate (Davidovits, 1991; Panias and Giannopoulou, 2004; Patankar, Ghugal and Sanjayn S. Jamkar, 2015)

Hence, sodium silicate and sodium hydroxide were preferred as activators because of their local availability and safer handling than potassium. Industrial-grade sodium silicate solution and NaOH flakes were obtained from Kiran Global Silica SA Company (Pty) Ltd in Boksburg, Gauteng Province. The solution consisted of 15% NaO, 29% SiO, and 56% water, with a SiO/NaO ratio of 2, while the NaOH was in the form of 99.8% NaOH flakes.

Furthermore, the study adopted specific ratios based on literature reviews indicating improved durability and mechanical properties in concrete outcomes. These included a Sodium Hydroxide (NaOH) solution concentration of 16 Molarity, a sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH) ratio of 2.5, 0.4 alkaline solution to fly ash ratio, and water to geopolymer solids ratio of 0.19, established as optimal from previous research (Patankar, Jamkar and Ghugal, 2013; Patil and Manojkumar, 2013; Lăzărescu *et al.*, 2017).

3.1.8 Chemical Admixture

To enhance concrete's workability, flow, and compaction, a superplasticiser named Sika Plastiment BV-40 was used. The manufacturer and supplier, Sika, has suggested a dose range of 0.2-1.5% relative to the weight of cement (see *Appendix C*). To get a design slump measurement of 50mm, a proportion of 0.5% of superplasticiser was employed. Consequently, a consistent dose was utilised for all the mixtures.

3.2 Experimental Stages and Material Replacements

This section covers the substitution percentages of sand with FCR aggregates and the replacement percentage of Portland cement with FA in conventional and rubberised concrete. Additionally, it delves into the proportionate substitution of PC with FA and GGBFS geopolymer binders in concrete.

3.2.1 Sand Replacement Percentage

In Chapter 2, specifically within section 2.4.1 of the literature review, it was noted that substituting sand with CR aggregates below 5% did not significantly affect the concrete's mechanical aspects, like splitting tensile and compressive strength. However, a noticeable change occurred at and above a 10% replacement rate, prompting the selection of 10% and 20% replacements for this research. These substitution rates of sand with FCR aggregates were consistently applied across all investigation stages (A, B, and C).

Two control mixtures were formulated for the experimental design: conventional concrete (CM) and geopolymer concrete (C0), detailed in section 3.2. CM comprised Portland cement (PC) and natural aggregates, while C0 comprised natural aggregates and FA-based geopolymer binders. In stages A and B, CM acted as the baseline mix, and C0 served as the reference for stage C. Material quantities for stages A and B were derived from CM, while those for stage C were inferred from C0.

3.2.2 Stage A

Stage A was designed to explore the implications of partially replacing PC with 10% and 20% of FA and the effects of substituting sand with 10% and 20% FCR aggregates in concrete. Table 3.3 illustrates this, where specimen ID A1 and A2 represent the replacement of sand by 10% and 20% of FCR aggregates, respectively. Meanwhile, specimens A3 and A4 showcase the replacement of PC by 10% and 20% of FA, respectively.

3.2.3 Stage B

In this stage, the aim was to study the impact of replacing PC with 10% and 20% of FA on concrete containing 10% and 20% of FCR aggregates. As shown in Table 3.3, specimen ID B1 and B2, sand was replaced by 10% and 20% of FCR aggregates, respectively, while PC was replaced by 10% of FA on both specimens. Regarding specimens ID B3 and B4, sand was replaced by 10% and 20% of FCR aggregates, respectively, and PC was replaced by 20% of FA in both specimens.

3.2.4 Stage C

Stage C investigated geopolymer binders' influence on conventional and rubberised concrete. As demonstrated in Table 3.2, sand was replaced by 10% to 20% of FCR aggregates across all mixes except for C0. In C0, C1, and C2, FA was employed as a geopolymer binder. For C3 and C4, a geopolymer binder constituted 40% PC and 60% GGBFS. Meanwhile, C5 and C6 utilised a 40% FA and 60% GGBFS geopolymer binder.

Table 3.2: Replacement percentage of sand with FCR, PC, FA and GGBFS in conventional and rubberised geopolymer concrete

	Mix / Specimen ID.	Replacement %
Stage C	C0	100%FA
	C1	10%FCR; 100%FA
	C2	20%FCR; 100%FA
	C3	10%FCR;40%PC+60%GGBFS
	C4	20%FCR;40%PC+60%GGBFS
	C5	10%FCR;40%FA+60%GGBFS
	C6	20%FCR;40%FA+60%GGBFS

3.3 Control Mix Design

The control mix design considered a specific gravity of 3.12 for cement and 2.65 for both sand and coarse aggregates, and material test results are discussed in section 3.2 of this chapter. The design compressive strength for a water-to-cement ratio of 0.6 was 50Mpa after 28 days (see *Appendix B, Figure B.1* and *Appendix A, Table A.3*). The water content was set at a volume of 210 litres, and a plasticiser, namely

plastiment was added in an amount equal to 0.5% of the weight of the cement to achieve a slump value of around 50mm. Therefore, Table 3.3 below displays the mix design for the control mix for stages A and B. Material quantities used for stages A and B were derived from the control mix (CM), considering the material percentage replacements for each mix as discussed in section 3.3. Refer to Table 3.3 below for stage A and B replacement and concrete mix proportions.

Table 3.3: Concrete mix proportions for stages A and B

Mix/ Specimen ID	Replacement %	Water (litres)	Cement (kg/m ³)	Stone (kg/m ³)	Sand (kg/m ³)	FA (kg/m ³)	FCR (kg/m ³)
Stage A							
CM	0%	210	350	954	842	-	-
A1	10% FCR	210	350	954	758	-	84
A2	20% FCR	210	350	954	673	-	168
A3	10% FA	210	315	954	842	35	-
A4	20% FA	210	280	954	842	70	-
Stage B							
B1	10%FCR + 10%FA	210	315	954	758	35	84
B2	20% FCR + 10%FA	210	315	954	673	35	168
B3	10% FCR + 20%FA	210	280	954	758	70	84
B4	20% FCR + 20%FA	210	280	954	673	70	168

3.4 Geopolymer Concrete Mix Design

In alkali-activated/geopolymer concrete, the same material test results and C&CI mix design guide were adopted as in conventional concrete, except for the water-to-cement (w/c) ratio, which is referred to as the alkaline solution/binder (Al/b) ratio in the context of geopolymer concrete, and to according to Rangan (2008) study al/b ratios between 0.35 and 0.45 yielded more favourable outcomes than other ratios. Therefore, in the context of this investigation, an al/b ratio of 0.4 was adopted (See *Appendix A, Table A.4*).

In contrast to the data presented in Table 3.3, 210 litres of the alkaline solution was employed instead of 210 litres of water, representing the typical water content in conventional concrete. A solution of 150kg/m^3 of Na_2SiO_3 and a NaOH solution with a 60 kg/m^3 concentration was used. Similar to the control mix (CM), the quantities of all materials were derived from the C0 control mix. Concerning FCR aggregates, the proportion of sand replacement remained at 10% and 20%.

Table 3.4 below shows quantity calculations for the alkaline solution and water required for the geopolymer concrete mix, considering Molarity, NaOH/ Na_2SiO_3 ratio and Molarity. Table 3.4 below shows four columns: Column 1 represents the material description, column 2 represents the formula variable, column 3 represents the formulae derived from the formula variables, and column 4 represents the quantity required per material in column 1. As a result, Table 3.5 displays the quantities of materials required for each mix in stage C.

Table 3.4: Mass of alkaline solution and water required for geopolymer concrete

Description	Formula variable	Formula	Kg/m ³
FA Content (kg/m ³)	a		525
Alkaline solution/FA	b		0.4
NaOH/ Na_2SiO_3	c		2.5
Molarity	d		16
Alkaline Solution (kg/m ³)	e	$a * b$	210
Mass of NaOH solution (kg/m ³)	f	$\frac{e}{1 + c}$	60
Mass of NaOH/Mass of the Solution	g	$\frac{d}{25 + 0.685 * d}$	0.445
Mass of NaOH	h	$g * f$	26.70
Mass of water	i	$g - h$	33.30
Mass of Na_2SiO_3 Solution	j	$e - f$	150
NaO	j ₁	$j * 14.7\%$	22.05
SiO	j ₂	$j * 29.4\%$	44.1
Water	j ₃	$j * 55.9\%$	83.85
Mass of Solids (kg/m ³)	k	$a + h + j_1 + j_2$	617.85
Water (kg/m ³)	i	$i + j_3$	117.15
Water-to-geopolymer solids	m	$\frac{i}{k}$	0.19

Table 3.5: Stage C Mix design and percentage replacement

Mix ID	% Replacement	Additional water	FA	GGBFS	PC	Stone	Sand	FCR
C0	100% FA	84	525	-	-	954	534	0
C1	10% FCR; 100%FA	84	525	-	-	954	481	53
C2	20% FCR; 100%FA	84	525	-	-	954	427	107
C3	10% FCR; 40%PC + 60% GGBFS	84	-	315	210	954	534	53
C4	20% FCR; 40%PC + 60% GGBFS	84	-	315	210	954	427	107
C5	10% FCR; 40% FA + 60% GGBFS	84	210	315	-	954	481	53
C6	20% FCR; 40% FA + 60% GGBFS	84	210	315	-	954	427	107

3.5 Preparation of Concrete Mixes

All materials required for stage A, B and C concrete mix were weighed according to the quantities shown in Tables 3.3 and 3.5 using a scale. The concrete was mixed with an electrically operated tilting drum concrete mixer.

In conventional and rubberised concrete, the aggregates and the binders were thoroughly blended in a dry condition for 5 minutes utilising a concrete mixer. Subsequently, water was introduced into the desiccated mixture, which was then followed by the addition of a plasticiser. The process of mixing concrete continued until the mixture achieved homogeneity.

In the context of geopolymer concrete, the alkaline solution was achieved by mixing Na_2SiO_3 and NaOH solutions, which allowed them to react fully and cool for 24 hours before placing the concrete. Like the conventional concrete mix, the aggregates were mixed with binders in a dry state for 5 minutes. Then, an alkaline solution was added to the mixture of binder and aggregates, followed by additional water and a plasticiser to enhance the workability of the concrete. The concrete mixture was thoroughly mixed until a state of homogeneity was achieved.

For stages A, B and C, cube moulds of 100x100mm were used to cast concrete cubes for compressive strength and splitting tensile strength tests. Twelve (12) concrete cubes for each mix were cast for both 7-day and 28-day intervals—3 cubes for each 7 and 28-day compressive strength and the same for splitting tensile strength. In addition to 12 concrete cubes, two (2) concrete cubes of 150x150mm were cast for durability testing. The casted cubes with moulds were placed onto the vibrating table for 15 minutes, then labelled and placed into the curing room. Lastly, the stripping of moulds was done after 24hrs of casting.

3.6 Curing

Due to limited water curing facilities at the laboratory, after stripping the moulds, the concrete cubes for stages A and B were carefully positioned within a controlled environment with a temperature range of around $\pm 21^{\circ}\text{C}$ for 7 and 28 days. As for geopolymer concrete in stage C, the concrete specimens (C0 - C6) were subjected to a 60°C thermal curing process for 24 hours; Figure 3.2 below shows the oven with concrete cubes ready for curing. Subsequently, the specimens were exposed to a controlled room temperature of about $\pm 21^{\circ}\text{C}$ for 7 and 28 days.

The decision to employ temperature curing was made in light of research indicating that the hardening process of geopolymer concrete is hindered by the sluggish reactivity of alumino-silicate material at ambient temperature. Therefore, temperature curing was deemed important in expediting the reaction. Among various curing temperatures, it was shown that curing at 60°C yielded superior outcomes, as supported by several studies (Patil and Manojkumar, 2013; Heniegal *et al.*, 2015; Risdanareni *et al.*, 2016; Kothari, 2017; Karuppuchamy, Ananthkumar and Raghavapriya, 2018).



Figure 3.2: (a) Closed oven set to 60°C and (b) Oven open view

3.7 Mechanical and Durability Index Concrete Testing

This section examines the tests performed on fresh and hardened concrete. As part of this, the slump test was carried out on freshly mixed concrete to assess its workability and consistency. Meanwhile, tensile and compressive strength tests were performed to investigate the mechanical characteristics of concrete.

Durability index tests were conducted on concrete to assess its capacity to withstand weathering; durability index tests performed were water sorptivity, porosity, oxygen permeability, and chloride conductivity tests.

The specimens used for the durability index tests were prepared following the guidelines outlined in SANS Test methods 3001-CO3-1:2015. The oxygen permeability index test was done per SANS 3001-CO3-2:2015, while the chlorine conductivity test was performed using the procedures specified in SANS 3001-CO3-3:2015. The UCT Part 3 of the durability index testing method handbook, version 4.5.1 from April 2018 (Alexander, 2018), was utilised for specimen preparation and the subsequent execution of the water sorptivity test. The outcomes were evaluated utilising the performance criteria suggested by Alexander, Mackechnie and Ballim (1999), as presented in Table 3.6.

Additionally, the sorptivity and porosity categorisation values, as suggested by Moore, Bakera and Alexander, (2021), are included in Table 3.7. The durability class shown in Tables 3.8 and 3.9 indicates the rating on the ability of concrete to resist the effects of oxygen permeability, water absorption, porosity, and chloride conductivity. It categorises concrete as excellent, good, poor, or very poor based on its resistance to these factors.

Table 3.6: Proposed durability index values range (Alexander, Mackechnie and Ballim, 1999a)

Durability Class	OPI (log scale)	Sorptivity (mm/hr ^{0.5})	Conductivity (mS/cm)
Excellent	>10	<6	<0.75
Good	9.5–10	6–10	0.75–1.50
Poor	9.0–9.5	10–15	1.50–2.50
Very Poor	<9.0	>15	>2.50

Table 3.7: Durability classification table for sorptivity and porosity values (Moore, Bakera and Alexander, 2021)

Sorptivity (mm√h)	Porosity (%)	Durability classification
<6	<10	Excellent
6-10	<10	Excellent to Good
	>10, <12	Good to Poor
10-15	<12	Good to Poor
	>12, <15	Poor to very poor
>15	-	Very Poor

3.7.1 Durability Index Test Specimen Preparations

150mm x 150mm concrete cube specimens were used. The cube specimens were cored after 28 days of casting and curing. The coring procedure complied with the specifications outlined in SANS 3001-CO3-1:2015. A round core disc was employed to extract specimens with a diameter of 70±2mm. The cores were subjected to natural drying conditions at room temperature for three (3) days. After three days, 5mm thick segments on the surface of both ends of the core were removed and then sliced into 30±2mm thick segments, which were used to conduct the tests. One hundred twenty-eight (128) specimens were produced for the various stages of the investigation, with four specimens being produced on every DI test. Concrete core specimens for oxygen permeability were also used for water sorptivity and porosity tests.

3.7.2 Slump Test

As depicted in Figure 3.3 (a), a slump cone was used to perform a slump test was shown in Figure 3.3 (b). The slump test assessed the influence of cement extenders and alkali activation on the consistency and homogeneity of concrete mixtures for both conventional and rubberised. The slump test was performed on all the concrete mix in stages A, B and C, and the test was done per the standards outlined in 5862-1:2006 of the South African National Standards (SANS).

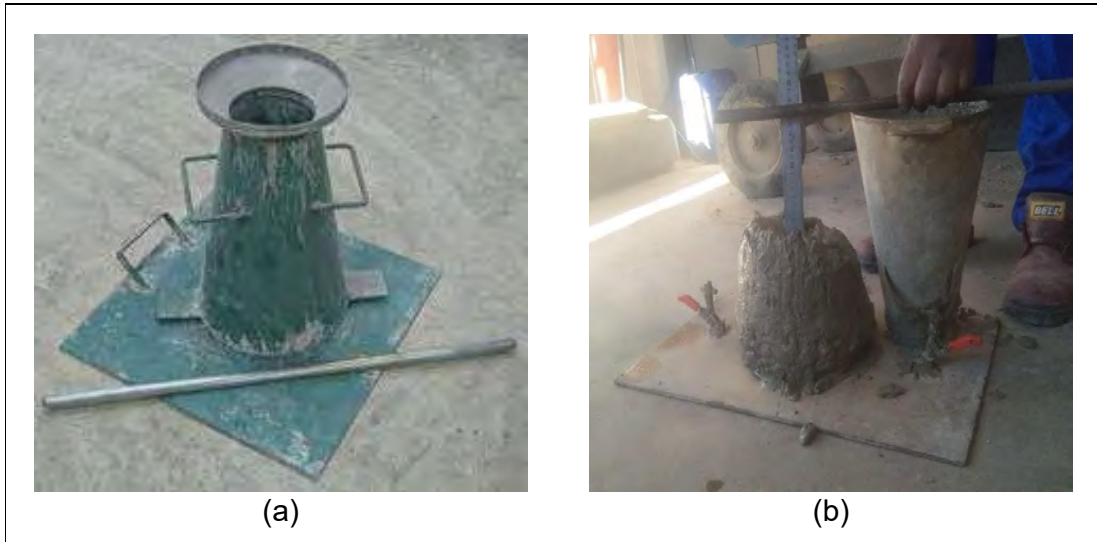


Figure 3.3: (a) Slump cone used for slump; (b) Illustration of slump Test

3.7.3 Compressive Strength

A compressive strength test was conducted per the SANS 5863:2006 standard. As shown in Figure 3.4, the test was done using an Avery Danison Electronic press machine. The machine was used to crush the 100x100mm concrete cubes against the fixed head by applying the load on the concrete cubes until they reached the maximum compression stresses.

Testing was carried out following the curing of the concrete specimens for 7 and 28 days. The results obtained from three cubes as discussed in section 3.6 were averaged and recorded. A similar procedure was then carried out with cube specimens that underwent a 28-day curing period. This procedure was relevant in all stages. Lastly, the evaluation of the influence of FCR aggregates, FA, and geopolymer binders on concrete was conducted using a comparative analysis of the average compressive strength of the specimens.

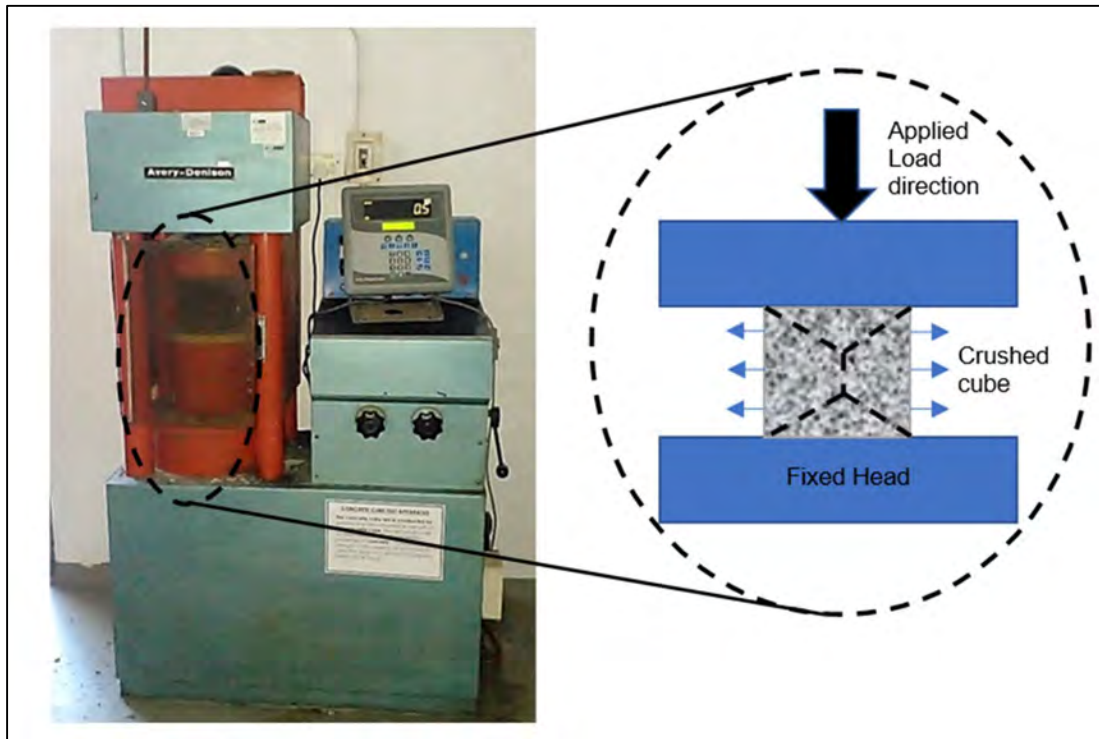


Figure 3.4: Compressive strength machine and testing layout

3.7.4 Splitting Tensile Strengths

A tensile strength test was conducted on 100x100mm concrete cube specimens. The concrete specimens underwent testing at ages 7 and 28 days. The cubes were split using the Rohloff machine, as shown and illustrated in Figure 3.5 below. The cubes were placed under the splitter and pressed against supplementary and fixed plates until they reached the maximum splitting stresses. The test results were recorded similarly to those of compressive strength. The test was done following the guidelines established in SANS 6253:2006; the test results of the specimen from all stages were compared to examine the effects of FA and geopolymer binders on rubberised concrete. This comparison aimed to assess the strength reduction and enhancement and identify potential causes for these changes.

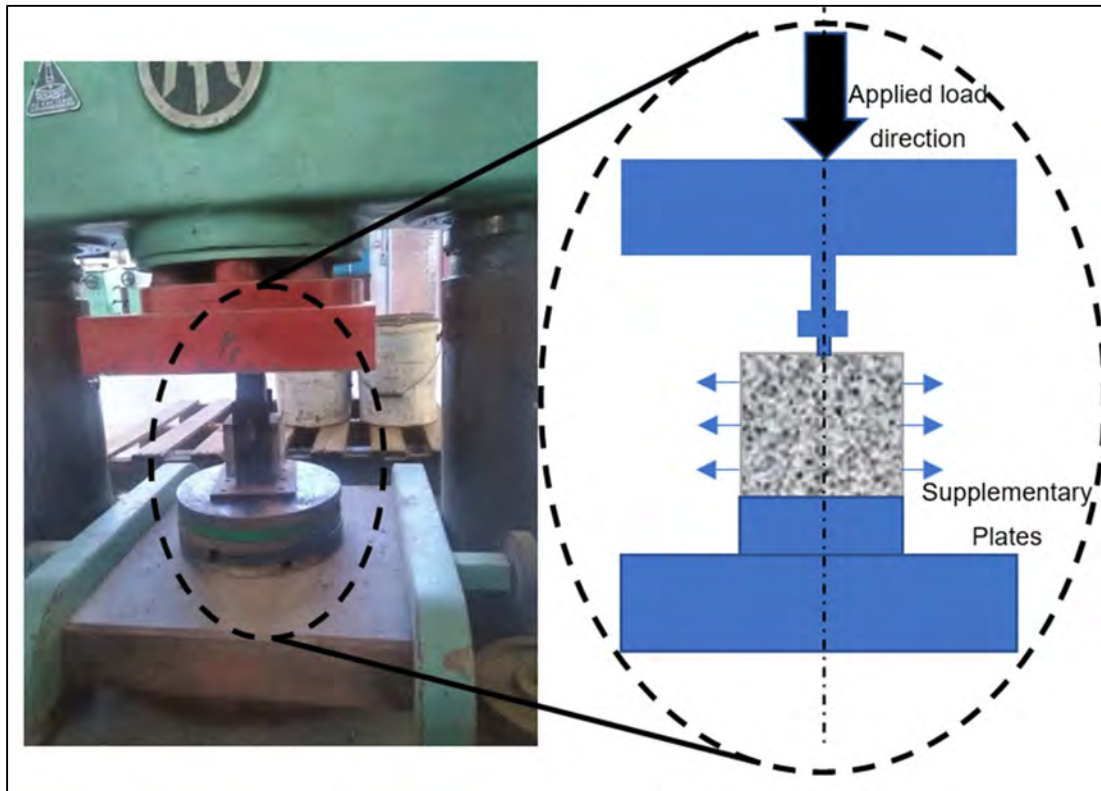


Figure 3.5: Cube under splitting tensile strength testing layout

3.7.5 Oxygen Permeability Index

The Oxygen Permeability Index (OPI) measures the concrete's ability to allow the passage of oxygen through its structure. This index is particularly relevant in civil engineering, where the performance of concrete in various structures, such as bridges, buildings, and infrastructure, are crucial considerations.

