OPTIMIZATION OF TERNARY BLENDED CEMENT USING PFA AND GGBS

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Technology (Honours) Construction Management

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"OPTIMIZATION OF TERNARY BLENDED CEMENT USING PFA AND GGBS"** was prepared by **CHEONG ZHEN ZHUAN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Technology (Honours) Construction Management at Universiti Tunku Abdul Rahman.

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OPTIMIZATION OF TERNARY BLENDED CEMENT USING PFA AND GGBS

ABSTRACT

An increase in the price of the cement together with its high CO_2 emission level makes low-carbon alternatives more desirable. As such, research on optimizing the use of ternary blended cement through the use of supplementary cementitious materials such as Pulverized Fuel Ash and Ground Granulated Blast-Furnace Slag is gaining momentum. In this regard, this paper aims to investigate the effects of the two materials on optimizing ternary blended cement based on workability, strength and durability parameters. This is achieved through experimentation in the laboratory where experiments were conducted based on the 100% OPC control blend together with other ternary blends. In this experiment, the ratios of water-binder at 0.5 and binder-sand at 1:3; binder contains 2% sodium hydroxide and 4% sodium silicate as alkali activators are kept constant for each ternary blend. Flow tests, compressive and flexural strength, water absorption and porosity were done on each blend at 3,7,14 and 28 days. From the analysis, it can be concluded that an increased addition of both PFA and GGBS enhanced the workability in the fresh state, with the maximum flow being recorded as 132.5% compared to 40.0% in the case of pure OPC. On the other hand, all the ternary blends had lower compressive and flexural strength after 28 days than the pure OPC; however, both compressive and flexural strength increased as the curing age advanced. Compressive strength of the ternary blend with the highest value was observed in C40-P15G45 with 16.99 MPa, whereas the blend with the highest durability was C20-P20G60, with flexural strength of 6.29 MPa, water absorption of 3.55%, and porosity of 17.50% after 28 days of curing. From this analysis, it is evident that a blend of cement with a high amount of GGBS and a moderate amount of PFA is the most effective combination.

Keywords: Ternary Blended Cement; Ordinary Portland Cement (OPC); Pulverized Fuel Ash (PFA); Ground Granulated Blast-Furnace Slag (GGBS); Supplementary Cementitious Materials (SCMs); alkali activation; compressive strength; flexural strength; water absorption; porosity; sustainable construction materials; low-carbon cement.

Subject Area: HD9715-9717.5 Construction Industry

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LIST OF SYMBOLS

%	Percent
kg	Kilogram
RM	Ringgit Malaysia
US$	U.S. Dollar
mm	millimeter
g	gram
N	Newton
mm^2	Square millimeter
N/mm^2	Newton per square millimeter
cm	Centimeter
cm^2/g	Square centimeters per gram
ºC	Degree Celsius
MPa	Megapascal
$<$	Less than
$>$	More than
$\leq$	Less than or equal to
$\geq$	More than or equal to

LIST OF ABBREVIATIONS

OPC	Ordinary Portland Cement
SCMs	Supplementary Cementitious Materials
PFA	Pulverized Fuel Ash
GGBS	Ground Granulated Blast-Furnace Slag
FA	Fly Ash
SF	Silica Fume
MK	Metakaolin
PC	Portland cement
GBFS	Granulated Blast Furnace Slag
CO_2	Carbon dioxide
NaOH	Sodium hydroxide
Na_2SiO_3	Sodium silicate
Ca	Calcium
Si	Silicon
$Ca(OH_2)$	Calcium hydroxide
CaO	Calcium oxide
C-S-H	Calcium-silicate-hydrate
C-A-S-H	Calcium-aluminum-silicate-hydrate
SiO_2	Silicon dioxide
Al_2O_3	Aluminium oxide
CH	Carbon-hydrogen
Fe_2O_3	Iron(III) oxide
Al	Aluminum
Na	Sodium
$(SiO_4)^{4-}$	Silicate monomer
$Al\ (OH)_4^-$	Aluminate monomer