The Oxygen Permeability Index is expressed as the rate at which oxygen can penetrate a unit area of the material over a specific period. Lower values of the index indicate better resistance to oxygen permeation, which is desirable for preventing reinforcing steel corrosion in concrete structures, which can compromise the structural integrity and longevity of buildings and infrastructure.

Various factors, including the material's composition, porosity, and curing conditions, can influence its oxygen permeability. Engineers and researchers use this index to assess and compare the durability of different construction materials,

helping to select materials that can withstand environmental conditions and maintain their structural integrity over time.

a) Testing Procedure

After the specimens had been prepared, as detailed in section 3.8.2, they were placed in an oven set at 50°C for 7 days to ensure uniform drying. Once the oven drying process was completed, these specimens were allowed to cool for 2 hours in a desiccator maintained at 23°C. As illustrated in permeability configuration Figure 3.6, the specimens were placed into a compressible collar within a rigid sleeve. The assembly was then positioned on the permeability cell to cover its hole, and a solid ring was placed to seal the gap between the sleeve and collar.

The top screw of the cover plate was centred and tightened to prevent any potential gas leaks. Following this, both the outlet and inlet valves of the permeability cell were opened, and oxygen from the tank was supplied at a pressure of 100kPa, flowing through the cell for 5 seconds. The outlet valve was closed afterwards to ensure no gas leakage. Subsequently, the pressure within the permeability cell was raised to 100kPa, and the inlet valve was closed, marking the recording of the time (t_0) to the nearest minute. Throughout the test, time and pressure readings were recorded at intervals of five minutes, with at least eight readings taken as the pressure dropped by 5kPa. The testing concluded when the pressure dropped to 50kPa.

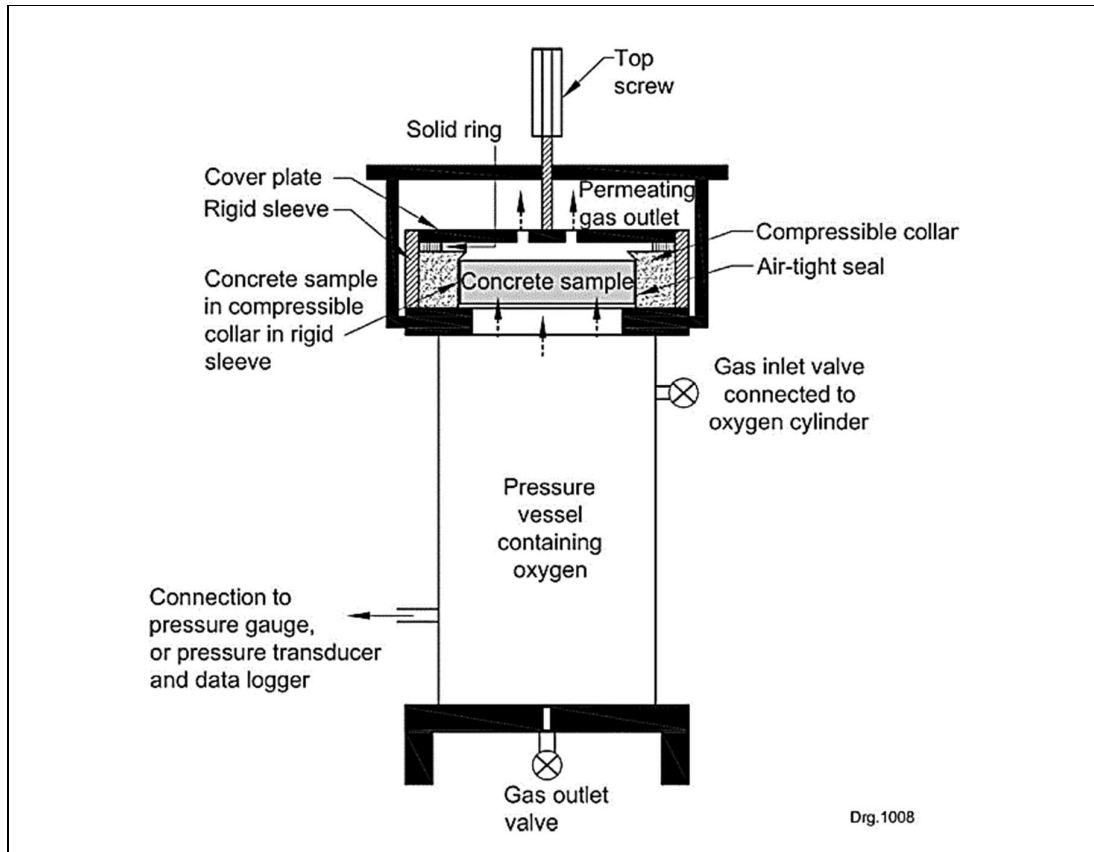


Figure 3.6: Permeability cell configuration (SANS 3001-CO3-2, 2015)

After that, for each specimen, the Darcy permeability coefficient was calculated using formula 3.1 below;

$$K = \frac{\omega \times v \times g \times d \times z}{R \times A \times T} \quad (3.1)$$

Where;

v = Volume of the permeability cell recorded to the nearest 0,01 L or 0,00001 m³

g = gravitational acceleration (9,81 m/s²)

d = average specimen thickness to the nearest 0,00002m

z = the slope of the linear regression line forced through the (0,0) point in reciprocal seconds (s⁻¹)

R = universal gas constant (8,313 Nm/K mol)

A = cross-sectional area of the test specimen (m²)

T = temperature (K)

The coefficient of permeability K was calculated for each specimen. The oxygen permeability index (OPI) was calculated by averaging the results of the OPI specimens.

$$OPI = \frac{OPI_1 + OPI_2 + OPI_3 + OPI_4}{4} \quad (3.2)$$

For instance, OPI_1 was calculated as the negative log of the k value;

$$OPI_1 = -\log_{10}(k) \quad (3.3)$$

3.7.6 Chloride Conductivity Test

Chloride conductivity often called the chloride ion conductivity or chloride diffusion coefficient, measures how easily chloride ions can move through a material, such as concrete. This property is crucial in assessing the durability of concrete structures, especially in environments where chloride ions can penetrate and potentially corrode the steel reinforcement, leading to structural deterioration.

Concrete's resistance to chloride ion penetration is typically characterised by its chloride diffusion coefficient, which quantifies the rate at which chloride ions move through the concrete matrix. Lower chloride conductivity indicates better resistance to chloride ion penetration and, consequently, enhanced durability of the concrete. Several factors influence chloride conductivity in concrete, including its mix design, water-cement ratio, curing conditions, and exposure environment.

a) Testing Procedure

After the specimens had been prepared, as detailed in section 3.8.2, they were placed in an oven set at 50°C for 7 days to ensure uniform drying. Once the oven drying process was completed, these specimens were allowed to cool for 2 hours in a desiccator maintained at 23°C.

Vernier calliper was used to measure the thickness and diameter of each specimen, and the readings were recorded, ensuring the accuracy of 0.02 mm at four points equally distributed around the specimen's perimeter, and then readings averaged to the nearest 0.02mm. The specimen dry mass (M_d) was measured to 0.01g accuracy. Then, the specimen was placed in a vacuum saturation vessel, as illustrated in Figure 3.7, which was locked and sealed to keep the tank at a pressure of -75kPa and -80kPa for 3hr 15min. The tank was isolated, and a salt (NaCl) solution containing 2.93kg of NaCl in 10 litres of water was permitted to flow into the chamber until the solution reached a height of about 40mm above the top of the specimen. Then, the pressure in the tank was re-established at -75 kPa and -80 kPa for 1 hour and 15 minutes. Then, the vacuum was released and allowed the gas to enter the chamber. The object was then immersed in NaCl solution for 18 hours and 1 hour.

The specimens were removed from the solution and then dried to the saturated surface in a dry condition, weighed to an accuracy of 0.01g, and the readings were recorded as a vacuum-saturated mass (M_s). Conduction cells were unscrewed, and plastic tubes of chloride cells were filled with NaCl solution. As depicted in chloride cell configuration Figure 3.8 below, the specimen was placed within the flexible rubber collar in the centre of the cells, ensuring that the specimens were placed with face against the plastic lip of the rigid ring.

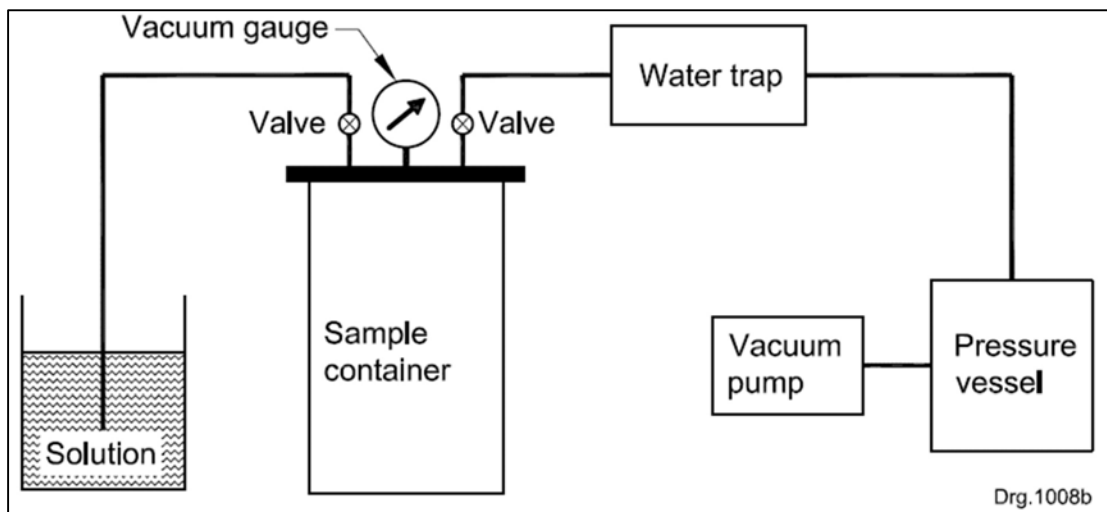


Figure 3.7: Vacuum saturation tank (SANS 3001-CO3-3, 2015)

The anode and cathode portions were fastened to the specimen's seal. A 5M NaCl solution was poured into the anode and cathode compartments. The ammeter and voltmeter were attached, and the DC power source was turned on until the voltage across the specimen was approximately 10V. The voltage and current readings were logged. The electricity was then turned off. After withdrawing a specimen from the NaCl solution, the testing was finished in 15 minutes.

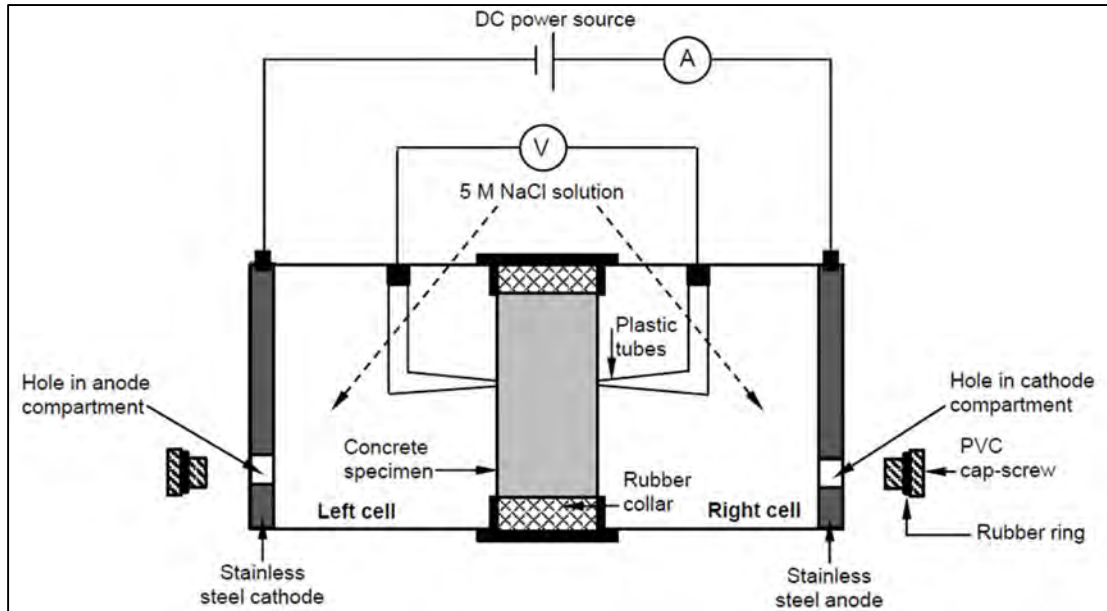


Figure 3.8: Chloride cell configuration (SANS 3001-CO3-3, 2015)

Chloride conductivity was calculated using equation 3.4 below;

$$\sigma = \frac{i \times d}{V \times A} \quad (3.4)$$

Where;

σ = chloride conductivity of the specimen(mS/cm)

i = electric current (mA)

d = average specimen thickness (cm)

V = voltage difference (V)

A - cross-sectional area of the specimen (cm²).

The chloride conductivity index was calculated as an average of chloride conductivity of three individual tests. The chloride solution porosity of the specimens was calculated by equation 3.5;

$$n = \left(\frac{M_s - M_d}{A \times d \times \rho_s} \right) \times 100 \quad (3.5)$$

Where;

n = porosity as a fraction of the volume of the specimen that is occupied with the solution (%)

M_s = vacuum saturated mass of the specimen (g)

M_d = mass of the dry specimen (g)

A = cross-sectional area of the specimen (mm²)

d = average specimen thickness (mm)

ρ_s = density of the salt solution (i.e. $1,19 \times 10^{-3}$ g/mm³) (g/mm³)

3.7.7 Water Sorptivity and Porosity

Water sorptivity refers to the ability of a material to absorb water through capillary action. It is often used to measure the material's porosity, the volume of voids or pores affecting its ability to absorb water. Materials with higher porosity tend to have higher water sorptivity because there is more void space for water to be absorbed. Conversely, materials with lower porosity have lower water sorptivity because water has fewer voids to occupy. Water sorptivity and porosity are important in construction materials, as they can impact the material's durability, strength and resistance to environmental factors such as moisture.

a) Testing Procedure

The oxygen permeability index test specimens were also used to determine water sorptivity and porosity. The oxygen permeability index test specimens were tested immediately upon removal from the oxygen permeability cell. In cases where specimens were not tested immediately, they were placed at 50°C for one night, followed by a desiccator for cooling before testing. The specimen was tested under

a control room temperature of $\pm 23^{\circ}\text{C}$. Dry mass (M_{s0}) was measured 30 minutes after removing the specimen from the oxygen permeability chamber. In the tray, ten layers of paper towels were saturated with calcium hydroxide solution; the solution was kept 2mm above the lower border of the specimen. The specimen test face was put on the wet paper pad, and a stopwatch was initiated at the time (t_0). Specimens were weighed after patting them once on wet absorbent paper at 3,5,7,9,12,16,20, and 25 minutes and their masses were noted.

In addition, the specimen was placed in a pressure saturation vessel as shown in Figure 3.7, within one day of being weighed. The support was placed at their curved edges to maximise their visible area. The tank was emptied between -75 and -80 kPa, the vacuum was held for 3 hours and 15 minutes, and the pressure was held at -75 kPa. The tank was then separated, and calcium hydroxide solution was permitted to trickle into the compartment until it reached 40mm head above the top of the specimen. The pressure was restored to -75kPa and -80kPa for 1 hour and 15 minutes. The vacuum was then released, allowing oxygen to penetrate. The specimen was wet for 18 hours and 1 hour. Finally, the specimen was withdrawn from the solution, the surface was dried to SSD state, and the saturated mass M_{sv} was measured.

Then, porosity was calculated using equation 3.6 below;

$$n = \left(\frac{M_{sv} - M_{s0}}{A \times d \times \rho_w} \right) \times 100 \quad (3.6)$$

Where;

M_{sv} = vacuum saturated mass of the specimen (g)

M_{s0} = the mass of the specimen at time t_0 (start of the test) (g)

A = cross-sectional area of the specimen mm^2

d = average specimen thickness (mm)

ρ_w = density of water 10^{-3} g/mm^3

The mass gain was calculated and plotted using equation 3.7;

$$M_{wt} = F\sqrt{t}$$

(3.7)

Where;

F – the slope of the best-fit line from plotting M_{wt} (g)

t – time in hours after a specimen was first exposed to water on its lower face (hours)

The mass gain was calculated using this equation 3.8;

$$M_{wti} = M_{st} - M_{s0} \quad (3.8)$$

Where;

M_{st} – the mass of the specimen at a particular time t (g)

M_{s0} – the mass of the specimen at the initial time (t_0),

The correlation coefficient r^2 of the data was calculated by equation 3.9;

$$r^2 = \left(\frac{\sum (\sqrt{t_i} - T) (M_{wti} - \bar{M}_{wt})}{\sqrt{\sum (\sqrt{t_i} - T)^2 \sum (M_{wti} - \bar{M}_{wt})^2}} \right)^2 \quad (3.9)$$

Where;

M_{wti} = mass gain (g)

t_i = time corresponding to the mass gain M_{wti}

$\bar{M}_{wt}$ = equation 3.9

T = equation 3.10

n = data point number

$$\bar{M}_{wt} = \frac{\sum M_{wti}}{n} \quad (3.10)$$

$$T = \frac{\sum \sqrt{t_i}}{n} \quad (3.11)$$

Calculate the slope of the best-fit line (F) using linear regression;

$$F = \left(\frac{\sum(\sqrt{t_i} - T)(M_{wti} - \bar{M}_{wt})}{\sum(\sqrt{t_i} - T)^2} \right) \quad (3.12)$$

Lastly, the specimen water sorptivity (S) in (mm/ $\sqrt{h}$) was calculated by equation 3.13.

$$S = \frac{Fd}{M_{sv} - M_{s0}} \quad (3.13)$$

Where;

F – best-fit line slope (g/ $\sqrt{h}$)

d – average specimen thickness (mm)

M_{sv} – Vacuum saturated mass to the nearest 0.01g of the specimen in grams

M_{s0} – Mass to the nearest 0.01g of the specimen at the initial time (t_0) in grams

3.8 Chapter Summary

This chapter detailed the types of materials utilised in the study, such as the mix design, material quantities, tests conducted on the material, as well as fresh and hardened concrete. Additionally, the chapter delved into determining the material quantities required for both concrete types. Chapter 4 of this study focuses on the comprehensive analysis and subsequent discussion of the obtained data.

CHAPTER 4 : RESULTS AND DISCUSSION

This chapter presents the interpretation and discussion of the test results obtained from the experimental study. The results were acquired through different tests such as the splitting tensile strength, compressive strength, slump and durability index, as outlined in Chapter 3.

The findings for stage A illustrate the effects of replacing PC with 10% and 20% of FA in conventional concrete and the effects of substituting sand with 10% and 20% of FCR aggregates in concrete. The results obtained in Stage B demonstrate the influence of 10% and 20% of FA content on concrete properties that incorporate 10% and 20% of FCR aggregates. Lastly, stage C highlights the influence of geopolymer binders on concrete containing 10% and 20% of FCR aggregates. Table 4.1 displays the assortment of Mix or specimen IDs and the corresponding replacement percentages across different stages.

Table 4.1: Mix/specimen ID and replacement percentage for stages A, B and C

Mix / Specimen ID	Stages	Replacement %
CM	Stage A	No replacement
A1		10% FCR
A2		20% FCR
A3		10% FA
A4		20% FA
B1	Stage B	10%FCR; 10%FA
B2		20% FCR;10%FA
B3		10% FCR;20%FA
B4		20% FCR; 20%FA
C0	Stage C	0%FCR; 100%FA
C1		10%FCR;100%FA
C2		20%FCR;100%FA
C3		10%FCR;40%PC + 60%GGBFS
C4		20%FCR; 40%PC + 60%GGBFS
C5		10%FCR;40%FA + 60%GGBFS
C6		20%FCR;40%FA + 60%GGBFS

4.1 Slump Test

The slump test in this study was conducted to assess the impact of FCR aggregates, FA and geopolymer binders on concrete workability (see *Appendix A, Table A.7*).

4.1.1 Stage A – Slump Test Results

Figure 4.1 presents a comparison between A1 and A2 with CM, and the results reveal a 60% and 100% decrease in concrete workability for A1 and A2, respectively. In contrast, the concrete workability of mix A3 and A4 improved by 60% and 190%, respectively. These findings suggest that adding 10% and 20% of FA enhanced the concrete's workability. While 10% and 20% of FCR aggregate decreased the concrete workability.

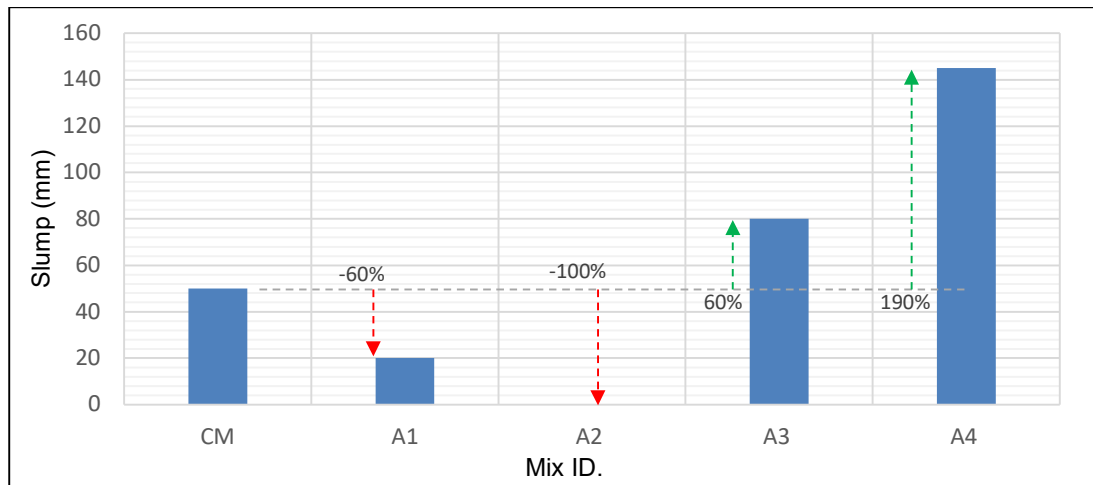


Figure 4.1: Slump test results of concrete mixes in stage A

4.1.2 Stage B – Slump Test Results

Figure 4.2 illustrates the impact of substituting PC with 10% and 20% FA in concrete with 10% and 20% FCR aggregates on the workability of concrete. The comparison between specimens B1 and B2 with the control mix (CM) revealed a significant reduction in workability by 60% and 100%, respectively, when FCR aggregates and FA were introduced. A comparable trend was noted in specimens B3 and B4, with workability decreasing by 40% and 100%, respectively.

Moreover, 20% FA in concrete with FCR aggregates resulted in enhanced workability. For example, comparing specimens B1 (with 10% FA) and B3 (with 20% FA) showed a 33% improvement in workability, directly linked to the increased FA content. These findings suggest that while FCR aggregates negatively impact workability, the presence of higher FA proportions can mitigate these effects and enhance the concrete mix workability.

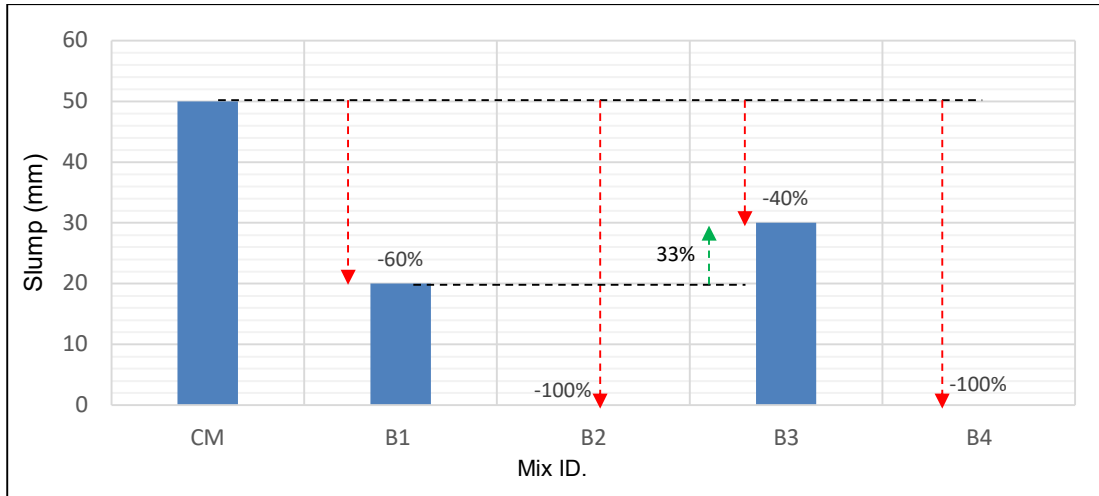


Figure 4.2: Slump test results for concrete mixes in stage B

In summary, this highlights that 20% FA can significantly improve the workability of concrete mixes containing 10% FCR aggregates, indicating that FA is pivotal in balancing the adverse effects of FCR on workability. These results highlighted the importance of optimising the binder and aggregate composition to achieve the desired workability in concrete mixes, particularly when using alternative materials such as FCR and FA.

4.1.3 Stage C – Slump Test Results

This section details the results of the slump test, which was conducted to assess how geopolymer binders affect the workability of concrete containing 10% and 20% FCR aggregates. As illustrated in Figure 4.3, all geopolymer concrete mixes, despite achieving the expected slump values, were observed to have a syrupy consistency compared to conventional concrete, as depicted by specimens C2, C6, and C0.

In addition, the slump values for the geopolymer concrete mixes with FCR aggregates met expectations, however, the viscous consistency (syrupy texture) of the geopolymer mixtures resulted from the incorporation of alkaline solutions into the concrete mix, adversely affected the workability of the geopolymer concrete, making it more difficult to handle and finish as concrete was sticky compared to traditional concrete mixes.

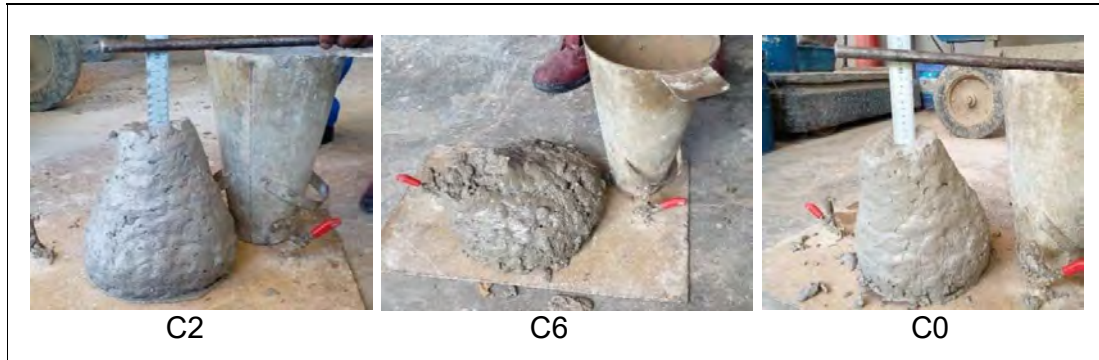


Figure 4.3: Concrete slump test pictures for stage C; C2, C6 and C0 mixes

Figure 4.4 illustrates the slump test results, offering key insights into how different proportions of FCR aggregates and various geopolymer binder compositions affect the workability of the concrete. The reference mix, C0, exhibited a slump of 120 mm, indicating baseline workability for the geopolymer concrete. In comparison, mixes C1 and C2, which included 10% and 20% FCR aggregates, respectively, showed slumps of 115 mm and 110 mm. This demonstrates a decrease in workability with increasing FCR content.

Further, mixes C3 and C4, which incorporated geopolymer binders with 40% FA and 60% GGBFS, experienced a more pronounced reduction in a slump, measuring 55 mm and 30 mm, respectively. This substantial decrease indicates a significant impact of the FCR aggregates and binder composition on the mix's workability.

In contrast, mix C5 and C6, which also used geopolymer binders but with a different formulation of 40% FA and 60% GGBFS, demonstrated improved workability with slumps of 185 mm and 160 mm, respectively. This indicates that incorporating both

FA and GGBFS in the binder formulation improves the workability of the mix, effectively counteracting the negative effects of FCR aggregate inclusion.

Lastly, the overall findings revealed that increased proportion of FCR aggregates from 10% to 20% led to a decreased slump values, indicating a declined workability. However, mixes with a binder composition of 40% FA and 60% GGBFS (C5 and C6) exhibited improved workability compared to other mixes, highlighting the positive impact of binder composition on the workability of geopolymer concrete.

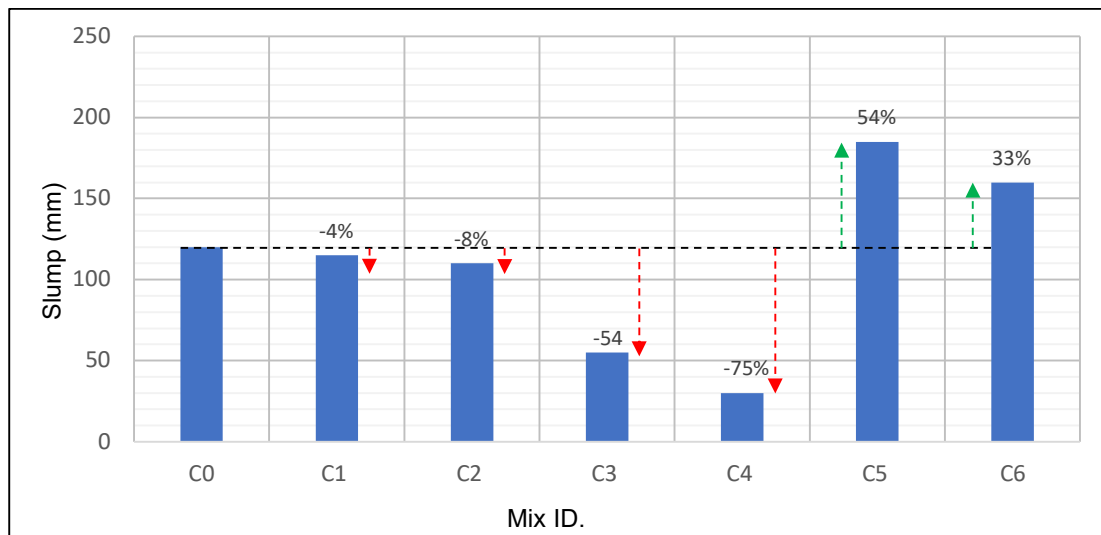


Figure 4.4: Slump test results of concrete mixes in stage C

4.1.4 Slump Test Results Discussion

The investigation into concrete workability across different stages (A, B, and C) offers important insights into the influence of varying proportions of fine crumb rubber (FCR) aggregates, fly ash (FA), and geopolymer binders on concrete mixes.

In Stage A, as illustrated in Figure 4.5, the introduction of 10% and 20% FCR aggregates led to a noticeable decrease in concrete workability. This observation aligns with Chylík *et al.* (2017) findings, who found that FCR aggregates have a higher specific surface area, which tends to trap more air and water molecules. This trapping effect decreases the overall concrete mix workability. Meherier (2016)

further supports this observation by noting that FCR aggregates can stiffen the mix, thus contributing to decreased workability.

In Stage B, as shown in Figure 4.5, the addition of FA improved concrete workability, as indicated by the green arrows. This enhancement is due to the FA fine particles, which help displace air within the binder paste and aggregate matrix. The increased volume of binder paste enhances the concrete's plasticity and cohesion. Marthong and Agrawal* (2012) emphasise that the fine particles of FA improve workability by reducing air voids and enhancing paste cohesion.

Stage C demonstrated a notable improvement in workability, as supported by the results shown in Figure 4.5. This enhancement is due to the use of geopolymer binders combined with the increased water content in the concrete mix. The benefits of using geopolymer binders are consistent with the findings of Marthong and Agrawal* (2012); Bala, Sehgal and Saini (2014); Porwal and Dwivedi (2016), who highlighted that FA's fine and spherical particles act similarly to ball bearings, reducing friction between aggregates and enhancing overall concrete consistency.

A comparative analysis across Stages A, B, and C reveals that Stage C exhibited superior workability. This improved workability can be attributed to the use of geopolymer binders and the inclusion of additional water, which were not present in Stages A and B. The enhanced workability in Stage C is a direct result of these factors, which contribute to a more workable and cohesive concrete mix.

Overall, the results underscore the significant role that FCR aggregates, FA, and geopolymer binders play in influencing the workability of concrete. The findings suggest that while FCR aggregates can negatively impact workability, FA and geopolymer binders improve concrete workability.

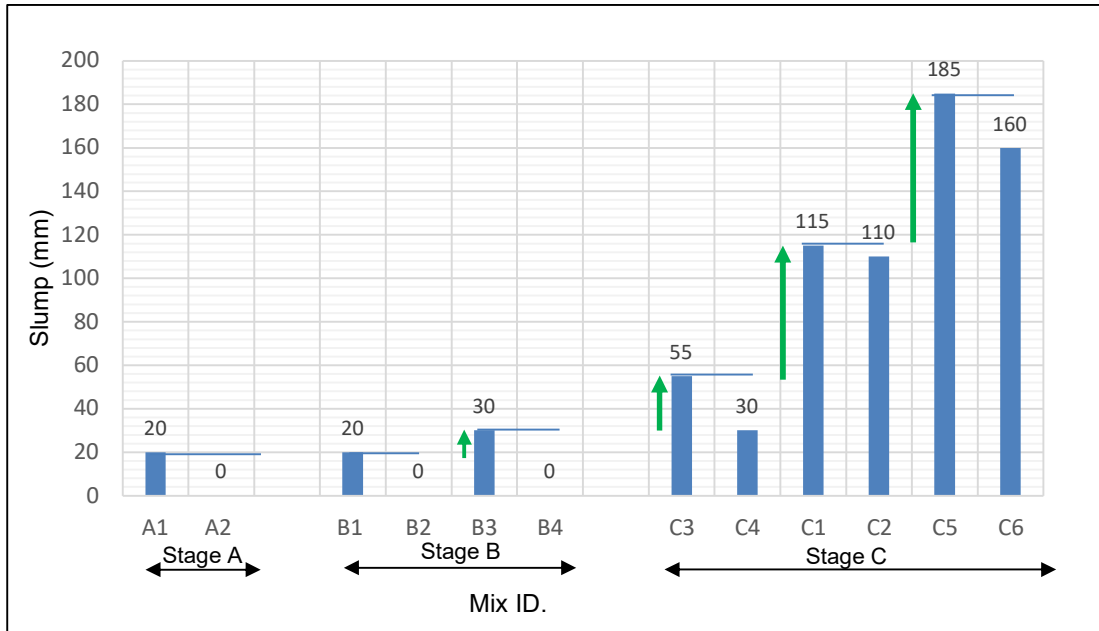


Figure 4.5: Slump test results for stages A, B and C

4.2 Concrete Mechanical Properties

The concrete mechanical characteristics were evaluated by measuring the maximum amount of compressive and tensile stresses that the concrete can withstand before failing, this measurement were carried out on the hardened specimens at 7 and 28-day intervals, as tabulated in *Appendix A, Tables A.5 and A.6*, respectively. The collected data was rigorously analysed to evaluate the impact of FCR aggregates, FA, and geopolymer binders on both conventional and rubberised concrete.

The results data evaluated in the subsequent section, provides a detailed account of how these variables impact the mechanical performance of both conventional and rubberised concrete

4.2.1 Stage A – Compressive Strength

This section explores the influence of substituting sand with FCR aggregates and PC with FA on concrete compressive strength. The impact was assessed by replacing sand with 10% and 20% FCR aggregates in specimens A1 and A2, respectively, and replacing PC with 10% and 20% FA in specimens A3 and A4,

respectively. Ultimately, to analyse the impact FCR and FA, specimens results for A1, A2, A3, and A4 were compared against the reference CM results.

- **Impact of FCR Aggregates on Compressive Strength of Conventional Concrete**

Substituting sand with 10% (A1) and 20% (A2) FCR aggregates, as depicted in Figure 4.6, led to significant reductions in both 7 and 28-day compressive strength. Specifically, A1 showed a 55% drop in average compressive strength compared to CM at 28-day, while A2 exhibited a more substantial 78% decrease. The increase to 20% FCR aggregates intensified the decline in compressive strength. Hence, the strength reduction indicates that 10% and 20% FCR aggregates adversely affect concrete strength development.

Several researchers, including, inter alia, Ganjian, Khorami and Maghsoudi (2009); El-Gammal *et al.* (2010); Boudaoud and Beddar (2012); Bravo and De Brito (2012); Dumne (2013) and Gupta, Chaudhary and Sharma (2014) have noted similar observations. They attribute this decline to the polar properties of FCR aggregates, which resist water and attract air, leading to voids that hinder the link between FCR aggregate surfaces and the cement matrix. Consequently, these voids promote crack propagation under compressive loads, ultimately causing failure of the specimens.

Additionally, the decrease in compressive strength may be linked to the non-uniform distribution of ingredients in the specimens due to the low specific gravity of FCR aggregates. During vibration, FCR aggregates migrate towards the surface, resulting in uneven stress distribution and crack propagation, further compromising concrete strength (Thomas and Gupta, 2016).

- **Impact of 10% And 20% FA on Compressive Strength of The Concrete**

Figure 4.6 demonstrates that substituting PC with 10% and 20% FA leads to a drop in concrete strength. Specifically, the drop in strength was more pronounced with the higher FA content. Comparative analysis reveals that the strength of concrete

with 10% FA (A3) and 20% FA (A4) decreased by 35% and 38%, respectively, compared to the conventional mix (CM).

The observed reduction in specimens A3 and A4 can be ascribed to the replacement of PC with FA. This decline is likely related to the tardy pozzolanic reaction caused by low alumina-silica content in FA, which typically activates only after hydration has generated calcium hydroxide (CH). Additionally, FA's higher carbon content, as indicated by the Loss on Ignition (LOI) found the used FA, may contribute to the strength reduction, as higher carbon content can negatively impact the bonding and strength development in the concrete mix (Anganoo, 2021).

In summary, the addition of FA or FCR aggregates into concrete formulations results in decreased compressive strength, underscoring their significant impact on concrete performance.

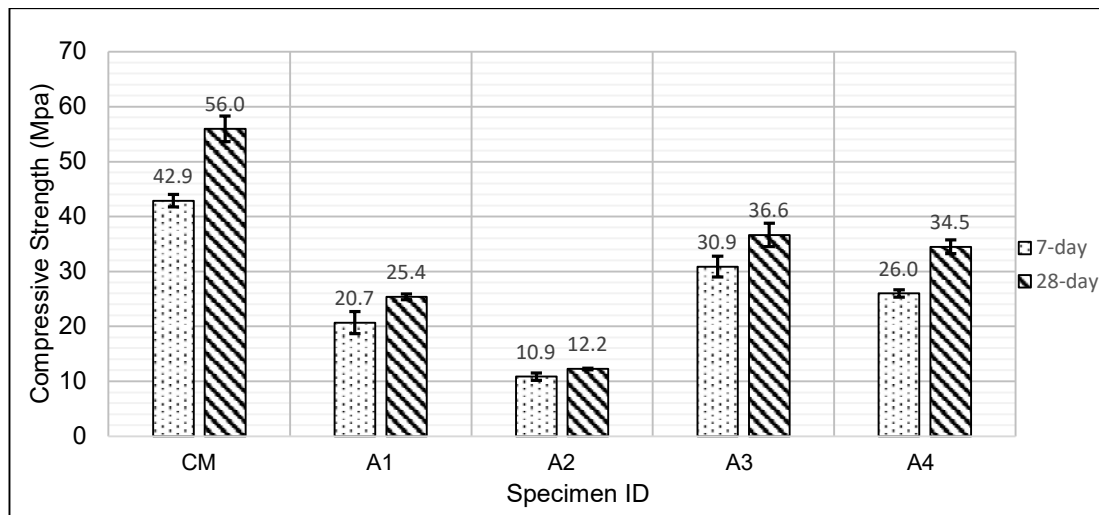


Figure 4.6: Stage A – 7 and 28-day average compressive strength results

4.2.2 Stage B – Compressive Strength

This section delves into the FA impact on the compressive strength of concrete containing FCR aggregates. PC was substituted with 10% and 20% FA, while sand was replaced with 10% and 20% FCR aggregates.

- **Impact of FA on Compressive Strength of Concrete Incorporating FCR Aggregates**

To investigate the FA influence on concrete containing FCR aggregates, the compressive strength results from stage A were compared with those from stage B. Figure 4.7 illustrates these comparisons for specimens incorporating 10% and 20% FA alongside 10% and 20% FCR aggregates.

In the case of specimens with 10% FA (B1) and 20% FA (B3) in concrete with 10% FCR aggregates, the compressive strengths were measured at 24.0 MPa and 21.8 MPa, respectively, representing decreases of 5.3% and 13.9% compared to the corresponding A1 and A2 results. These results indicate that including 10% and 20% FA reduced compressive strength in concrete with 10% FCR aggregates. Similarly, the effect of substituting PC with 10% FA (B2) and 20% FA (B4) in concrete containing 20% FCR aggregates was analysed and compared with A2. It was found that B2 exhibited an increase in compressive strength by 6.2%, whereas B4 showed a decrease of 5.2%.

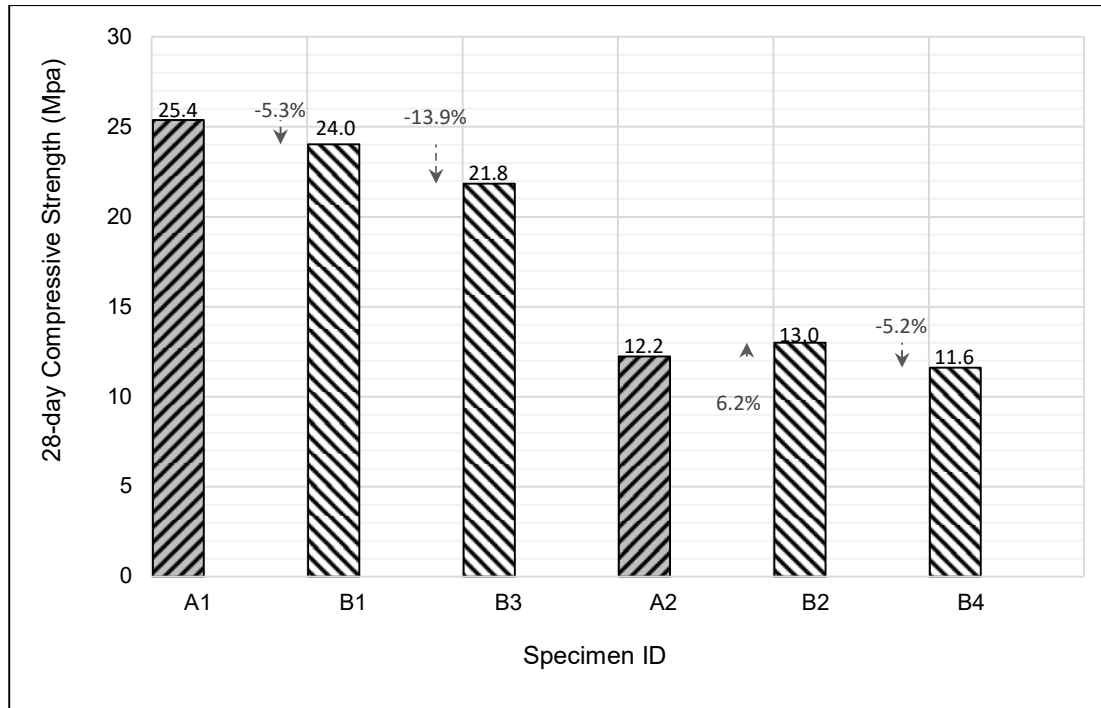


Figure 4.7: 28-day compressive strength comparisons for Stage A and Stage B

Overall, the findings indicate that the addition of 10% FA reduced the strength of concrete containing 10% FCR aggregates. This reduction in performance may be attributed to factors such as the loss on ignition (LOI) and potential delays in the pozzolanic reaction during hydration due to the low silica-alumina content (Thokchom, Dutta and Ghosh, 2011; Anganoo, 2021). However, when comparing samples B2 and B4 with A2, a slight improvement in strength was observed, with B2 (10% FCR + 20% FA) showing an increase of 1 MPa, while B4 exhibited no significant change. This suggests that the 20% FA improved the strength of concrete with 10% FCR aggregates, likely due to the high fineness of FA, which helped fill voids between the aggregates and binder matrix.

4.2.3 Stage C – Impact of Geopolymer Binders on Concrete Compressive Strength

This section evaluates the impact of different geopolymer binders—specifically FA, a blend of GGBFS and FA, as well as GGBFS combined with PC on the strength of concrete containing 10% and 20% FCR aggregates. The compressive strength data for all specimens (C1, C2, C3, C4, C5, and C6) were compared against samples A1 and A2.