N-A-S-H	Sodium-aluminosilicate-hydrate
C-(N-)-A-S-H	Calcium-sodium-aluminosilicate hydrate
KOH	Potassium hydroxide
Na_2O	Sodium oxide
C_3S	Alite
C_2S	Belite
C_3A	Celite
C_4AF	Felite
H_2O	Water
$NaO(SiO_2)_2$	Sodium disilicate

CHAPTER 1

INTRODUCTION

1.1 Research Background

Construction projects actively contribute to societal development and bolster economic growth. Although financial factors are among the key limitations in construction projects, cost overruns are a common occurrence in the industry. One of the most significant drivers of cost overruns is inflation, which significantly affects the cost of building materials throughout the project. According to a 2024 report by Business Today, the cement unit price index has gone up in almost all areas in June 2024, increasing between 0.1% and 2.1% compared to the previous month, based on data from Malaysia's Department of Statistics (DOSM). On the other hand, the year-on-year change in June 2023 to June 2024 showed a rise in the cement price indices of 0.4% to 4.7% in all areas, with the highest increase of 4.7% again recorded in the Selangor/Kuala Lumpur/Malacca/Negeri Sembilan areas, while Tawau showed a 2.2% increase, and Penang, Kedah, and Perlis showed a 2.0% increase each. It was also noted that the average retail price of ordinary Portland cement recorded a marginal increase of 0.3%, or RM23.10 per 50kg bag, compared to the average retail price of RM23.04 per 50kg bag in May 2024 (feature editor BusinessToday, 2024).

Factors contributing to the sustained price increases in Malaysia's cement industry include rising raw material and coal prices, escalating transportation costs, and the strengthening of the US dollar against the ringgit. Market demand has increased, and with corporate profit margins declining, future demand growth is expected to become even more robust. The government's plan to remove electricity subsidies for medium- and high-voltage industrial users, as a measure to alleviate high coal costs in the energy sector, is expected to exacerbate the challenges facing the cement industry. The DOSM reported that this move could lead to a RM200 (approximately US$45.7) per ton increase in cement prices to offset rising operational costs (International Cement Review, 2023). According to Hume Cement, there have been delays in delivering cement due to a lack of transport because of the strict enforcement of rules against overloading. In order to manage the rising logistical expenses and inefficiencies, Hume Cement raised its price for cement by around 10%. Combined with strong demand and supply constraints, this puts upward pressure on cement prices (Chelsea J Lim and John Lai, 2026). The increase in cement prices will definitely cause a rise in the market price of other building materials, construction costs, service prices, and house prices, depending on how much the increased cost of materials affects the overall construction costs.

Concrete has become the most commonly utilized one because of its numerous advantages compared to other materials. It is highly regarded primarily for its exceptional mechanical properties and cost-effectiveness. It also has the tendency to be shaped into different sizes and shapes. In addition, normal concrete is approximately to be manufactured at around 6 billion tonnes annually across the globe. As the primary cementitious material in concrete, cement's core function lies in forming a robust material capable of withstanding loads, and its importance cannot be underestimated. Ordinary Portland Cement (OPC) has been employed by the construction industry as the primary component of concrete for over 200 years. However, the production process of OPC consumes an extremely high amount of energy, accounting for 7% to 8% of global carbon dioxide emissions (Mohamad et al., 2021). With increasing global attention on environmental protection and sustainable development, efforts are underway to reduce the use of OPC by partially replacing it with Supplementary Cementitious Materials (SCMs).

The use of supplementary cementitious materials such as blast furnace slag, a byproduct of pig iron production and fly ash generated from coal combustion enables partial substitution of Portland cement. Since these materials do not require additional clinker sintering processes, their application significantly reduces carbon dioxide emissions per ton of cementitious material, considering that the energy consumed in concrete grinding, mixing, and transportation is far lower than that required for clinker sintering. Additionally, the practice is cost-effective, which allows the reuse of by-products resulting from industrial production processes (Lothenbach, Scrivener and Hooton, 2011). The application of SCMs is becoming increasingly widespread and the average proportion of clinker in global cement production has decreased from 85% in 2003 to 77% in 2010. It is projected to continue declining to 71% in the coming years. In the United States, cementitious materials are primarily used in concrete rather than blended with clinker, with over 60% of ready-mix concrete currently incorporating such materials (Juenger and Siddique, 2015).

SCMs such as Ground Granulated Blast-Furnace Slag (GGBS), Fly Ash, and Silica Fume are all industrial byproducts. These materials are either incorporated into the yielding process of Portland cement or replace a portion of concrete mixtures. These admixtures significantly reduce the energy consumption required for clinker production, thereby promoting the development of sustainable concrete and enhancing energy efficiency, primarily due to their lower carbon footprint. However, focusing solely on carbon dioxide emissions reduction is insufficient. Evaluating the structural performance and functionality of novel concrete is crucial (Al-Waked et al., 2024). In the evaluation of the sustainability of concrete mixed with supplementary cementitious materials, three interrelated and interdependent factors must be analysed and comprehensively considered: environmental impact, mechanical properties, and durability.

This project aims to develop a ternary blended cement mix with PFA and GGBS. Later, the mechanical properties of the final model are optimized and the durability characteristics are tested against the OPC standard.

Furthermore, the impact of different proportions of PFA and GGBS in influencing the properties of concrete in its fresh state and in the hardening state was investigated experimentally in this research. The study contributes more knowledge on alternative materials in the construction industry via the innovative use of ternary blends of both the cementing materials and the high-performance concrete, making it possible to produce high-performance concrete that satisfies both the performance and sustainability criteria. In this study, the incorporation of PFA and GGBS in ternary-blended cement was examined to achieve sustainable development. This study explores the addition of PFA and GGBS in ternary blended cement to reduce the use of OPC and supports sustainable development by utilising sustainable construction materials while maintaining concrete performance and helping to reduce the concrete price.

1.2 Problem Statement

1.2.1 Emissions of carbon dioxide released from OPC

Ordinary Portland Cement (OPC) is still considered the most widespread binder material used in construction; however, it is important to highlight that the process of OPC production involves significant emissions of CO_2. Large amounts of energy are used in the process of producing cement, especially in clinker burning, and considerable quantities of CO_2 are emitted into the air by burning lime. As global demand for construction materials continues to grow, the environmental burden of OPC production is expected to increase further. For this reason, this problem poses an important task which needs to decrease its carbon footprint to ensure the sustainability of the construction industry. In this situation, the implementation of supplementary cementitious materials such as GGBS and PFA may be regarded as an efficient solution. It is important to mention that certain replacement ratios need to be selected to avoid compromising the properties of concrete in order to minimize CO_2 emissions. Therefore, it is vital to determine the optimal ternary blend ratio to minimize CO_2 emission without decreasing the quality of the building material.

1.2.2 Replacer of OPC

OPC is extensively used in construction works, but it requires intensive resource consumption, high costs, and poses a threat to the environment due to its extensive use of OPC. Its usage causes increased emissions of greenhouse gases, higher energy consumption, and high consumption of natural resources. Consequently, there is an increasing trend towards partial replacement of ordinary portland cement with by-products from industries. Such by-products can act as supplementary cementitious materials for producing ternary blended cement. These by-products have their advantages since their utilization helps solve environmental and economic issues related to the disposal of waste, decreases the consumption of virgin raw materials, and increases the economy of cement. Nevertheless, it is vital to determine the extent of OPC replacement. Too much replacement leads to reduced early strength of the material, increased setting times, and even affects the durability of cement products. Thus, it becomes necessary to determine the optimal percentage of replacement that will increase the efficiency of the cement in terms of environment and economy without decreasing its characteristics, such as workability, strength, and durability.