- Impact of FA-Based Geopolymer Binder on Compressive Strength of Concrete**

As shown in Figure 4.8, specimen C0 attained a strength of 31Mpa, which is the concrete made of FA-based geopolymer binder. However, notably, the data suggests a negligible variance in compressive strength progression between the 7-day and 28-day periods. This marginal difference could be influenced by the temperature curing on geopolymer concrete, a phenomenon elucidated by (Hardjito, Cheak and Ing, 2008). Their research emphasises that higher curing temperatures accelerate the geopolymerisation reaction, leading to rapid strength development in concrete. Hence, this results in minimal additional strength gain beyond the 7-day testing period, a characteristic distinct from conventional concrete.

- **Impact of FA-Based Geopolymer Binder on Concrete Incorporating FCR Aggregates**

The results shown in Figure 4.8 indicate that replacing sand with 10% (C1) and 20% (C2) FCR aggregates resulted in a reduction in the 28-day compressive strength compared to the reference mix C0. The strength values for C1 and C2 were recorded as 27.7Mpa and 25.8Mpa, respectively. It is noteworthy to highlight a modest 2MPa reduction in strength between C1 and C2, corresponding to 10% and 20% replacement of sand with FCR aggregates, respectively.

This strength reduction contrasts sharply with the substantial decrease of 13.1MPa between A1 and A2. The discernible difference pertaining to FA-based geopolymer binder suggests that there is no noticeable alteration in the strength of concrete for both 10% and 20% FCR aggregate replacements. Hence, to some extent, the incorporation of FA-based geopolymer binder appears to impact the strength of concrete with FCR aggregates positively.

However, the FA used for this study contained less than 40% SiO₂, which is considered insufficient to attain the necessary Alumino-Silicate content crucial for effective interaction with the alkaline solution during the geopolymerisation process. This limitation was emphasised by Lăzărescu *et al.* (2017), who noted that a higher SiO₂ content positively influences the strength of the Si-O-Si chain, leading to a more robust material.

In contrast, Thokchom, Ghosh and Ghosh (2009) highlighted the beneficial impact of Na₂O on concrete strength development. However, this study diverges from their findings as the FA used lacked Na₂O and had a low SiO₂ content, ultimately restricting the strength development of C0, C1 and C2 specimens. The results underscore the importance of FA composition in geopolymer concrete, emphasising the need for FA with appropriate chemical constituents to ensure optimal strength development.

- **Impact of GGBFS+PC-Based Geopolymer Binder on Concrete Incorporating FCR Aggregates**

Figure 4.8 illustrates that the 28-day strength of C3 and C4 specimens demonstrated a noteworthy increase, measuring 50.4 MPa and 45.8 MPa, respectively, compared to C0, C1, and C2. A comparative analysis of the performance between C3 and A1, A2 and C4 highlighted that GGBFS and PC-based geopolymer concrete contributed to an enhanced compressive strength in concrete with FCR aggregates.

The observed improvement can be attributed to SiO_2 in GGBFS and a significant amount of calcium in PC. These components contributed significantly to facilitating the formation of geopolymeric gel and calcium-silicate hydrate (C-S-H), which are crucial in determining concrete strength over time, as purported by Neupane (2016). In addition, C3 and C4 obtained higher results than other specimens, which implies that the combination of GGBFS+PC has better performance than other combinations.

Like the trends in stages A and B, the compressive strength in stage C, except for C2 and C3, decreased as the proportion of FCR aggregates increased to 20%. This deviation in the pattern suggests the need for careful consideration and optimisation of FCR aggregate content to ensure the desired compressive strength outcomes in concrete formulations.

- **Impact of GGBFS+FA-Based Geopolymer Binder on Concrete Incorporating FCR Aggregates**

Figure 4.8 illustrates that C5 and C6 achieved 28-day strengths of 46.8 MPa and 35.5 MPa, respectively, surpassing those of A1 and A2. However, it is important to note that the strengths of C5 and C6 were lower than those of C3 and C4 due to the lower CaO content in C5 and C6. This relationship between SiO_2 and CaO in forming calcium-silicate hydrate was previously explained as a crucial factor in determining concrete strength. Similar to the trends observed in stages A, B, and C, excluding C1 and C2, compressive strength diminished as the FCR aggregate content increased from 10% to 20%, indicating a negative impact on compressive strength as the FCR aggregates proportion increased.

The results suggest a more significant increase in compressive strength after 7 days compared to C1 and C2. This strength increase could be attributed to the continued interaction between FA and GGBFS during the thermal curing of the specimens. Consequently, combining GGBFS and FA in a binary mixture demonstrated an enhanced strength growth rate compared to other binary mixtures examined in the study. Lastly, the rate of change in compressive strength between 10% replacement and 20% was higher than that of other specimens' results, possibly due to external factors affecting this specific specimen.

- **Summary**

Upon examining the findings illustrated in Figure 4.8, comparing A1 with C1, C3, C5 and A2 with C2, C3 and C6, it becomes evident that the alkali-activation of FA, GGBFS+FA, and GGBFS+PC resulted in notable enhancements in the compressive strength of concrete when contrasted with conventional concrete incorporating FCR aggregates. Consequently, it is reasonable to deduce that geopolymerisation outperforms conventional concrete in mitigating compressive strength reduction of concrete with FCR aggregates, highlighting its efficacy in bolstering concrete strength.

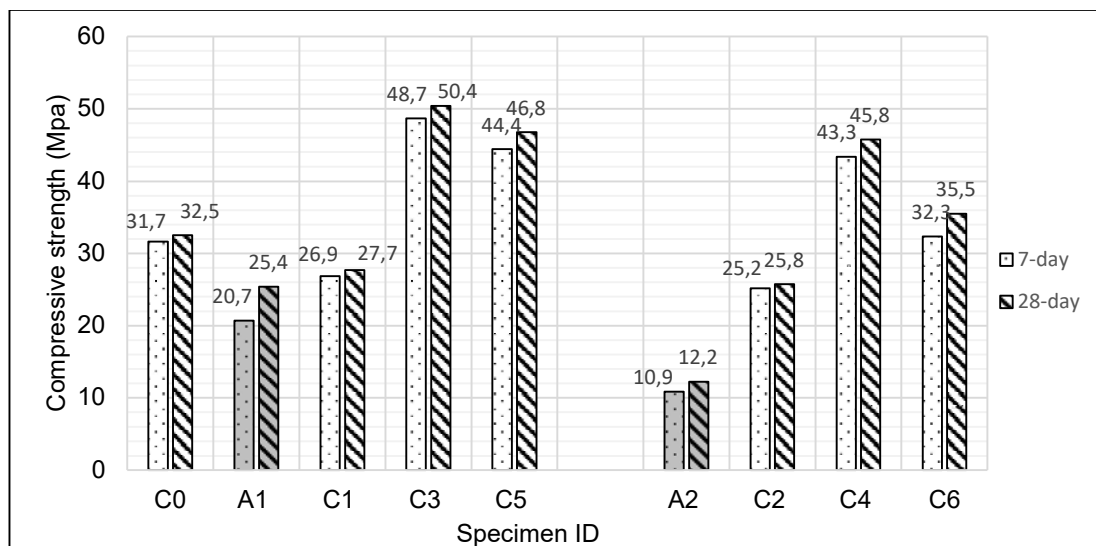


Figure 4.8: Stage C - 7 and 28-day average compressive strength results

4.2.4 Stage A – Splitting Tensile Strength

This section discusses the results related to how FCR aggregates and FA affect the splitting tensile strength of concrete. Specifically, 10% and 20% of the sand was replaced with FCR aggregates, and the PC was partially substituted with 10% and 20% FA.

- **Impact of 10% and 20% FCR Aggregates on Conventional Concrete**

The data displayed in Figure 4.9 indicates a decline in strength due to the substitution of sand with FCR aggregates. A comparison between the control mix (CM) and sample A1 shows that replacing 10% of the sand with FCR aggregates led to a reduction of 1.5 MPa in the 28-day strength. Increasing the FCR aggregate content to 20% resulted in a further decrease, with a 2.25 MPa reduction in strength after 28 days.

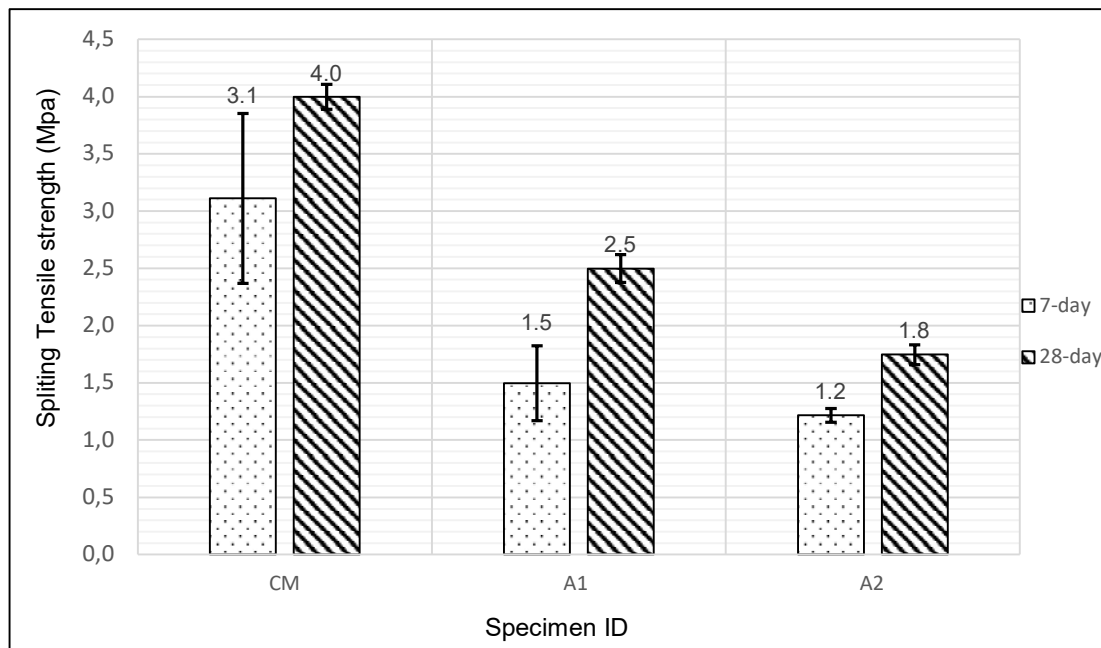


Figure 4.9: 7 and 28-day splitting tensile strength for CM, A1 and A2

This reduction in splitting tensile strength can be associated with poor bonding between the FCR aggregates and the cementitious matrix. FCR aggregates are known for their hydrophobic properties, which cause them to repel water and attract air, thereby weakening the bond with the binder and aggregate matrix. These

findings are consistent with earlier studies conducted by Adamu and Uche (2014) and Bala, Sehgal and Saini (2014), which reported similar impairments in bond integrity because of the hydrophobic properties of FCR aggregates.

In summary, the inclusion of FCR aggregates leads to a drop in the concrete strength, primarily due to inadequate bonding between the aggregates and the cementitious matrix, compounded by the hydrophobic characteristics of the FCR aggregates that disrupt the bond formation.

- **Impact of 10% And 20% FA on Conventional Concrete**

Figure 4.10 below shows a consistent drop in tensile strength as the partial substitution of PC with FA was introduced. Specifically, with a 10% substitution of PC by FA, the tensile strength exhibited a reduction of 1.0MPa. This decrease intensified when the substitution rate was increased to 20%, resulting in a strength reduction of 1.4MPa. This observed pattern aligns with the trends identified in the results of compressive strength, where the effect of FA on both tensile and compressive strengths is noticeable.

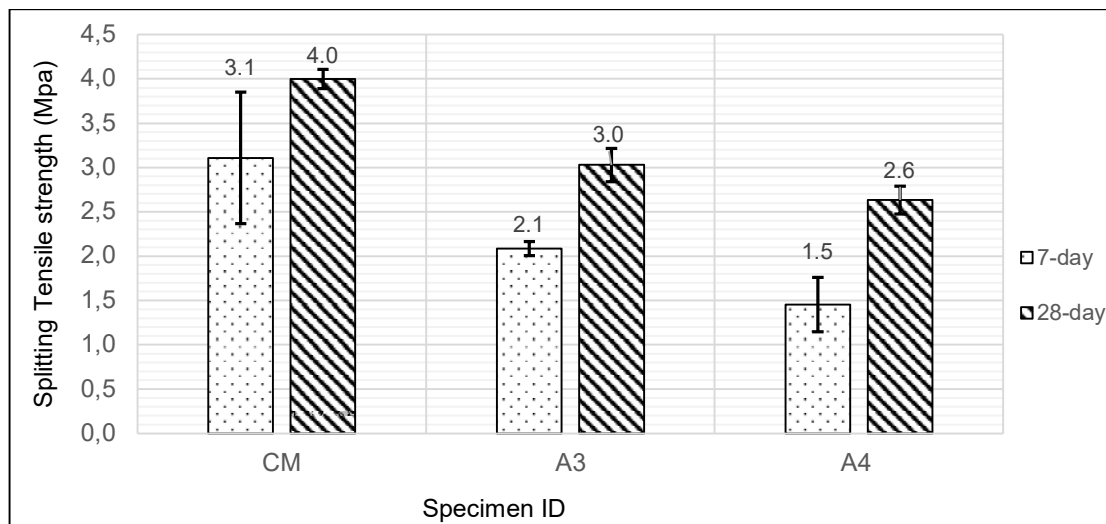


Figure 4.10: 7 and 28-day splitting tensile strength for CM, A3 and A4

The drop in strength, as discussed under the compressive strength section, can be linked to the particle size of FA, as it does not effectively enhance concrete density

or adequately fill the gaps within the binder and aggregate matrix. Additionally, the delayed hydration associated with FA contributes to a prolonged hydration process, further diminishing the overall strength development. The interplay of these factors underscores the intricate relationship between FA substitution and the mechanical properties of concrete.

4.2.5 Stage B – Splitting Tensile Strength

This section focuses on analysing how adding 10% and 20% FA affects the strength of concrete, which includes 10% and 20% FCR aggregates.

- **Impact of 10% And 20% FA on Concrete Incorporating FCR Aggregates**

As depicted in Figure 4.11, the splitting tensile strength of concrete incorporating FCR aggregates experienced a decline when 10% and 20% of PC was substituted with FA, particularly when compared to specimens A1 and A2. The splitting tensile strength exhibited no alteration as the FA percentage was elevated to 20%. For instance, the strength of the B1 specimen measured 1.84MPa and 2.20MPa at 7 and 28 days, respectively.

In addition, partially replacing PC with 20% FA in concrete that has 10% FCR aggregates (represented as B3) resulted in an unaltered splitting tensile strength, measuring 2MPa and 2.3MPa after 7 and 28 days, respectively. A matching trend was evident in the B2 and B4 samples, where FA content was increased to 20%, and the splitting tensile strength exhibited no change from 1.4 MPa (B2) to 1.4 MPa (B4).

In general, the incorporation of FA in concrete has consistently shown a diminishing impact on the strength of concrete with FCR aggregates. These discoveries are commensurate with the research of Porwal and Dwivedi (2016) and Reddy, Reddy and Krishnan (2017), which indicated a consistent pattern in the impact of FA on splitting tensile strength. Analogous to compressive strength, the reduction in splitting tensile strength reduction can be ascribed to the interplay of particle size and chemical composition of the FA employed in the concrete mixture.

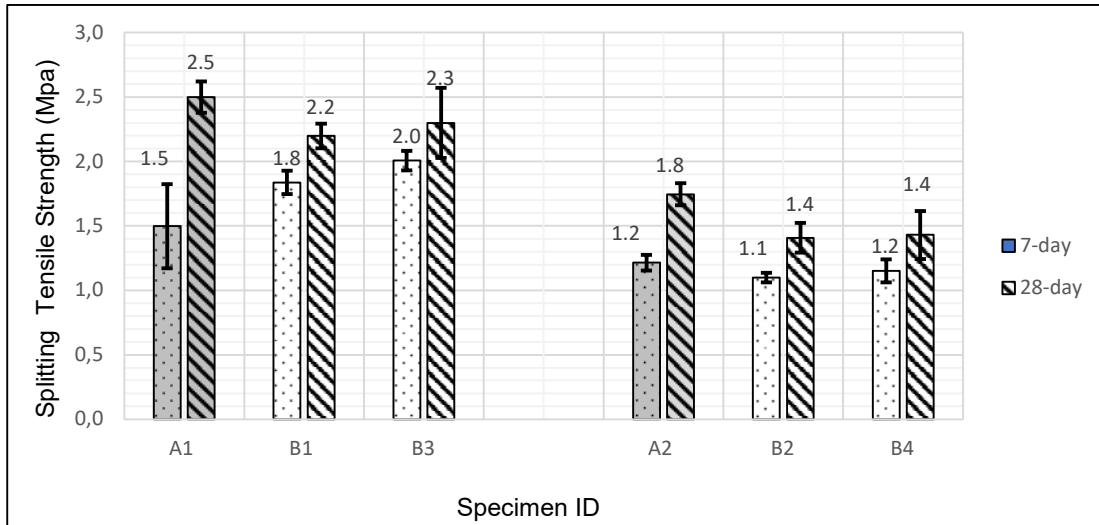


Figure 4.11: Stage B – 7 and 28-day splitting Tensile strength results

4.2.6 Stage C – Splitting Tensile Strength

The bond strength between the binder and aggregates plays a crucial role in determining the splitting tensile strength of concrete. This section explores how different geopolymer binders affect the splitting tensile strength of concrete containing FCR aggregates. The results were assessed in relation to the control mix samples labelled as C0

- **Impact of FA-Based Geopolymer Binder on Concrete Incorporating FCR Aggregates**

An analysis of the results, as shown in Figure 4.12, reveals a modest increase in the splitting tensile strength for specimens C1 and C2 in comparison to A1 and A2, respectively. Specifically, the 28-day strength of C1 increased by 0.5 MPa. Also, the results of concrete incorporating 20% FCR aggregate (C2) exhibited an increase of 0.2 MPa. Notably, a marginal 1.0 MPa difference in splitting tensile strength between the 7 and 28-day periods was observed for both C1 and C2 specimens.

This marginal difference could also be related to effects, as highlighted in section 4.2.3 It is essential to draw a parallel with the discussion on the impact of FA-based geopolymer binder on the compressive strength of concrete containing FCR aggregates. The findings across these analyses collectively underscore the

nuanced influence of FA on various mechanical characteristics, emphasising the importance of detailed consideration of specific properties of the FA in use for optimal performance in geopolymer concrete formulations.

- **Impact of GGBFS+PC-Based Geopolymer Binder on Concrete Incorporating FCR Aggregates**

As depicted in Figure 4.12 below, specimens C3 and C4 exhibited superior splitting tensile strength compared to specimens A1 and A2, with increments of 28-day strength results of 2.1MPa and 2.2MPa, respectively. Notably, the disparity in strength alteration between the 7-day and 28-day periods was more pronounced for C3 and C4 when contrasted with C1 and C2. Consequently, the geopolymer composed of GGBFS and PC led to a significant enhancement in the strength of concrete containing FCR aggregates.

The improvement was attributed to the interaction dynamics between PC and GGBFS within the first 24 hours of the heat curing period, followed by the ongoing cement hydration. Comparable findings observed in studies by Neupane (2016) and Park et al. (2015) support this rationale by attributing the alterations to the presence of calcium, which accelerates the geopolymerisation process, resulting in the formation of geopolymeric gel and calcium-silicate hydrate (C-S-H).

- **Impact of GGBFS+FA Based Geopolymer Binder on Concrete Incorporating FCR Aggregates**

As evidenced by the data displayed in Figure 4.12, it is apparent that the strength values for C5 and C6 surpassed those of A1 and A2, respectively. While A1 exhibited a strength of 2.5 MPa at 28 days, C5 exhibited 4.3Mpa, and A2 exhibited 1.7Mpa, while C6 recorded values of 3.7MPa. As a result, the GGBFS+FA-based geopolymer binder showcased a considerable improvement in the strength of concrete containing FCR aggregates.

As detailed in section 2.7.1, the presence of SiO_2 and Al_2O_3 in GGBFS initiates a reaction with alkaline solutions, forming a geopolymer Si-O-Al-O bond. This bond is pivotal in bolstering the connectivity between aggregate surfaces and the paste matrix. However, it is noteworthy that, compared to C3 and C4, the recorded

strength for C5 and C6 is somewhat lower. This discrepancy could be attributed to the absence of calcium, which also contributes to strength development, as discussed in the preceding section. These results parallel the observations made in the context of compressive strength results.

- **Summary**

Upon reviewing the data presented in Figure 4.12, it is evident that alkali-activation of GGBFS+FA and GGBFS+PC led to improvements in the splitting tensile strength of the concrete vis-a-vis conventional concrete formulations with FCR aggregates (A1 and A2). These observations suggest that alkali activation enhances the interface strength between the binder matrix and aggregates. A comparable pattern was noted in the compressive strength.

However, when considering FAs geopolymer binder, the maximum split stress of conventional and geopolymer concrete incorporating FCR aggregates remained nearly unchanged. These results indicate that FA's alkali activation did not significantly impact splitting tensile strength in this scenario. Overall, these findings underscore the potential of alkali activation to improve concrete performance, particularly in terms of bond strength. However, the effects may vary depending on the materials and conditions involved.

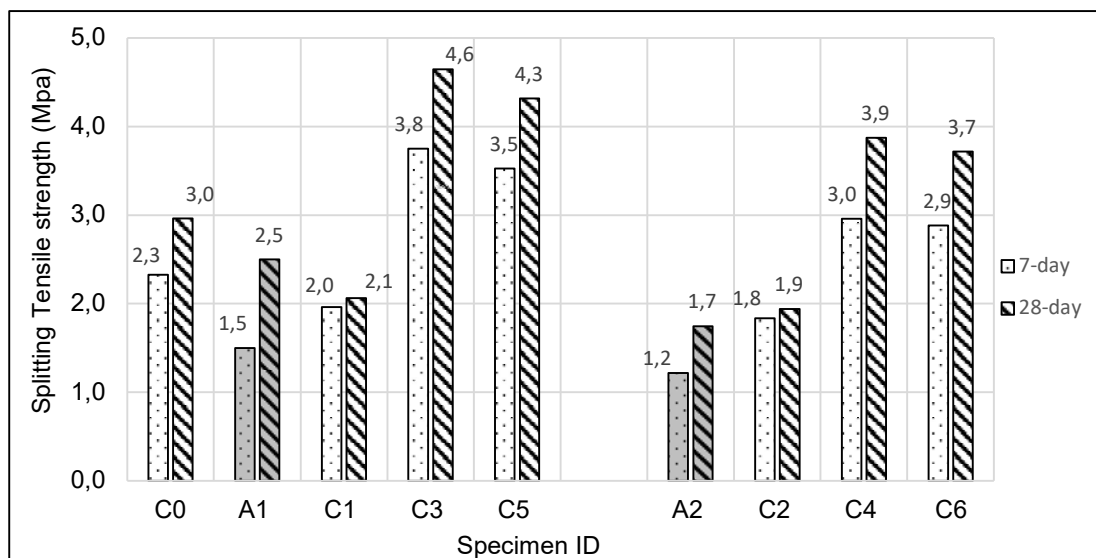


Figure 4.12: Stage C - 7 and 28-day Splitting tensile Strength results

4.3 Concrete Durability Properties

This section outlines the findings from the data analysis, followed by a discussion on the impact of fly ash (FA) and geopolymer binders on the durability characteristics of concrete incorporating 10% and 20% FCR aggregates. FA, a combination of FA with GGBFS and PC were employed as geopolymer binders (*see Appendix A, Table A.8*). The findings were deliberated and examined utilising the index values range recommended by Alexander, Mackechnie and Ballim (1999), as presented in Table 3.6 of section 3.11. Additionally, the porosity analysis was conducted using sorptivity and the porosity classification table proposed by Moore, Bakera and Alexander, (2021), displayed in Table 3.7 of section 3.11.

4.3.1 Stage A – Impact of FCR Aggregates and FA on Oxygen Permeability of Conventional Concrete

The results from Figure 4.13 show that adding FA and FCR aggregates had a notable impact on the concrete specimens' oxygen permeability index (OPI). The specimens with 10% and 20% FCR aggregate replacements (A1 and A2) exhibited a decrease in OPI of 0.3 and 0.8, respectively, in comparison to the control mix (CM). Similarly, the specimens with 10% and 20% FA replacements (A3 and A4) showed a decrease in OPI of 0.3 and 0.7, respectively.

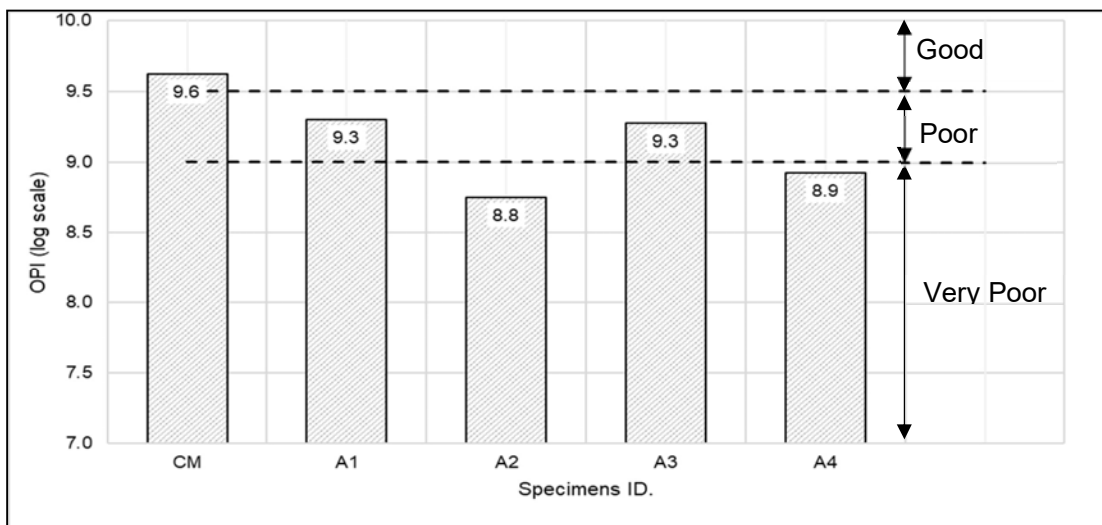


Figure 4.13: Oxygen permeability index results for Stage A

Regarding OPI classification, according to the scale proposed by Alexander et al. (2001), the CM achieved good results, while A1 and A2 yielded poor and very poor results, respectively. The findings show a corresponding increment in the rate of oxygen ingress with added FA and FCR aggregates in conventional concrete. The decrease in OPI observed in the FCR aggregate specimens was attributed to the lack of cohesion between the cement paste and FCR aggregates, which is linked to the polar characteristics of FCR aggregates. This characteristic causes water repulsion and air attraction, increasing oxygen ingress through the concrete pores (Bjegović, Baričević and Serdar, 2011). The same results were also presented by Gesoğlu and Güneyisi (2011) and Azevedo *et al.* (2012).

Substituting PC with FA resulted in a drop in the concrete's oxygen permeability index (OPI). This decrease suggests that adding FA did not positively impact conventional concrete, as the OPI continued to decline when the content of FA was increased up to 20%. This decline in OPI is attributable to the low FA silica content utilised in the investigation, which was below 40%. This pattern of findings is in line with previous research works by Azevedo *et al.* (2012) and Zulu (2017), which demonstrated that incorporating FA with a high silica concentration can enhance the oxygen permeability index of conventional concrete.

These studies also indicate that fly ash with elevated silica levels can improve concrete microstructure, reducing pore connectivity and enhancing oxygen permeation resistance. In contrast, the low silica content in the FA utilised in this study most likely limited its ability to improve the OPI of the concrete. This observation highlights the importance of considering the silica content when selecting fly ash for concrete mixtures.

4.3.2 Stage B – Impact of FA on Oxygen Permeability of Concrete Incorporating FCR Aggregates

This section thoroughly investigates the effect of 10% and 20% FA OPI of concrete containing 10% and 20% FCR aggregates. By comparing the results of stages A (A1 & A2) and B, the aim is to discern the influence of FA on concrete with FCR aggregates. As illustrated in Figure 4.14 below, a comparison between concrete specimens A1 (containing 10% FCR aggregates) and B1 (containing 10% FCR

aggregates and 10% FA) reveals that the OPI remained unchanged at 9.3. Meanwhile, concrete specimen B2, incorporating 20% FCR aggregates and 10% FA, showed a minor increase of 0.1 in OPI relative to A2.

Moreover, increasing the FA content from 10% to 20% in concrete with 10% FCR aggregates (B3) led to a reduction of 0.1 in OPI compared to A2. Similarly, in concrete with 20% FA and 20% FCR aggregates (B4) compared to A2, a decrease of 0.1 in OPI was observed, in accordance with the scale proposed by Alexander et al. (2001), specimens B1 and B3 exhibited poor OPI results while B2 and B4 demonstrated very poor OPI results.

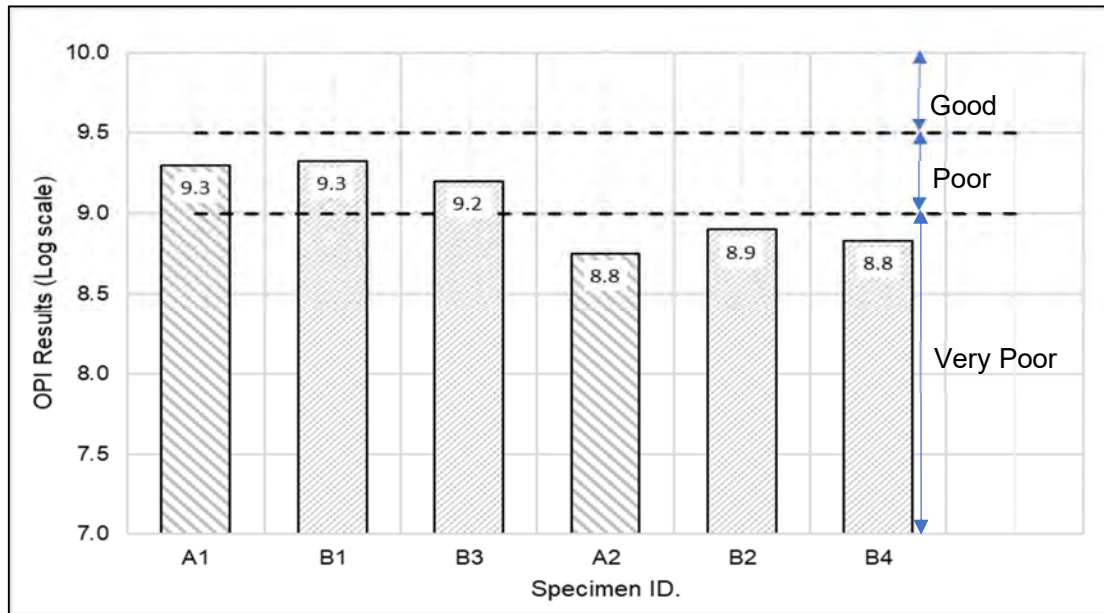


Figure 4.14: Oxygen permeability index for stage A and Stage B

In contrast to the previous section, where the OPI of conventional concrete declined with the addition of FA, adding FA to concrete with FCR aggregates resulted in OPI values remaining almost unchanged with no significant variation. This consistent behaviour can likely be attributed to the low silica content in FA, as explained in the preceding section.

These results suggest that FA did not notably affect the OPI of the concrete incorporating FCR aggregates. The OPI remained relatively stable, indicating

consistent oxygen ingress rates across all stage B specimens compared to stage A. This observation underscores the need for further investigation into the interplay between FA, FCR aggregates, and concrete properties to optimise the concrete mixture behaviour in various applications.

4.3.3 Stage C – Impact of Geopolymer Binders on Oxygen Permeability of Concrete Incorporating FCR Aggregates

In this study section, the investigation delved into the effects of geopolymer binders on concrete incorporating FCR aggregates, with a detailed comparison between the results obtained at stage C and those observed during stage A (A1 & A2). The examination centred on assessing the oxygen permeability through the concrete specimens, a key factor reflective of durability and long-term performance.

The data presented in Figure 4.15 unveiled a peculiar observation: the absence of Oxygen Permeability Index (OPI) results for the C0 samples, signifying a complete lack of readings. This anomaly raised concerns as it hinted towards exceptionally high permeability within these specimens, an unexpected occurrence given the presence of measurable OPI values for the subsequent samples, C1 and C2. Such an anomaly may be ascribed to the development of continuous interlinked cracks within the specimens, likely induced by the rapid water loss during the 24-hour oven heat-curing process.

Despite the unavailability of results for C0, both C1 and C2 exhibited notably poor OPI outcomes, a trend that persisted throughout the subsequent samples, including C3, C4, C5, and C6. Intriguingly, the introduction of FA, PC+GGBFS and FA+GGBFS geopolymer binders demonstrated a notable improvement in OPI ratings. For instance, the OPI increased to 8.8 for C3 and 8.9 for C4 with PC-GGBFS, while with FA-GGBFS, the OPI surged to 9.2 for C5 and 9.3 for C6, indicating a significant enhancement from very poor to poor OPI ratings.

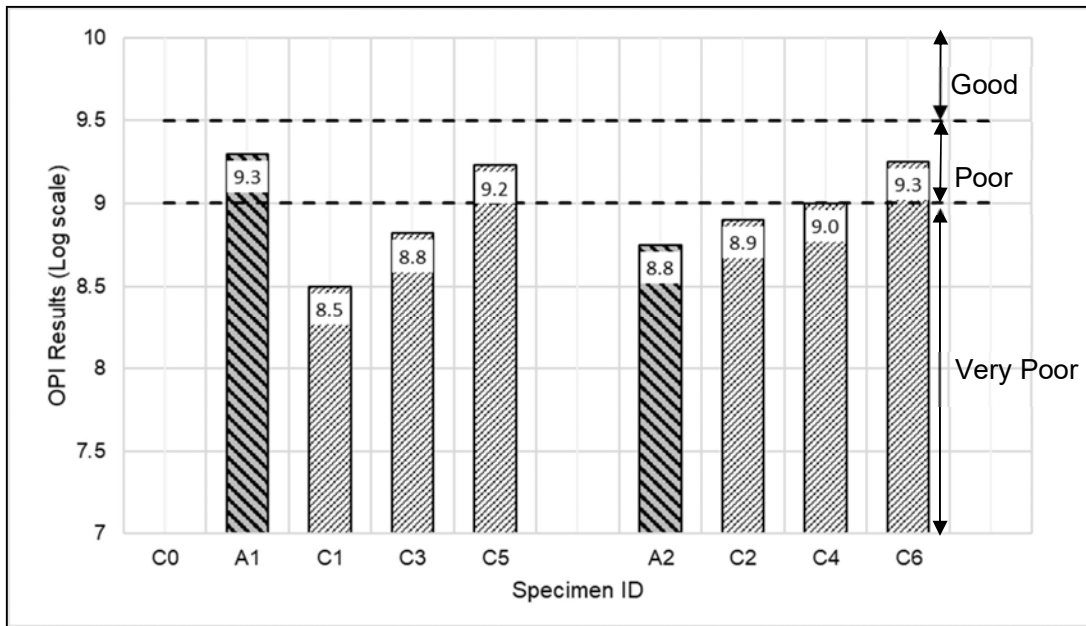


Figure 4.15: Oxygen permeability index results for stage C specimens

These compelling findings suggest that geopolymer binders, particularly when incorporating FA-GGBFS and PC-GGBFS blends, outshine the performance of concrete formulations solely reliant on FA. This enhancement results in a notable reduction in oxygen permeability through the concrete specimens, a critical factor in ensuring long-term Resilience and protection from environmental impacts.

In summary, the comparison of OPI results among A1, A2, and stage C reveals that the addition of geopolymer binders did not lead to improvements in reducing oxygen permeability in concrete specimens containing 10% FCR aggregates (C1, C3, & C5) compared to conventional concrete with 10% FCR aggregates (A1). However, in the case of concrete with 20% FCR aggregates (A2) compared to C2, C4, and C6, there was an improvement in oxygen permeability. This improvement could be traced to the higher concentration of FCR aggregates, which are non-absorbent to oxygen, and some pozzolanic reaction, thus improving oxygen ingress through concrete specimens.

Lastly, C5 and C6 were observed to have yielded better results as compared to other specimens, which are related to the chemical composition of binders using silica, Na₂O and calcium, which have different impacts on concrete, as discussed in

preceding sections. These results underscore the complexity and variability of factors influencing concrete durability and performance.

4.3.4 Stage A - Impact of FCR Aggregates and FA on Water Sorptivity and Porosity of Conventional Concrete

As delineated in Figure 4.16, a significant decrease in the water absorption rate was noted when comparing it to the control mix (CM) with concrete compositions containing 10% (A1) and 20% (A2) FCR aggregates, showcasing reductions of 55% and 77%, respectively. This compelling data underscores that substituting sand with FCR aggregates led to substantial mitigation in water ingress through the concrete specimens, achieving an excellent rating according to the sorptivity classification by Moore, Bakera and Alexander (2021).

The diminished sorptivity in A1 and A2 can be ascribed to the polar characteristics of FCR aggregates, which naturally repel water and trap air within their structure. Additionally, FCR aggregates exhibit non-water absorbent properties, contributing to a significant reduction in the water absorption rate, along with a decrease in water sorptivity (Bjegović, Baričević and Serdar, 2011). These findings underscore FCR aggregates' effectiveness in curtailing the water absorption rate through concrete specimens.

Conversely, substituting PC with 10% (A3) and 20% (A4) FA resulted in an escalation in water sorptivity by 7.8% and 21%, respectively. Nevertheless, the specimens still achieved a good rating as per the classification by Moore, Bakera and Alexander (2021), indicating that FA led to an increased rate of water ingress through the specimens. The heightened sorptivity associated with incorporating FA can be due to the sluggish pozzolanic reaction owing to the limited content of silica available for reaction with lime, impeding the development of durable calcium silicate hydrate.

This compound is essential for improving the pore structure of concrete by filling the voids within the material. Zulu (2017) observed that a reduction in sorptivity was attributed to the pozzolanic reaction between lime and silica, which contributed to

refining the microstructure of concrete's pores, filling its capillaries and consequently decreasing concrete sorptivity. However, it is important to point out that the FA utilised in Zulu's study boasted a significantly higher silica content of 53.19% compared to the 35% silica content found in the FA employed in this study, which may elucidate the disparate outcomes observed.

In conclusion, the outcomes depicted in Figure 4.16 highlight the significant influence of both FCR aggregates and FA on the sorptivity of concrete specimens. While FCR aggregates demonstrated remarkable efficacy in reducing water ingress through the specimens due to their inherent characteristics, FA exhibited a contrasting effect by increasing water sorptivity owing to the limitations in silica content available for the pozzolanic reaction.

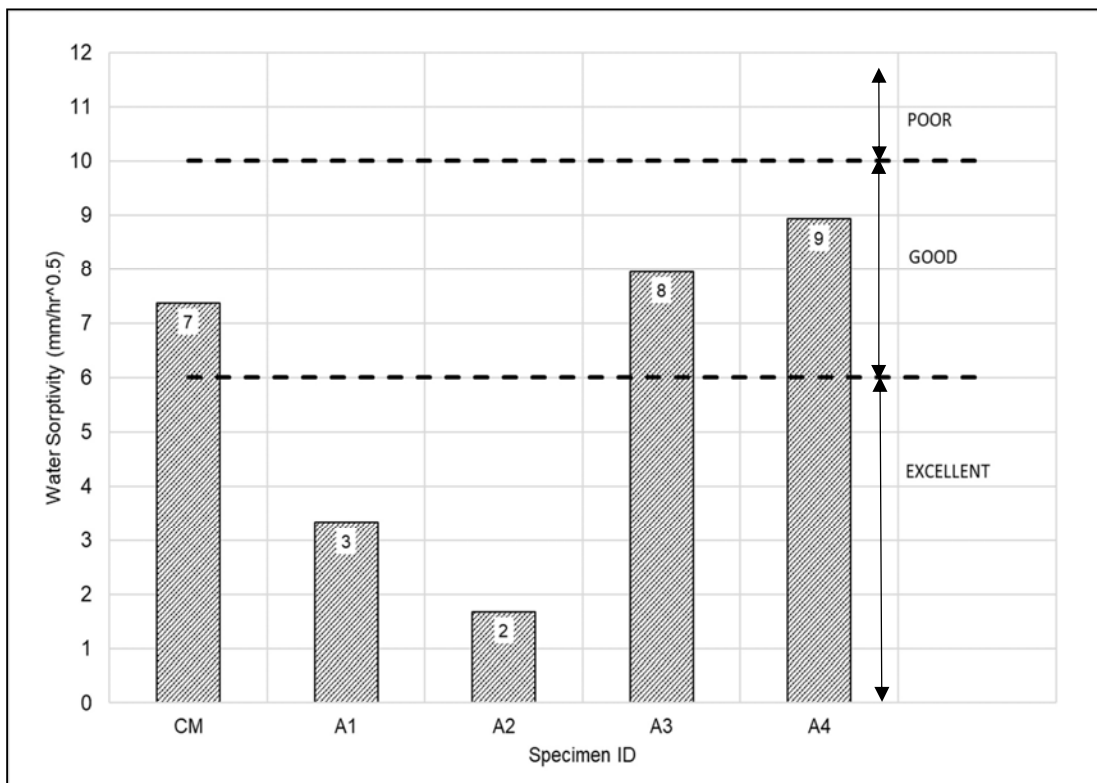


Figure 4.16: Water sorptivity results for stage A

Furthermore, based on the findings presented in Figure 4.17, incorporating FCR aggregates increased the porosity of the concrete structure. Specifically, adding 10% (A1) and 20% (A2) FCR aggregates led to 30% and 66% porosity increases,

respectively. According to the classification by Moore, Bakera and Alexander (2021), both A1 and A2 exhibited very poor porosity ratings. This increase in porosity can be attributed to the lack of adhesion between the FCR aggregate and the paste matrix, resulting in higher voids in the concrete structure. Similar patterns were observed by Adamu and Uche (2014); Huda (2014); Thomas *et al.* (2014) and Thomas and Gupta (2015).

In contrast, the incorporation of 10% FA (A3) resulted in an 8% reduction in porosity. Increasing the FA content to 20% (A4) resulted in a 45% rise in porosity. This increase in porosity with 20% FA content could be due to a higher proportion of FA particles remaining unreacted, possibly due to deficient silica content in the FA used. However, CM and A3 exhibited good porosity, while the other samples maintained poor to very poor results in porosity.

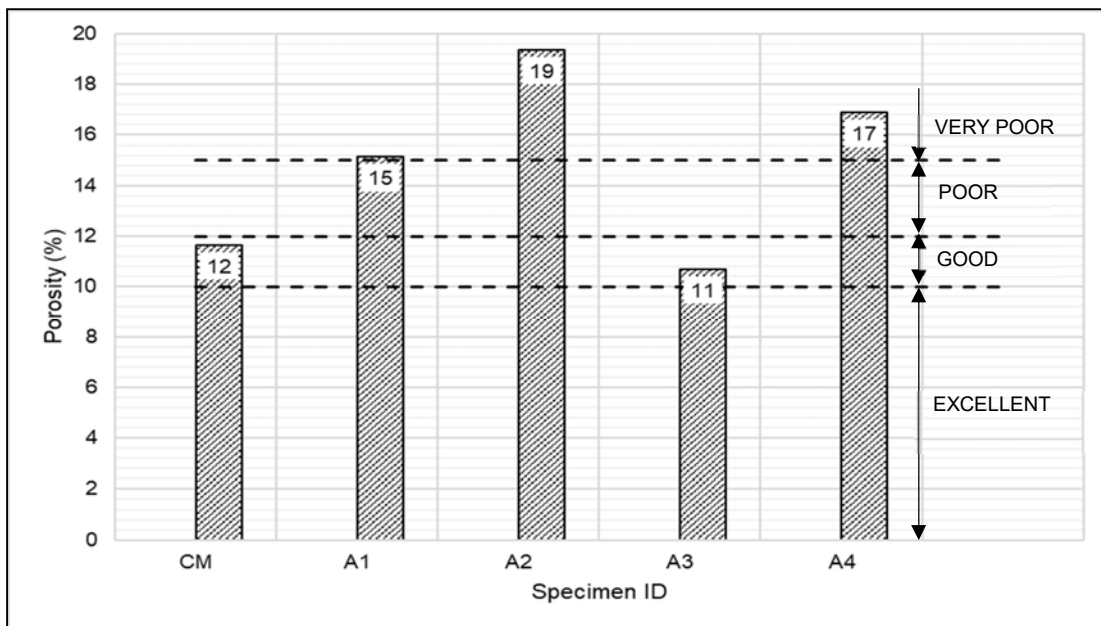


Figure 4.17: Stage A effective porosity results

The interlink between water sorptivity and porosity is evident, where materials with higher porosity tend to have higher water sorptivity. This is because there are more pathways for water to penetrate. Conversely, materials with lower porosity have fewer void spaces and lower water sorptivity. However, it is interesting to note that A1 and A2 exhibited low water sorptivity despite having higher porosity.

This behaviour is associated with the non-water absorbent physical properties of FCR aggregates, their polar behaviour attracting air and repelling water, or the connectivity of pores in the concrete structure. When pores are connected, the pathway for water is easier than when they are unconnected, leading to these results. On the other hand, CM, A3, and A4 exhibited high porosity and high sorptivity, which aligns with expectations. The results suggest that FA increased the volume of pores in the concrete structure, leading to increased water absorption. In contrast, FCR aggregates increased the volume of pores but reduced water sorptivity.

4.3.5 Stage B - Impact of FA on Water Sorptivity and Porosity of Concrete Incorporating FCR Aggregates

The preceding section examined the effects of FCR aggregates and FA on water sorptivity and porosity. Thus, it is imperative to delve deeper into how FA influences concrete's porosity and water sorptivity by incorporating FCR aggregates.

As illustrated in Figure 4.18, adding 10% FA to concrete with 10% FCR aggregates (B1) led to a slight increase in sorptivity by 3%. In contrast, in concrete with 10% FA and 20% FCR aggregates (B3), sorptivity showed a significant increase of 28.6% compared to A1. Similarly, an increment in FA content to 20% resulted in higher sorptivity for both concrete specimens containing 10% (B2) and 20% (B4) FCR aggregates compared to A2.

This outcome is not surprising as FA exhibited increased porosity and water sorptivity in conventional concrete, which aligns with its effects on concrete incorporating FCR aggregates. Despite the detrimental effect of FA on the water sorptivity of concrete, the water absorption for the specimens still achieved an excellent rating according to the classification by (Moore, Bakera and Alexander, 2021).

In conclusion, FA does not appear to improve the water absorption rate in concrete incorporating FCR aggregates. Instead, it may increase water sorptivity, particularly at higher FA contents and with higher FCR aggregate proportions.

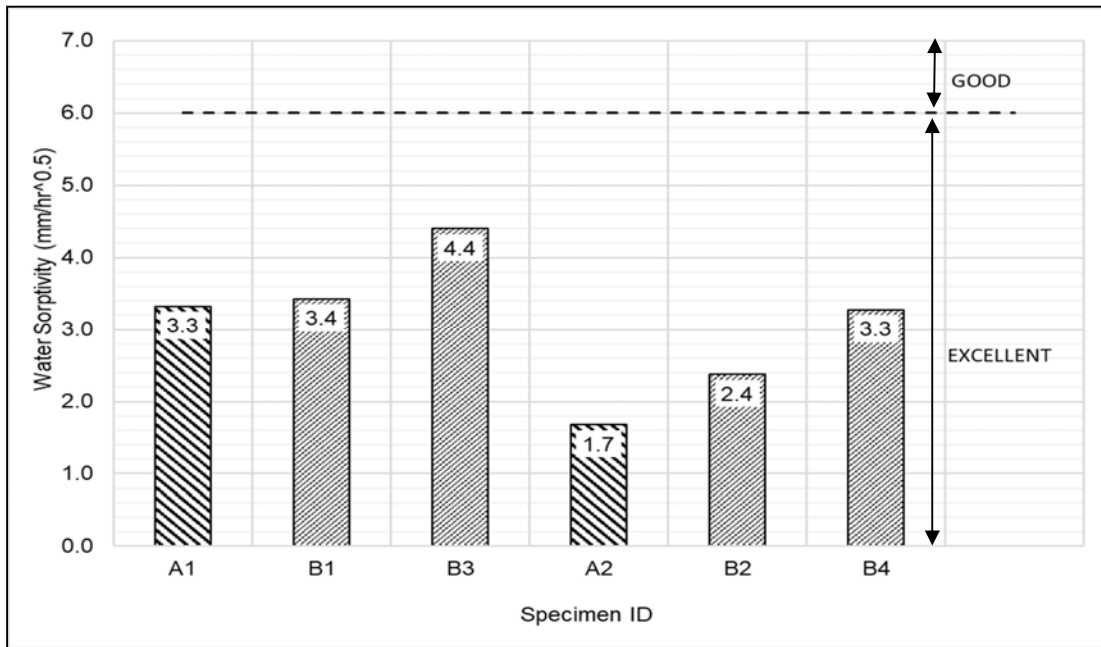


Figure 4.18: Stage A and B water Sorptivity results

As illustrated in Figure 4.19, the porosity of concrete specimens with 10% FA and 10% FCR aggregates (B1) decreased by 7%, whereas in specimens with 10% FA and 20% FCR aggregates (B3), porosity increased by 27% compared to concrete with 10% FCR aggregates (A1).

In contrast, the porosity of concrete specimens with 20% FCR aggregates decreased by including 10% FA (B2) compared to A1. Similarly, with an increase of FA to 20% in concrete with 20% FCR aggregates (B4), the porosity decreased further compared to A2. The results suggest that while 10% FA had no impact on the porosity of concrete with 10% FCR aggregates, 20% FA positively impacted concrete with 20% FCR aggregates.

Compared to the water sorptivity results, the water absorption for B1 and B3 increased with increased porosity, which is generally expected. However, for B2 and B4, opposite results were observed as the water absorption increased with decreased porosity. These observations could be tied to the packaging of

aggregates and binder particles in concrete, which may have improved the pore structure of the concrete.

Despite the improvements brought about by adding FA, the porosity of concrete incorporating FCR aggregates remains a significant concern, with a substantial 90% of the concrete specimens categorised as having very poor results, indicating a high porosity level.

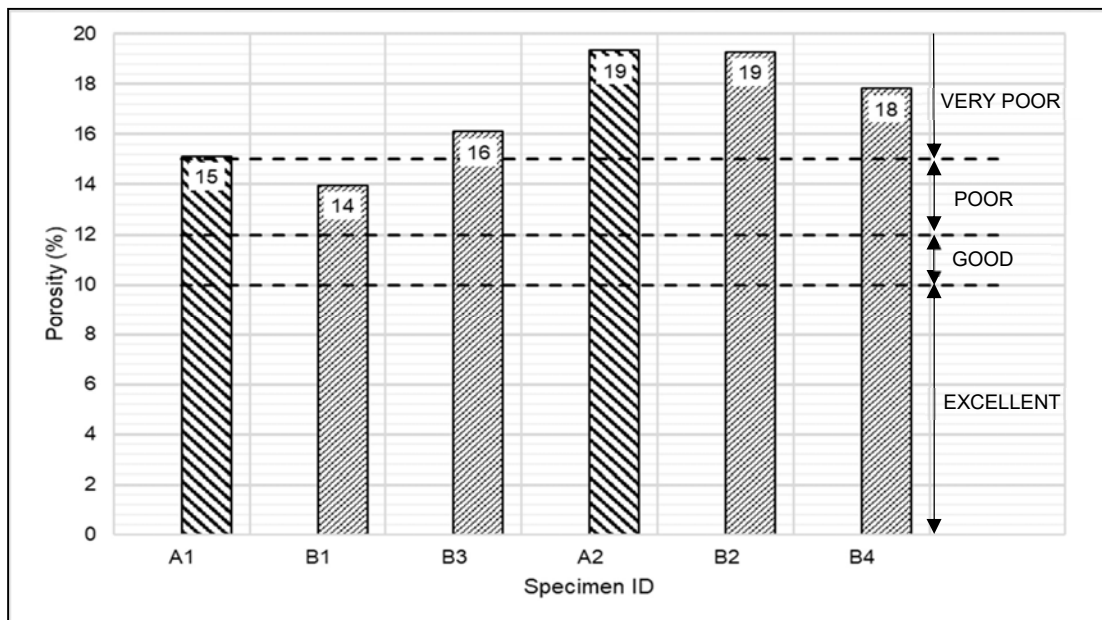


Figure 4.19: Stage A and B effective porosity results

4.3.6 Stage C – Impact of Geopolymer Binders on Water Sorptivity and Porosity of Concrete Incorporating FCR Aggregates

This section further discusses the impact of FA, PC+GGBFS and FA+GGBFS-based geopolymer binders on concrete incorporating FCR aggregates. Figure 4.20 indicates that the water absorption rate for C0 is higher compared to the other specimens at this stage. These results are consistent with the OPI findings discussed in the OPI section, as there was no reading, which implied that the specimen was porous.

However, adopting the same FA-based geopolymer binder on concrete incorporating 10% (C1) and 20% (C2) of FCR aggregates, the water absorption rate

decreased from 11.27 to 6.5 and 6.4, respectively. Comparing the A1 and A2 with C1 and C2, with the use of FA-based geopolymer binder, water sorptivity increased for both specimens and went from excellent to good as per Moore, Bakera and Alexander (2021) classification.

A similar pattern was also observed with FA+GGBFS (C5 and C6) and PC+GGBFS (C3 and C4) based geopolymer binders, however, they remained excellent in water absorption classification. This observation implies that the said binders' alkali activation increases the water absorption rate of concrete incorporating FCR aggregates, which could be attributed to high heat curing, as discussed in the OPI section.

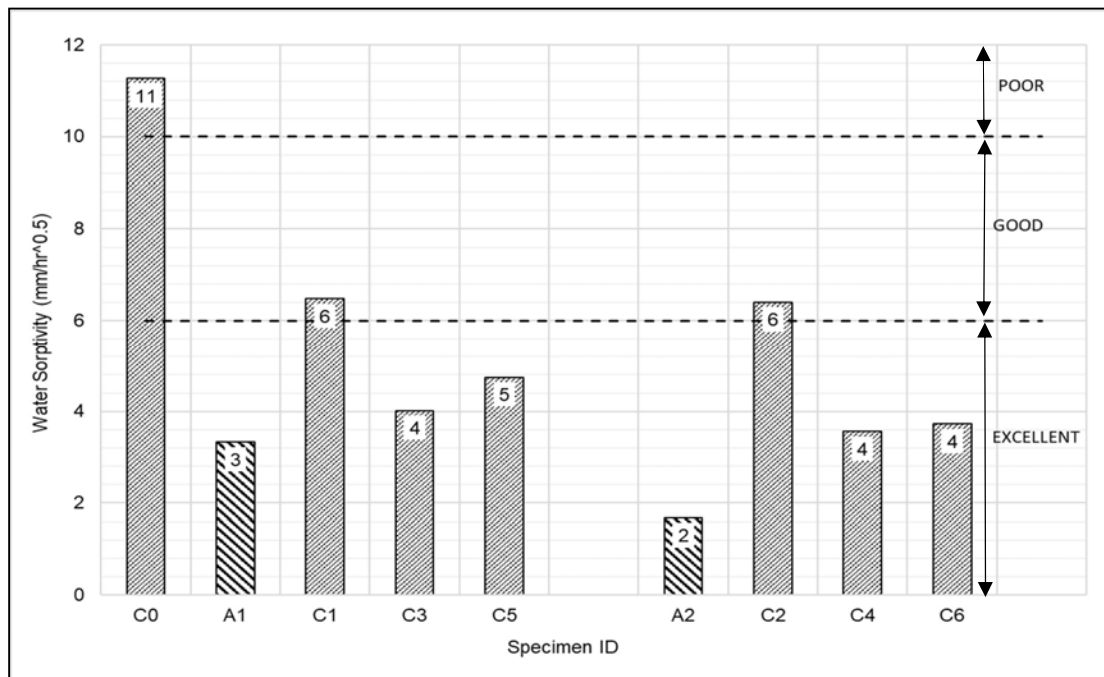


Figure 4.20: Stage C water sorptivity results

Additionally, from the results shown in Figure 4.21, the specimens exhibited a range of porosity levels, varying from good to very poor. In comparing the porosity results of A1 and A2, as depicted in Figure 4.21, with stage C results, it was noted that geopolymer binders improved the porosity of concrete by incorporating 10% and 20% of FCR aggregates. This enhancement can be ascribed to the geopolymerisation reaction between the binders and the alkaline solution, thus

forming a strong adhesion between the paste and aggregate matrix, decreasing the volume of pores within the concrete structure.

Comparing the porosity results with the stage C water absorption rate, It was noted that as the volume of voids increased, the rate of water absorption also rose within the concrete structure, which is a typical relationship between the two. Concrete specimens with 20% FCR aggregates exhibited a higher effective porosity than those with 10% FCR aggregates.

Compared to the other samples, C3 and C4 had good rating outcomes. The observed outcomes may be associated with the accelerated evaporation of moisture in concrete during the oven heat curing, resulting in the development of thermal surface cracks penetrating into the concrete body, and also as a result of the fast-paced reaction between the alkaline activator and binder particles (Farhan, Sheikh and Hadi, 2019).

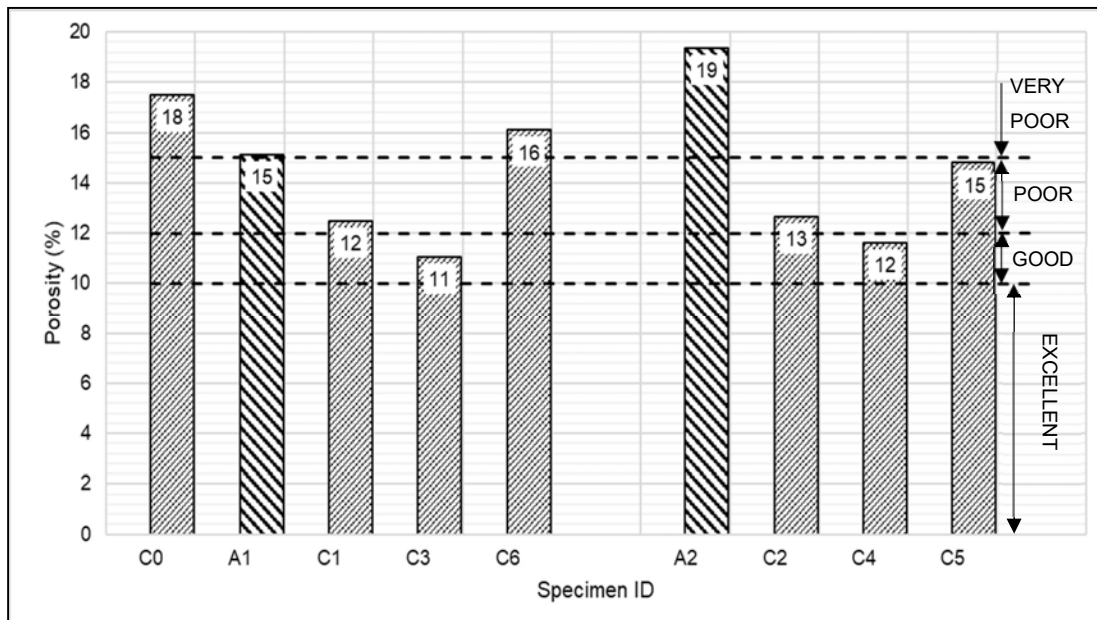


Figure 4.21: Stage C effective porosity results

4.3.7 Stage A – Impact of FA And FCR Aggregates on Chloride Conductivity of Conventional Concrete

Based on the findings in Figure 4.22 below, the results indicate a clear impact of incorporating FCR aggregates and FA on concrete specimens' chloride conductivity (CC). The control mix (CM) without any FCR aggregates or supplementary materials exhibited poor resistance to chloride conductivity, with a value of 2.0 mS/cm. This value serves as a baseline for comparison with other mixes.

When 10% and 20% of FCR aggregates were incorporated into the concrete mix, a noticeable improvement in resistance to CC was observed. Specifically, A1 and A2 showed good resistance, with CC values of 1.4mS/cm and 1.3mS/cm, respectively, compared to CM. This improvement can be ascribed to the polar and non-reactive properties of FCR aggregates, which can repel chloride ions and reduce their diffusion into the concrete.

Incorporating FA into the concrete mix increased CC values for A3 and A4, with values of 2.5 mS/cm and 2mS/cm, respectively. These higher values show that the presence of FA alleviated the resistance of the concrete to chloride ion penetration, leading to very poor resistance compared to CM. This unexpected result may be due to several factors, such as the FA pozzolanic reaction, which can lead to the formation of additional chloride-conductive compounds or a change in the void microstructure of the concrete.

Overall, the replacement of sand with FCR aggregates can enhance concrete's resistance to chloride ion ingress, while adding FA may have a detrimental effect. Further analysis and testing are necessary to understand the specific mechanisms behind these results and to optimise concrete mix designs for improved chloride ion resistance.

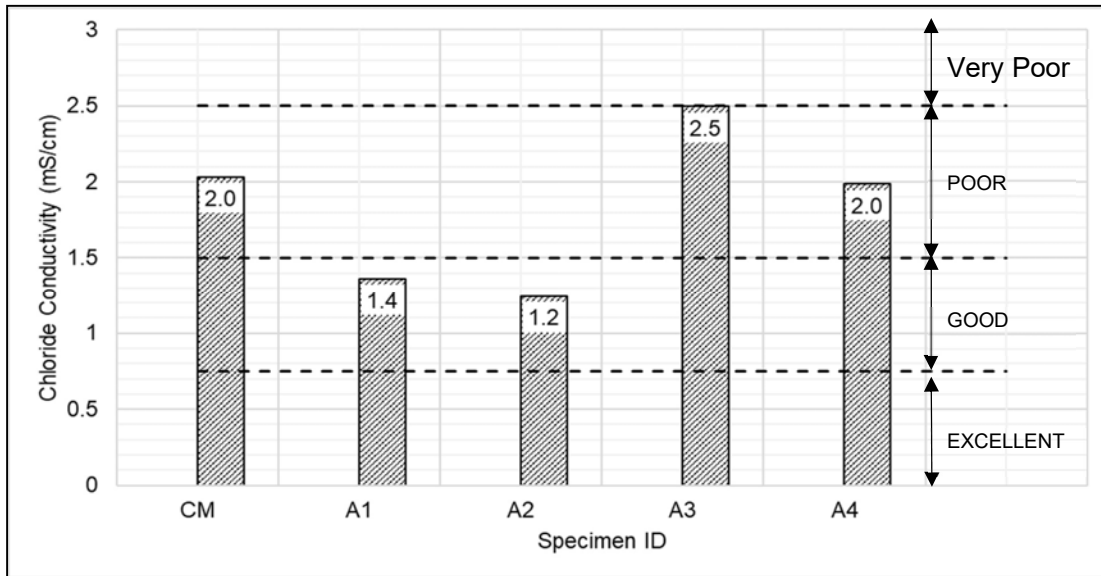


Figure 4.22: Chloride conductivity results for stage A specimens

4.3.8 Stage B – Impact of FA on Chloride Conductivity of Concrete Incorporating FCR Aggregates

The findings in Figure 4.23 suggest that incorporating FA into concrete containing FCR aggregates positively impacts chloride conductivity (CC), which is a measure of the chloride ion penetration in concrete. Specifically, when 10% of PC was replaced with FA in concrete containing 10% FCR aggregates (B1), the chloride conductivity decreased to 1.2mS/cm. Increasing the FA content to 20% (B3) resulted in a further reduction in CC to 0.9 mS/cm. A similar trend was observed in concrete with 20% FCR aggregates, where chloride conductivity decreased from 1.3 mS/cm in the control mix (A1) to 1.2mS/cm in B2 and further to 1.098mS/cm in B4.

This behaviour contrasts with the typical response of conventional concrete, where FA often leads to increased chloride ion diffusion. The improvement in chloride resistance observed in concrete containing both FA and FCR aggregates can be attributed to several factors. Firstly, FA particles may help fill the voids created by the polar behaviour of FCR aggregates, thereby reducing the number of pathways available for chloride ions to penetrate the concrete. Additionally, the pozzolanic reaction of FA helps to densify the concrete's microstructure, further limiting the pore spaces that could facilitate chloride ingress.

In conclusion, these findings suggest that the combination of FA and FCR aggregates can augment the chloride resistance of concrete, thereby improving its durability in environments with high chloride exposure. This enhanced resistance is likely due to the synergistic effects of FA's pore-filling ability and pozzolanic reaction, which together contribute to a denser and less permeable concrete matrix.

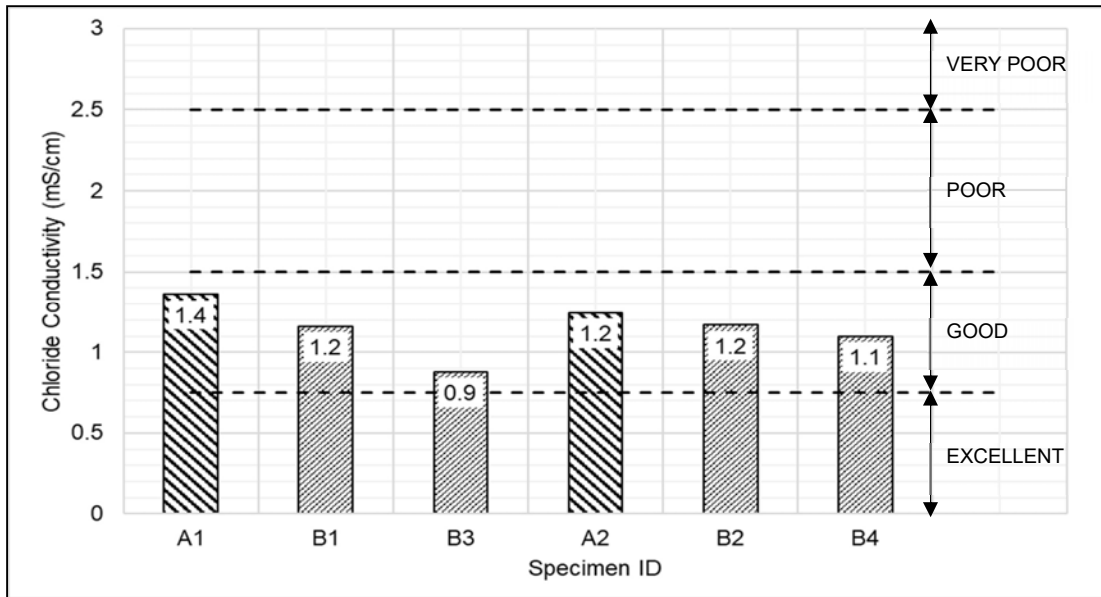


Figure 4.23: Chloride conductivity results for stage B specimens

4.3.9 Stage C – Impact of Geopolymer Binders on Chloride Conductivity of Concrete Incorporating FCR Aggregates

The results from Figure 4.24 present an overview of the impact of geopolymer binders on the chloride ion conductivity (CC) of concrete incorporating FCR aggregates. From the results, reference mix C0 exhibited a high conductivity of 9.39mS/cm, indicating poor resistance to chloride ion diffusion.

When FA-based geopolymer binder was used in concrete with 20% FCR aggregates (C2), there was a significant rise in chloride ion ingress, with a 6.83mS/cm conductivity. This increase in conductivity compared to A2 (1.4mS/cm) suggests that adding FA in this mix led to a decrease in resistance to chloride ion diffusion, moving from good to very poor resistance. An anomaly was observed with mix C1, where no readings were recorded for 15 minutes during the test for all concrete sample

disks. This behaviour is unusual, especially considering that C1 recorded results for water sorptivity, indicating that cracking of the concrete sample may have influenced the results and made the specimens more susceptible to chloride ion ingress.

Comparing the results of A1 and A2 with C3 and C4, an increase in chloride ion ingress was noted. This trend was also observed in C5 and C6. Overall, all stage C specimens exhibited very poor chloride ion diffusion resistance. However, when alkali-activated GGBFS and PC were used in the concrete composition (C3 and C4), there was a reduction in chloride ion ingress compared to mix C2. A similar pattern was observed when alkali-activated GGBFS and FA were used in concrete with 10% and 20% FCR aggregates (C5 and C6). Notably, C3 and C4 exhibited better results than other specimens in stage C.

These results suggest that the type of binder and the presence of FCR aggregates significantly impact chloride ion conductivity. Additionally, there is a relationship between water sorptivity, porosity, and chloride ion conductivity, indicating that the concrete microstructure and water content significantly impact the transmission of chloride ions through the concrete pores.

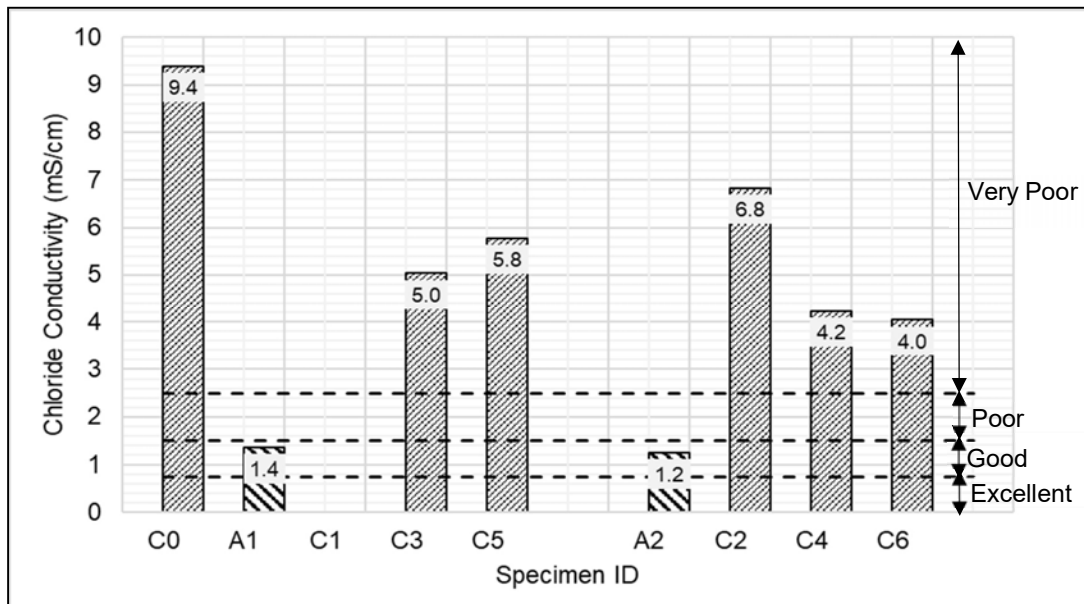


Figure 4.24: Chloride conductivity results for stage C specimens

4.4 Chapter Summary on Mechanical and Durability Properties of Concrete Incorporating FCR Aggregates

The study investigated the impact of FCR aggregates on concrete's mechanical and durability characteristics. As depicted in Figure 4.25, it was initially noted that the inclusion of FCR aggregates resulted in a decrease in the concrete's compressive and splitting tensile strength. Subsequently, initiatives were pursued to augment the strength by replacing FA in concrete mixes containing FCR aggregates. Surprisingly, this substitution resulted in further declines in both strength parameters. However, a substantial improvement in compressive and splitting tensile strength was observed after adopting geopolymer binders. These results suggest that geopolymer binders have the potential to augment the mechanical characteristics of concrete containing FCR aggregates.

Furthermore, the study evaluated the influence of FCR aggregates on durability properties such as oxygen penetration, porosity, water sorptivity, and chloride conductivity. FCR aggregates were found to increase oxygen penetration and porosity, while improvements were noted in water sorptivity and chloride conductivity. FA was utilised as a substitute for PC to boost concrete durability with FCR aggregates.

However, the results indicated that FA had no substantial impact on the durability properties of concrete, as the patterns of oxygen penetration, sorptivity, and chloride conductivity remained similar to those observed with FCR aggregates alone. Additionally, the alkali activation of binders was explored to improve the concrete durability characteristics. While enhancements were observed in the porosity and oxygen permeability of concrete with 20% FCR aggregates, geopolymer binders did not significantly improve the oxygen permeability of concrete with 10% FCR aggregates, water sorptivity, or chloride conductivity.

Overall, the investigation highlights the capability of geopolymer binders to improve the mechanical properties of concrete containing FCR aggregates. Despite this, further research is imperative to optimise the durability characteristics of such concrete formulations.

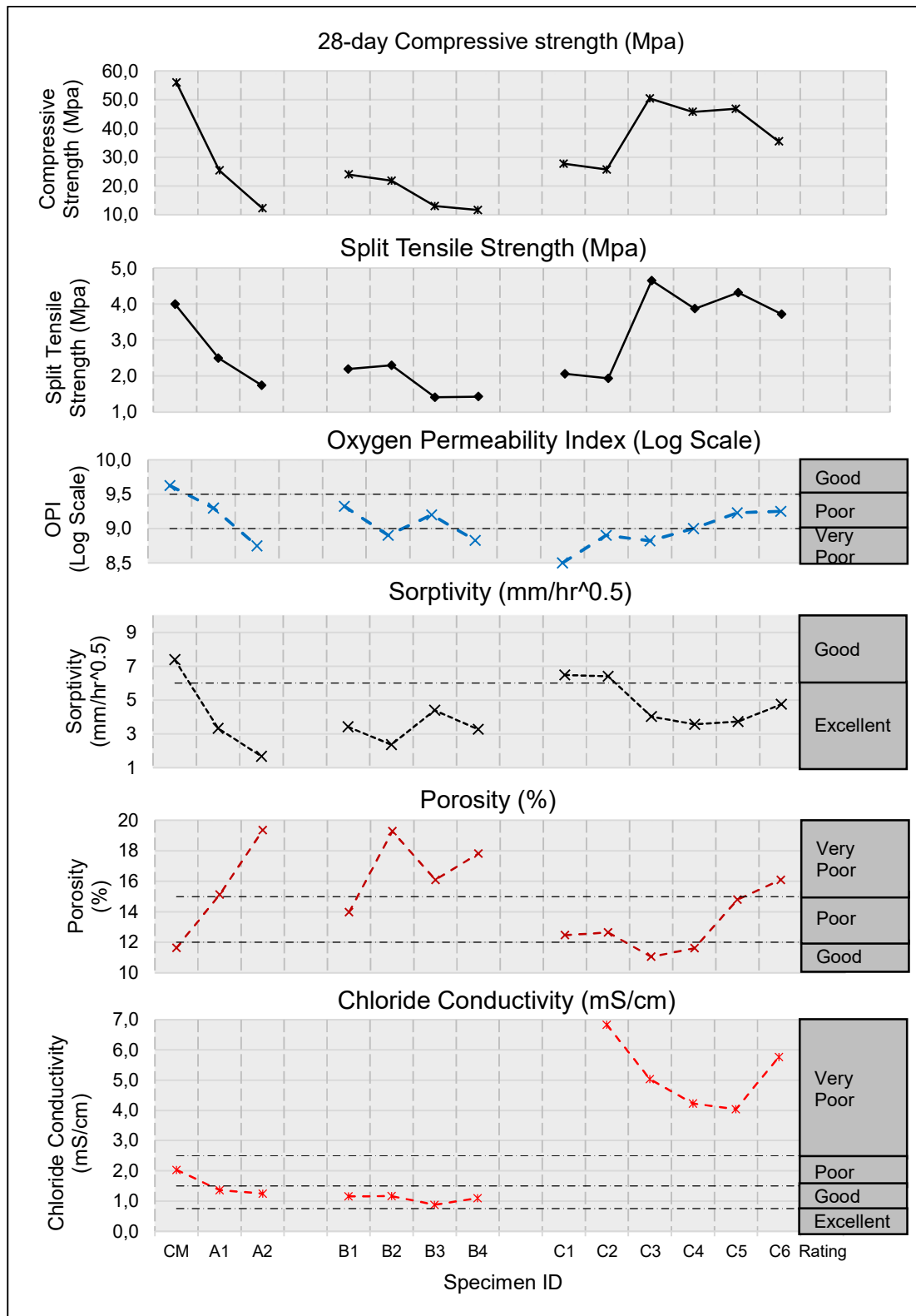


Figure 4.25: Test results summary for concrete incorporating FCR aggregates

4.5 Optimum Mix Designs of Concrete Incorporating FCR Aggregates

A meticulous selection of mix design parameters was imperative to achieve ideal concrete mixes incorporating 10% and 20% FCR aggregates. Parameters such as the water-to-cement (w/c) ratio, alkaline-to-binder (Al/b) ratio, sodium hydroxide (NaOH) molarity, and NaOH-to-sodium silicate (NaOH/Na₂SiO₃) ratio were meticulously chosen. These selections were informed by an exhaustive review of relevant literature in Chapter 2, which indicated their propensity to produce favourable outcomes.

Adopting these selected parameters in the Cement and Concrete Institute (C&CI) mix design processes facilitated the formulation of conventional and geopolymer concrete mix designs. After executing these mix designs to generate concrete specimens, the specimens underwent comprehensive testing to evaluate their durability and mechanical properties. The specimens' mix design, which exhibited superior performance to others, was considered the optimum mix design.

The culmination of this investigative process led to the identification of concrete compositions that excelled in mechanical and durability properties tests. Specifically, the specimens composed of 40% PC and 60% GGBFS geopolymer binder, denoted as C3 and C4, emerged as frontrunners in terms of performance. This conclusion is corroborated by the findings summarised in Figure 4.25, which unequivocally illustrate the superiority of C3 and C4 over other specimens.

In light of these results, Table 5.1 below outlines a detailed breakdown of the mix design used to achieve the exemplary outcomes observed in specimens C3 and C4. Notably, the only variation introduced in the mix design pertains to the sand content substituted by 10% and 20% FCR aggregates.

Table 4.2: Optimum Mix design for concrete incorporating FCR aggregates

Description	Mix design parameters
GGBFS	315kg/m ³
PC	210kg/m ³
Molarity	16

Description	Mix design parameters
a/l ratio	0.4
NaOH solution	150kg/m ³
Na ₂ SiO ₃	60kg/m ³
Additional water	80kg/m ³

CHAPTER 5 : CONCLUSION AND RECOMMENDATIONS

In addressing the bonding challenges associated with incorporating waste tyres in concrete, several studies have explored various substitution percentages of traditional aggregates with FCR and CCR aggregates, considering different w/c ratios, gradations, treatment of rubber aggregates with acid to improve surface texture and others as detailed in chapter 2.

However, these studies have led to conflicting conclusions regarding the optimal replacement percentages for FCR aggregates and their impact on the properties of concrete. Additionally, a range of studies has assessed the impact of modified cement extenders, such as modified forms of FA and GGBFS, through alkali activation (geopolymerisation) on conventional concrete, which has shown positive mechanical characteristics.

However, there is insufficient in-depth understanding regarding their impact on the mechanical and durability properties of concrete incorporating FCR aggregates. This knowledge gap hinders understanding their effect on bonding strength and establishing a standardised mix design for the efficient and sustainable utilisation of waste tyre rubber in concrete production. Therefore, this study addresses these gaps by systematically investigating the influence of FA, modified FA, and GGBFS on concrete's mechanical and durability properties incorporating FCR aggregates.

The substitution of sand with 10% and 20% of FCR and the replacement of PC with FA led to a notable drop in the mechanical characteristics of concrete. However, it also resulted in partial enhancement in the durability of the concrete. Nevertheless, geopolymer binders have been found to enhance concrete's mechanical qualities while somewhat mitigating its durability.

Thus, this section presents the conclusions and recommendations derived from the results, ensuring alignment with the study's objectives as outlined in section 1.2.

5.1 Objective 1 – Different Methods or Approaches to Improve/Modify the Cement Extenders (FA & GGBFS).

The objective was thoroughly examined in Chapter 2, and various approaches were discussed, including the effects of FA and the modification of cement extenders through alkali-activation (geopolymerization) on concrete, with limited feedback on their impact on concrete with crumb rubber aggregates. Additionally, the treatment of crumb rubber with NaOH (sodium hydroxide) to improve texture and address voids between the paste matrix and crumb rubber, enhancing adhesion, was explored.

The researchers' findings suggested that alkali activation was the most effective method for enhancing concrete properties. Therefore, this study adopted this approach, implementing the optimal parameters proposed by previous researchers. However, it is important to note that the materials used in this study were chosen based on their availability in the immediate vicinity, indicating a practical and context-specific application of the research findings.

5.2 Objective 2 – Impact of Partial PC Replacement with FA and Modified Cement Extenders in Concrete Incorporating FCR Aggregates.

For this specific objective, the study was divided into three main stages: A, B, and C. Stage A investigated the impact of FCR aggregates and FA on conventional concrete. Stage B focused on the effects of FA on concrete containing FCR aggregates. Finally, Stage C explored the effects of FA, GGBFS+FA, and GGBFS+PC-based geopolymer binders in concrete incorporating FCR aggregates.

5.2.1 Stage A

The effects of using FCR aggregates and FA on concrete's mechanical and durability properties were studied. The results revealed that substituting sand with FCR aggregates significantly reduced splitting tensile strength and compressive strength of concrete, with higher FCR aggregate content causing more pronounced strength reductions. This decrease was ascribed to the polar properties of FCR aggregates, which caused water repulsion and air attraction, leading to void formation and reduced bonds with the cement paste matrix. Additionally, FCR

aggregates' non-uniform distribution in the concrete specimens affected stress distribution, leading to crack propagation and specimen failure.

Similarly, substituting PC with FA reduced compressive strength, which was attributed to delayed pozzolanic reactions and higher carbon content than Portland cement. This strength decreases intensified with higher FA content due to limitations in silica content available for reaction with lime. FA substitution also resulted in a decrease in splitting tensile strength.

Regarding durability properties, the study found that FCR aggregates increased oxygen permeability and porosity but reduced water sorptivity. FA, on the other hand, increases oxygen permeability and porosity. FCR aggregates reduced chloride ion penetration, while FA incorporation increased chloride ion penetration. The study concludes that while FCR aggregates can improve certain durability characteristics, like water sorptivity and chloride ion conductivity, they have a detrimental impact on mechanical properties, like compressive and splitting tensile strength. FA, on the other hand, negatively impacts both mechanical and durability properties.

5.2.2 Stage B

This study investigated how integrating FA into concrete containing FCR aggregates affects mechanical and durability properties. The results showed that adding FA decreased the compressive strength of concrete with 10% FCR aggregates but had mixed effects on concrete with 20% FCR aggregates. FA also decreased splitting tensile strength, with no significant change at higher FA contents.

Regarding durability, FA had minimal impact on the oxygen permeability index (OPI) and water absorption but increased porosity, especially at higher FA contents. However, FA improved resistance to chloride conductivity in both 10% and 20% FCR aggregate concretes. Thus, it can be inferred that FA enhances certain durability properties while reducing the mechanical properties of concrete containing FCR aggregates.

5.2.3 Stage C

This study investigated the effects of FA, GGBFS+PC, and GGBFS+FA geopolymer binders on concrete containing FCR aggregates. The results showed that substituting sand with FCR aggregates led to decreased compressive strength, with FA-based geopolymer binder positively impacting compressive strength compared to conventional concrete with FCR aggregates. However, the presence of FA with low SiO₂ content limited its effectiveness in improving strength. The combination of GGBFS and PC exhibited the best performance in enhancing compressive strength.

Regarding splitting tensile strength, FA-based geopolymer binder showed mixed results, with some specimens exhibiting an increase compared to conventional concrete with FCR aggregates. GGBFS+FA and GGBFS +PC geopolymer binders demonstrated a notable improvement in splitting tensile strength, with GGBFS+PC achieving better results than other geopolymer binders.

Regarding durability, adding geopolymer binders led to varying effects on the oxygen permeability index (OPI), improving only on concrete with 20% FCR aggregates and porosity while increasing water sorptivity. While some specimens showed improvement in OPI, others exhibited poor outcomes. Chloride ion conductivity results indicated that geopolymer binders had varying effects, with some specimens showing an increase in chloride ion penetration compared to conventional concrete with FCR aggregates.

The study thus concludes that adding geopolymer binders can improve the compressive strength and splitting tensile strength of concrete containing FCR aggregates. Geopolymer binders also showed varying effects on durability properties, with some specimens exhibiting improvements in OPI while others showed increased water sorptivity and porosity. The type of binder and the presence of FCR aggregates significantly influenced chloride ion conductivity, with some specimens exhibiting poor resistance to chloride ion diffusion.

5.3 Objective 3 – To Identify the Optimum Mix Design of Concrete Incorporating Cement Extenders and CR Aggregates.

The mix design of concrete made of 40% PC and 60% GGBFS-based geopolymer binder obtained superior mechanical and durability properties compared to other mix designs. This conclusion is also supported by the results summarised in Figure 4.25.

5.4 Recommendations

The primary emphasis of the study was to investigate the impact of cement extenders in concrete incorporating FCR aggregates to enhance concrete durability and mechanical properties. The study's findings indicate that geopolymer binders have a beneficial effect on rubberised concrete. Nevertheless, a significant limitation of geopolymer binder rubberised concrete lies in its requirement for oven heat curing, impeding its widespread use in large-scale concrete structural components. Hence, it is crucial to consider the following proposals for future consideration.

- a) The study utilised low-silica and low-alumino content FA, focusing solely on thermal curing. Therefore, it is crucial to investigate further the behaviour of FA-based geopolymer binders with high silica and aluminium content concerning the durability properties of concrete containing FCR aggregates. This research should encompass various curing methods to enhance its applicability in the large-scale concrete industry.
- b) The performance of GGBFS+PC and GGBFS+FA on the mechanical and durability properties of concrete incorporating FCR aggregates while considering different curing regimes.
- c) Perform thorough microstructural analyses of concrete containing geopolymer binders and FCR aggregates, focusing on the influence of various curing methods. This examination will offer valuable insights into crack formation and its implications on chloride conductivity, thereby improving our comprehension of the material's performance characteristics.
- d) Long-Term Performance Studies: Conducting long-term studies to assess the durability of concrete mixtures incorporating geopolymer binders and FCR aggregates under real-world conditions would provide valuable insights for practical applications.

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APPENDIX A: TABULATED INFORMATION AND RESULTS

Table A.1: Sand sieve analysis results

Material:	<u>Umgeni river sand</u>		Sample Mass	500g
Sieve Size (microns)	Mass Retained (g)	Mass retained (%)	Cumulative Mass retained (%)	Cumulative mass passing (%)
4750	6.70	1.34	1.34	98.66
2360	20.30	4.06	5.40	94.60
1180	57.60	11.52	16.92	83.08
600	108.40	21.68	38.60	61.40
300	189.00	37.80	76.40	23.60
150	103.00	20.60	97.00	3.00
Pan	14.00	2.80	99.80	0.20
		FM	3.4	

Table A.2: FCR aggregates sieve analysis results

Material:	<u>FCR aggregates</u>		Sample Mass	500g
Sieve size (microns)	Mass retained (g)	Mass retained (%)	Cumulative mass Retained (%)	Cumulative mass Passing (%)
4750	0.00	0.00	0.00	100.00
2360	9.00	1.80	1.80	98.20
1180	36.00	7.20	9.00	91.00
600	121.00	24.20	33.20	66.80
300	247.00	49.40	82.60	17.40
150	77.00	15.40	98.00	2.00
Pan	10.00	2.00	100.00	0.00
		FM	3.2	

Table A. 3: Concrete mix design

WORKSHEET: CONCRETE MIX DESIGN											
CLIENT: STUDENT No		215059689		PROJECT:							
REQUIREMENTS:		STRENGTH:		50.95 MPa		SLUMP:		50 mm		W/C: 0.60	
MATERIAL	TYPE AND SOURCE	SIZE [mm]	RD:	LBD [kg/m ³]	CBD [kg/m ³]	FM	K VALUES	HAND	MOD	HEAVY	
CEMENT	CEM 1 52.5R		3.12				STONE	COMP	VIBR	VIBR	
FA/SLAG							9.5	0.75	0.8	1	
STONE 1	COEDMORE QRTZ	19	2.65	1360	1446		13.2	0.84	0.9	1.05	
STONE 2							19.0	0.94	1	1.05	
SAND 1	UMGENI RIVER SAND		2.65	1320	1400	3.40	26.5	1	1.06	1.1	
SAND 2							FOR CBD [kg/m ³]		1446		
TEST MATERIAL	INDUSTRIAL WASTE		Dosage:	0	% mass		STONE		19		
1 m ³ (1000 l)		NOTE: kg/RD = litres						SELECTED K		1	
								STONE REQD [kg]		954.36	
STONE REQUIRED [from chart using stone size and FM of sand]						954.36 kg					
MIX 1			MIX 2			MIX 3			MIX 4		
MATERIAL	kg	litre	kg	litre	kg	litre	kg	litre	kg	litre	
WATER	240	240	230	230	220	220	210	210	210	210	
CEMENT	400	128	383	123	367	118	350	112	350	112	
FA/SLAG	0	0	0	0	0	0	0	0	0	0	
STONE 1	954	360	954	360	954	360	954	360	954	360	
STONE 2	0	0	0	0	0	0	0	0	0	0	
SAND 1	720	272	761	287	801	302	842	318	842	318	
SAND 2	0	0	0	0	0	0	0	0	0	0	
ADMIXTURE	0	ml	0		0		0		0		
TOTAL	2314	1000	2328	1000	2342	1000	2356	1000	2356	1000	
FACTOR	mix size/1000 x (w ater mix 1)/(w ater mix X)										
	0.0216	0.0216	0.0225		0.0235		0.0246				
LAB MIX											
MIX 1			MIX 2			MIX 3			MIX 4		
MATERIAL	kg	Litre	Add kg	kg	Litre	Add kg	kg	Litre	Add kg	kg	Litre
WATER	5.2	5.2	0.0	5.2	5.2	0.0	5.2	5.2	0.3	5.5	5.5
CEMENT	8.6	2.8	0.0	8.6	2.8	0.0	8.6	2.8	0.0	8.6	2.8
FA/SLAG											
STONE 1	20.6	7.8	0.9	21.5	8.1	1.0	22.4	8.5	1.1	23.5	8.9
STONE 2											
SAND 1	15.5	5.9	1.6	17.1	6.5	1.7	18.8	7.1	1.9	20.7	7.8
SAND 2											
ADMIXTURE	0.0			0.0			0.0			0.0	
Total	49.9	21.6		52.4	22.5		55.1	23.5		58.4	24.94
SLUMP											50 mm
Comments:											
Mix done by:											
Cubes marked:											
Date:											

Table A.4: Geopolymer concrete mix design



WORKSHEET: CONCRETE MIX DESIGN											
CLIENT: STUDENT No		215059689		PROJECT:							
REQUIREMENTS:		STRENGTH:		-		MPa		SLUMP: -		mm W/C: 0.40	
MATERIAL	TYPE AND SOURCE	SIZE [mm]	RD:	LBD [kg/m ³]	CBD [kg/m ³]	FM	K VALUES	HAND	MOD	HEAVY	
FA	FLY ASH		2.45				9,5	0.75	0.8	1	
STONE 1	COEDMORE QRTZ	19	2.65	1360	1446		13,2	0.84	0.9	1.05	
STONE 2							19,0	0.94	1	1.05	
SAND 1	UMGENI RIVER SAND		2.65	1320	1400	3.40	26,5	1	1.06	1.1	
SAND 2											
TEST MATERIAL	INDUSTRIAL WASTE		Dosage:	0	% mass						
1 m ³ (1000 l)		NOTE: kg/RD = litres									
								FOR CBD [kg/m ³]		1446	
								STONE		19	
								SELECTED K		1	
								STONE REQD [kg]		954.36	
STONE REQUIRED [from chart using stone size and FM of sand]				954.36 kg							
MIX 1			MIX 2			MIX 3			MIX 4		
MATERIAL	kg	litre	kg	litre	kg	litre	kg	litre	kg	litre	
WATER	240	240	230	230	220	220	210	210	210	210	
FA	600	245	575	235	550	224	525	214	525	214	
FA/SLAG	0	0	0	0	0	0	0	0	0	0	
STONE 1	954	360	954	360	954	360	954	360	954	360	
STONE 2	0	0	0	0	0	0	0	0	0	0	
SAND 1	411	155	464	175	518	195	571	216	571	216	
SAND 2	0	0	0	0	0	0	0	0	0	0	
ADMIXTURE	0	ml	0		0		0		0		
TOTAL	2205	1000	2224	1000	2242	1000	2261	1000	2261	1000	
FACTOR		mix size/1000 x (water mix 1)/(water mix X)									
0.0206		0.0206		0.0215		0.0225		0.0236			
LAB MIX											
MIX 1			MIX 2			MIX 3			MIX 4		
MATERIAL	kg	Litre	Add kg	kg	Litre	Add kg	kg	Litre	Add kg	kg	Litre
WATER	5.0	5.0	0.0	5.0	5.0	0.0	5.0	5.0	0.0	5.0	5.0
CEMENT	12.4	5.1	0.0	12.4	5.1	0.0	12.4	5.1	0.0	12.4	5.1
FA/SLAG											
STONE 1	19.7	7.4	0.9	20.5	7.8	0.9	21.5	8.1	1.0	22.5	8.5
STONE 2											
SAND 1	8.5	3.2	1.5	10.0	3.8	1.7	11.6	4.4	1.8	13.5	5.1
SAND 2											
ADMIXTURE	0.0			0.0			0.0			0.0	
Total	45.5	20.6		47.9	21.5		50.4	22.5		53.3	23.57
SLUMP											
		mm		mm		mm		mm		mm	
Comments:											
Mix done by:											
Cubes marked:											
Date:											

Table A.5: Compressive strength results

Mix No.	% Replacement		7-day Compressive Strength			Avg.	STAV	28-day Compressive Strength			STAV	Avg.
			1.00	2.00	3.00			1.00	2.00	3.00		
CM	0%FA	Load (KN)	441.70	423.00	421.20			566.50	578.50	533.40		
	0%CR	Strength (Mpa)	44.17	42.30	42.12	42.86	1.14	56.65	57.85	53.34	2.34	55.95
A1	0%FA	Load (KN)	183.80	217.00	220.00			249.80	251.90	259.50		
	10%CR	Strength (Mpa)	18.38	21.70	22.00	20.69	2.01	24.98	25.19	25.95	0.51	25.37
A2	0%FA	Load (KN)	107.30	102.70	115.90			122.00	124.10	121.10		
	20%CR	Strength (Mpa)	10.73	10.27	11.59	10.86	0.67	12.20	12.41	12.11	0.15	12.24
A3	10%FA	Load (KN)	286.80	320.30	319.30			390.70	352.90	355.40		
	0%CR	Strength (Mpa)	28.68	32.03	31.93	30.88	1.91	39.07	35.29	35.54	2.11	36.63
A4	20%FA	Load (KN)	267.80	255.80	255.90			339.80	359.40	335.50		
	0%CR	Strength (Mpa)	26.78	25.58	25.59	25.98	0.69	33.98	35.94	33.55	1.27	34.49
B1	10%FA	Load (KN)	168.60	201.10	189.70			247.70	251.80	221.40		
	10%CR	Strength (Mpa)	16.86	20.11	18.97	18.65	1.65	24.77	25.18	22.14	1.65	24.03
B3	20%FA	Load (KN)	178.30	175.50	166.30			229.90	214.80	210.40		
	10%CR	Strength (Mpa)	17.83	17.55	16.63	17.34	0.63	22.99	21.48	21.04	1.02	21.84
B2	10%FA	Load (KN)	95.40	105.50	113.30			128.90	128.70	132.40		
	20%CR	Strength (Mpa)	9.54	10.55	11.33	10.47	0.90	12.89	12.87	13.24	0.21	13.00
B4	20%FA	Load (KN)	103.20	110.50	105.70			101.40	124.60	122.40		
	20%CR	Strength (Mpa)	10.32	11.05	10.57	10.65	0.37	10.14	12.46	12.24	1.28	11.61
C0	100% FA	Load (KN)	301.80	322.40	325.40			336.70	312.70	326.20		
	0% FCR	Strength (Mpa)	30.18	32.24	32.54	31.65	1.28	33.67	31.27	32.62	1.20	32.52
C1	100% FA	Load (KN)	269.40	267.40	269.60			283.00	274.90	273.50		
	10% FCR	Strength (Mpa)	26.94	26.74	26.96	26.88	0.12	28.30	27.49	27.35	0.51	27.71

Mix No.	% Replacement		7-day Compressive Strength			Avg.	STAV	28-day Compressive Strength			STAV	Avg.
			1.00	2.00	3.00			1.00	2.00	3.00		
C2	100% FA	Load (KN)	245.50	257.70	251.90			260.00	251.30	261.30		
	20% FCR	Strength (Mpa)	24.55	25.77	25.19	25.17	0.61	26.00	25.13	26.13	0.54	25.75
C3	60% GGBFS & 40% CEM1	Load (KN)	489.30	475.60	495.20			504.20	500.60	507.40		
	10% FCR	Strength (Mpa)	48.93	47.56	49.52	48.67	1.01	50.42	50.06	50.74	0.34	50.41
C4	60% GGBFS & 40% CEM1	Load (KN)	432.50	442.80	425.10			467.21	436.02	470.20		
	20% FCR	Strength (Mpa)	43.25	44.28	42.51	43.35	0.89	46.72	43.60	47.02	1.89	45.78
C5	60% GGBFS & 40% FA	Load (KN)	440.80	454.60	437.40			458.60	462.50	482.10		
	10% FCR	Strength (Mpa)	44.08	45.46	43.74	44.43	0.91	45.86	46.25	48.21	1.26	46.77
C6	60% GGBFS & 40% FA	Load (KN)	323.00	325.00	322.30			353.00	351.60	359.50		
	20% FCR	Strength (Mpa)	32.30	32.50	32.23	32.34	0.14	35.30	35.16	35.95	0.42	35.47

Table A.6: Splitting tensile strength results

Mix No.	% Replacement		7-days Split Tensile Strength			STAV	Avg.	28 days Split Tensile Strength			STAV	Avg.
			1.00	2.00	3.00			1.00	2.00	3.00		
CM	0%FA	Load (KN)	52.60	35.80	58.20			62.90	64.50	61.10		
	0%CR	Strength (Mpa)	3.35	2.28	3.70	0.74	3.11	4.00	4.10	3.89	0.11	4.00
A1	0%FA	Load (KN)	25.50	27.40	17.70			41.10	39.40	37.30		
	10%CR	Strength (Mpa)	1.62	1.74	1.13	0.33	1.50	2.62	2.51	2.37	0.12	2.50
A2	0%FA	Load (KN)	18.60	20.20	18.50			25.90	27.90	28.50		
	20%CR	Strength (Mpa)	1.18	1.29	1.18	0.06	1.22	1.65	1.78	1.81	0.09	1.75
A3	10%FA	Load (KN)	34.00	32.80	31.50			44.20	49.50	49.10		
	0%CR	Strength (Mpa)	2.16	2.09	2.00	0.08	2.09	2.81	3.15	3.12	0.19	3.03
A4	20%FA	Load (KN)	19.60	28.40	20.50			40.40	39.50	44.20		

Mix No.	% Replacement		7-days Split Tensile Strength			STAV	Avg.	28 days Split Tensile Strength			STAV	Avg.
			1.00	2.00	3.00			1.00	2.00	3.00		
	0%CR	Strength (Mpa)	1.25	1.81	1.30	0.31	1.45	2.57	2.51	2.81	0.16	2.63
B1	10%FA	Load (KN)	30.50	27.90	28.20			33.00	34.60	36.00		
	10%CR	Strength (Mpa)	1.94	1.78	1.79	0.09	1.84	2.10	2.20	2.29	0.10	2.20
B3	20%FA	Load (KN)	30.70	31.00	32.90			41.00	33.00	34.40		
	10%CR	Strength (Mpa)	1.95	1.97	2.09	0.08	2.01	2.61	2.10	2.19	0.27	2.30
B2	10%FA	Load (KN)	17.70	17.50	16.60			23.90	20.30	22.20		
	20%CR	Strength (Mpa)	1.13	1.11	1.06	0.04	1.10	1.52	1.29	1.41	0.11	1.41
B4	20%FA	Load (KN)	16.70	18.10	19.50			19.80	25.60	22.00		
	20%CR	Strength (Mpa)	1.06	1.15	1.24	0.09	1.15	1.26	1.63	1.40	0.19	1.43
C0	100% FA	Load (KN)	36.90	32.60	40.20			47.60	54.10	37.90		
	0% FCR	Strength (Mpa)	2.35	2.07	2.56	0.24	2.33	3.03	3.44	2.41	0.52	2.96
C1	100% FA	Load (KN)	32.30	31.10	29.00			34.50	31.10	31.60		
	10% FCR	Strength (Mpa)	2.06	1.98	1.85	0.11	1.96	2.20	1.98	2.01	0.12	2.06
C2	100% FA	Load (KN)	23.90	27.20	35.40			31.60	29.40	30.40		
	20% FCR	Strength (Mpa)	1.52	1.73	2.25	0.38	1.83	2.01	1.87	1.93	0.07	1.94
C3	60% GGBFS & 40% CEM1	Load (KN)	59.40	59.60	57.80			71.90	77.10	70.20		
	10% FCR	Strength (Mpa)	3.78	3.79	3.68	0.06	3.75	4.58	4.91	4.47	0.23	4.65
C4	60% GGBFS & 40% CEM1	Load (KN)	47.10	46.52	45.89			60.32	61.78	60.45		
	20% FCR	Strength (Mpa)	3.00	2.96	2.92	0.04	2.96	3.84	3.93	3.85	0.05	3.87
C5	60% GGBFS & 40% FA	Load (KN)	53.70	52.90	59.70			69.10	65.40	69.10		
	10% FCR	Strength (Mpa)	3.42	3.37	3.80	0.24	3.53	4.40	4.16	4.40	0.14	4.32

Mix No.	% Replacement		7-days Split Tensile Strength			STAV	Avg.	28 days Split Tensile Strength			STAV	Avg.
			1.00	2.00	3.00			1.00	2.00	3.00		
C6	60% GGBFS & 40% FA	Load (KN)	45.70	43.60	46.70			54.60	64.50	56.20		
	20% FCR	Strength (Mpa)	2.91	2.77	2.97	0.10	2.88	3.47	4.10	3.58	0.34	3.72

Table A.7: Slump test results

Mix ID	CM	A1	A2	A3	A4	CM	B1	B2	B3	B4	C0	C1	C2	C3	C4	C5	C6
Slump (mm)	50	20	0	80	145	50	20	0	30	0	120	115	110	55	30	185	160

Table A. 8: Durability Index test results

SAMPLE ID	Oxygen Permeability		Water Sorptivity (mm/hr ^{0.5})	Effective Porosity (%)	Chloride Conductivity (mS/cm)
	K (x10 ⁻¹⁰)	OPI			
	m/s				
CM					
CM-1	4.38	9.4	8.9	11.4	1.79
CM-2	1.25	9.9	6.4	11.9	2.39
CM-3	1.62	9.8	7.6	12.2	1.77
CM-4	4.4	9.4	6.6	11	2.18
Average	2.9	9.6	7.3	11.6	2.0
A1					
A1-1	3.82	9.4	3.5	15.1	2.57
A1-2	3.08	9.5	3.9	15.2	1.36
A1-3	6.3	9.2	2.6	14.6	0.81
A1-4	8.61	9.1	3.3	15.6	0.7
Average	5.4	9.3	3.3	15.1	1.4
A2					
A2-1	18.03	8.7	1.6	19.2	0.84
A2-2	17.65	8.7	2.2	17.8	1.02
A2-3	16.33	8.8	1.6	19.9	1.34
A2-4	16.39	8.8	1.3	20.5	1.78
Average	17.1	8.8	1.7	19.4	1.3
A3					
A3-1	5.41	9.3	8	10.5	2.84
A3-2	9.96	9	8.5	11.7	2.37
A3-3	5.15	9.3	7.8	10.8	2.71
A3-4	3.2	9.5	7.5	9.7	2.06
Average	5.9	9.3	8	10.7	2.5
A4					
A4-1	12.38	8.9	13.1	11.3	1.86
A4-2	20.71	8.7	21.4	13.4	1.75
A4-3	5.75	9.2	16.1	13.9	2
A4-4	11.18	8.9	16.9	13.4	2.33
Average	12.5	8.9	16.9	13	2
B1					
B1-1	5.66	9.2	3.4	14.2	1.66
B1-2	8.27	9.1	3.5	13.6	0.58
B1-3	2.92	9.5	3.2	14.5	0.33
B1-4	3.19	9.5	3.6	13.6	2.07
Average		9.3	3.4	14	1.0
B2					

SAMPLE ID	Oxygen Permeability		Water Sorptivity (mm/hr ^{0.5})	Effective Porosity (%)	Chloride Conductivity (mS/cm)
	K (x10 ⁻¹⁰)	OPI			
	m/s				
B2-1	24.58	8.6	2.1	19	1.1
B2-2	17.98	8.7	2.6	17.4	1.02
B2-3	30.17	9.5	2.9	18.3	1.37
B2-4	*p	-	1.9	22.4	1.18
Average		8.9	2.4	19.3	1.2
B3					
B3-1	7.53	9.1	4.6	15.1	0.8
B3-2	9.96	9	5.2	12	0.75
B3-3	5.17	9.3	3.6	20.9	1.09
B3-4	3.62	9.4	4.2	16.4	0.79
Average		9.2	4.4	16.1	0.9
B4					
B4-1	17.99	8.7	3.4	18.1	1.67
B4-2	*p	-	3.3	17.2	0.86
B4-3	17.06	8.8	3.5	17.9	0.81
B4-4	10.41	9	2.9	18.1	1.05
Average		8.8	3.3	17.8	1.1
CO					
CO-1	*p	-*	11.4	17.4	-*
CO-2	*p	-*	9.9	17.3	9.39
CO-3	*p	-*	12	17.7	-*
CO-4	*p	-*	11.8	17.6	-*
Average			11.3		9.4
C1					
C1-1	16.38	8.8	8.3	13.9	-*
C1-2	*d	-	4.1	15.5	-*
C1-3	17.6	8.8	5.6	10.9	-*
C1-4	16.5	8	7.9	9.6	-*
Average		8.5	6.5	12.5	
C2					
C2-1	10.64	9	8.4	13.8	-*
C2-2	18.46	8.7	4.2	15.3	-*
C2-3	9.9	9	5.4	11.3	-*
C2-4	13.17	8.9	7.6	10.2	6.83
Average		8.9	6.4	12.7	6.8
C3					
C3-1	20.82	8.7	7.8	16.1	6
C3-2	21.98	8.7	7.7	18.7	6.9
C3-3	11.21	8.9	7.7	19.8	6.25
C3-4	9.93	9	6.9	17.5	6.83

SAMPLE ID	Oxygen Permeability		Water Sorptivity (mm/hr ^{0.5})	Effective Porosity (%)	Chloride Conductivity (mS/cm)
	K (x10 ⁻¹⁰)	OPI			
	m/s				
Average		8.8	7.5	18	6.5
C4					
C4-1	5.67	8.9	3.23	12.42	5.4
C4-2	6.23	9.1	4.49	11.2	3.51
C4-3	4.56	9.3	3.52	9.62	4.33
C4-4	5.67	9.2	3	13.21	3.69
Average	5.5	9.1	3.56	11.6	4.23
C5					
C5-1	6.72	9.2	4.9	14.5	5.84
C5-2	9.49	9	4.9	15.5	5.36
C5-3	4.45	9.3	5.2	15.1	6.3
C5-4	3.92	9.4	4	14.1	5.58
Average		9.2	4.8	14.8	5.8
C6					
C6-1	6.55	9.2	3.8	16.1	4.09
C6-2	8.75	9	3.7	16.6	2.98
C6-3	4.19	9.4	3.4	16.4	4.17
C6-4	4.22	9.4	4	15.3	4.92
Average		9.3	3.7	16.1	4.0

Key:

- -* refers to no readings for oxygen permeability for 2 hours or more than 2 hours and chloride conductivity for 15 minutes. The samples are highly oxygen-permeable and penetrable to chloride ions in both cases. Hence, they are very poor according to the durability index classification. The case of chloride conductivity > 2.50 milliseimens per centimetre (mS/cm) is categorised as very penetrable chloride concretes.
- A digital multimeter (ammeter) is used for chloride conductivity; the maximum reading one can read is 400 mA. In those -* blank cases, samples couldn't read a 15-minute test in 0 to 400 mA ranges. All other results at least managed to measure within the mentioned ranges.
- NB: The durability index application is designed to monitor cement-based concrete mixtures' quality. Special concretes on these methods might give a wrong or a false signal that the material has high chloride conductivity.

- For example, geopolymer concretes (GPCs) are made of alkaline activator solutions that are highly conductive and give a false signal that GPCs are highly penetrable to chloride ions.
- Comment on samples.
- p*: porous. d*: defect. All were tested the first time.
- Suggestion: Discard or reject those *p and *d.

APPENDIX B: GRAPHICAL INFORMATION AND RESULTS

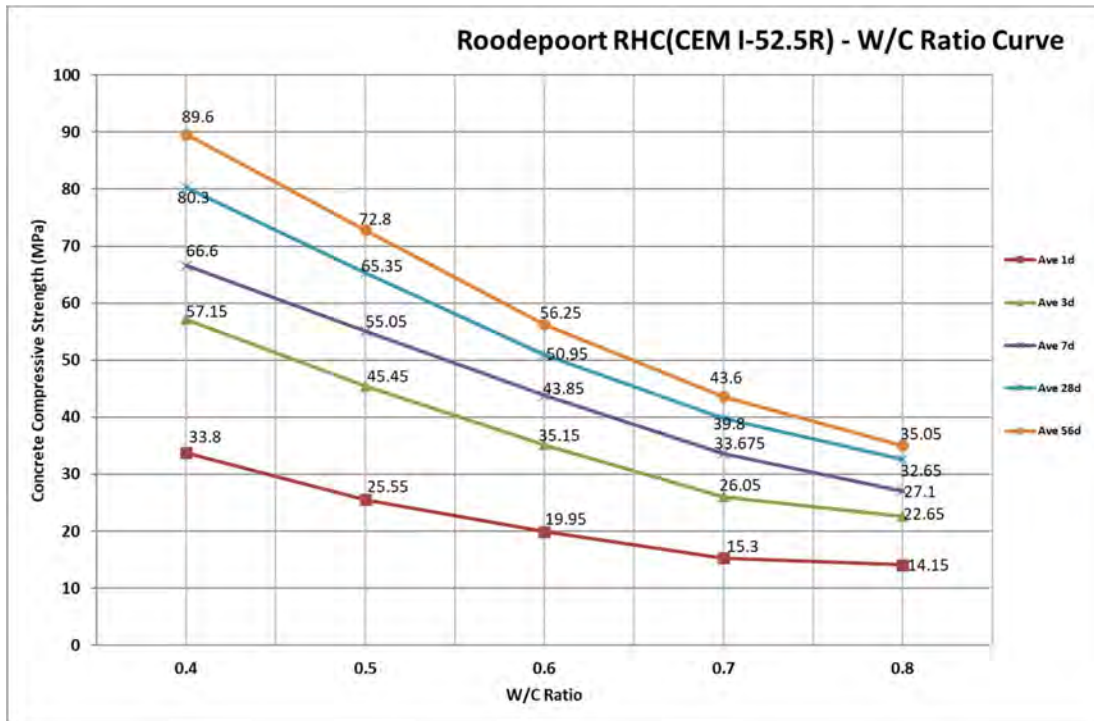


Figure B. 1: Cement W/C ration curve for PC

APPENDIX C: PLASTICIZER SPECIFICATION



PRODUCT DATA SHEET

Sika® Plastiment® BV-40

WATER REDUCING CUM INTEGRAL WATER PROOFING CONCRETE ADMIXTURE

DESCRIPTION

Sika® Plastiment® BV-40 is a versatile and economical concrete water reducer/plasticizer & waterproofing compound.

USES

Sika® Plastiment® BV-40 is used wherever high quality structural concrete is required. Its plasticising effect is particularly useful where:

- Exposed surfaces are important
- Maximum performance is desired
- Placing conditions are difficult
- Poor quality aggregates are found
- Pre-cast elements are produced
- Piling

..... and wherever quality concrete is required

CHARACTERISTICS / ADVANTAGES

Sika® Plastiment® BV-40 provides the following beneficial properties:

- Improved workability without increased water
- Reduced water without loss of workability
- Water tight / water proof concrete
- Increased strength / durability
- Cement saving / economy
- Improved surface finish
- Unaffected setting times
- Reduced shrinkage and creep

APPROVALS / STANDARDS

IS : 9103, IS 2645, ASTM C 494/C 494 M-99a

PRODUCT INFORMATION

Chemical Base	Modified lignosulfonates
Packaging	275 KG HDPE Barrel
Appearance / Colour	Dark Brown liquid
Shelf Life	12 months from date of production if stored properly in undamaged, unopened, originally sealed packaging.
Storage Conditions	Storage at temperatures between +10°C and +40°C. Protect from direct sunlight, frost and contamination.
Density	~ 1.18 kg/litre (at 25°C)
pH-Value	≥ 6

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APPLICATION INFORMATION

Recommended Dosage	0.2% to 0.5% by weight of cement. Actual dosage to be finalised on the basis of site trials. Stir well before use.
Compatibility	Sika® Plastiment® BV-40 may be combined with many other Sika products. Compatible with all types of cements and cementitious materials. Important: Always conduct trials before combining products in specific mixes and contact Sika Technical Service for more information and advice.

APPLICATION INSTRUCTIONS

DISPENSING

Sika® Plastiment® BV-40 can be added into the mixing water or directly into the concrete mixer after 50 – 70% of the mixing water has been added. The addition of Sika® Plastiment® BV-40 to dry aggregate or cement is not recommended. To achieve optimum performance a minimum wet mixing time, which is depending on the mixing conditions and the mixer performance, of 60 seconds is recommended.

LIMITATIONS

Excessive water addition or overdosing may cause bleeding or segregation. Overdosing may cause extension of initial and final setting times. If frozen and / or if precipitation has occurred, Sika® Plastiment® BV-40 may be used after thawing slowly at room temperature and after intensive mixing.

BASIS OF PRODUCT DATA

All technical data stated in this Product Data Sheet are based on laboratory tests. Actual measured data may vary due to circumstances beyond our control.

LOCAL RESTRICTIONS

ECOLOGY, HEALTH AND SAFETY

For information and advice on the safe handling, storage and disposal of chemical products, users shall refer to the most recent Safety Data Sheet (SDS) containing physical, ecological, toxicological and other safety-related data.

LEGAL NOTES

The information, and, in particular, the recommendations relating to the application and end-use of Sika products, are given in good faith based on Sika's current knowledge and experience of the products when properly stored, handled and applied under normal conditions in accordance with Sika's recommendations. In practice, the differences in materials, substrates and actual site conditions are such that no warranty in respect of merchantability or of fitness for a particular purpose, nor any liability arising out of any legal relationship whatsoever, can be inferred either from this information, or from any written recommendations, or from any other advice offered. The user of the product must test the product's suitability for the intended application and purpose. Sika reserves the right to change the properties of its products. The proprietary rights of third parties must be observed. All orders are accepted subject to our current terms of sale and delivery. Users must always refer to the most recent issue of the local Product Data Sheet for the product concerned, copies of which will be supplied on request.

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