1.2.3 Increase in the costs of materials

The rising cost of construction material is becoming a critical problem for the construction industry, as the cost of cement is expected to increase further due to variations in the price of raw materials, fuels, and energy. Since cement is one of the most expensive components in concrete, any increase in its price directly affects the overall cost of construction projects. This issue is especially significant for large-scale infrastructure developments, where material expenses can greatly influence project feasibility and budget control. To reduce dependence on costly OPC, supplementary cementitious materials such as PFA and GGBS suggested to be used as partial replacements. These industrial by-products may help lower material costs while also supporting more sustainable construction practices. However, without proper optimisation, the use of these materials may reduce performance and limit their practical application. Therefore, it is necessary to determine the optimum blend ratio of OPC, PFA, and GGBS that can produce a cement system which is not only cost-effective but also durable and suitable for real construction use.

1.3 Aim and Objectives

This study employs different mix proportions of Pulverised Fuel Ash and Ground Granulated Blast-Furnace Slag to replace the Ordinary Portland Cement material, thereby reducing materials costs and carbon footprint released. To achieve this aim, this study has established the following specific objectives:

i) To examine the best composition of ternary blended cement with PFA and GGBS.
ii) To evaluate the mechanical and durability properties of ternary blended cement with PFA and GGBS to get the applicable ratios.

1.4 Expected Outcome of Study

The expected outcome is the development of ternary blended cement with enhanced durability, improved mechanical strength, and favourable characteristics that reach the same standard of OPC strength. It is anticipated that these performance benefits can be achieved even with a reduction in carbon dioxide emissions during concrete production, which may also help lower the price of concrete.

1.5 Project Scope

This project will develop, test, and deliver an experimental optimization framework for ternary blended cement that uses Ground Granulated Blast-Furnace Slag and Pulverized Fuel Ash as partial substitutes for Ordinary Portland cement. The main objective is to determine a workable mix ratio and processing procedures that lower material costs and embodied CO_2 while still providing the necessary characteristics for typical structural applications. Instead of a commercial full-scale plant rollout, this scope is divided into coordinated work packages that collectively result in a functional laboratory prototype, including optimal mix designs, test results, and implementation advice.

In the first phase of the project, different ratios of the SCMs added to the cement will be implemented, which will allow identifying the best ratio to be applied in the real industry. Initial trial mixes covering a wide range of PFA and GGBS substitution levels will be prepared and tested for fresh properties of their flowability, setting time, and early age strength. By distributing the ratios of the addition of SCMs, the best performance of the final product can ensure that it significantly assists in reducing the use of OPC. Alkali solution will also add into the cement for early hydration and enhancing early strength development.

The project will incorporate laboratory-based investigation, which consists of the density test, water absorption test, porosity test, flexural strength test and compressive strength test. These techniques contribute to exploring the addition of PFA% and GGBS% replacement, binder-sand ratio and water-binder ratio, ensuring it can reach the standard hardened properties, such as performance, durability, and mechanical properties. This, in turn, allows for timely and precise ternary blended cement without overwhelming resources, making the system both effective and practical for large-scale deployment.

The performance assessment of the ternary blended cement will also be a research aspect. The project also plans to optimize the best ratio that can reach the standard of OPC, in terms of strength, mechanical properties and durability properties. The evaluation will be carried out at 3, 7, 14 and 28 days curing intervals to test the concrete, whether it can help to reduce the carbon footprint and the materials price by comparing its effectiveness to this baseline.

In this project, a control variable of 100% OPC without SCMs will also be included as a comparison to discuss the functioning of SCMs in the substitution of the OPC. The performance will be evaluated and compared with the state of the ternary blended cement optimize, on key dimensions like strength, mechanical properties, and durability properties. This comparison will help assess the suitable ratios of SCMs added to achieve comparable, if not better, performance of the OPC.

For real-world implementation, the project will evaluate the scalability of the SCMs used in the OPC and their deployment in the materials used. This will involve assessing the ease with which this mixture can be incorporated into the existing construction industry, as well as identifying any challenges, either strengths or durability, that could inhibit widespread adoption. Additionally, the pipeline will feature and list solutions to these hurdles preventing us from leveraging ternary blended cement in a real-world application.

In summary, this project aims to develop a proof of concept of a ternary blended cement that can guarantee the strength and durability are maintained by substituting PFA and GGBS, thus serving the dual purpose of ensuring the reduction of environmental impact and decrease of materials price for deploying this ternary blended cement in the construction industry.

1.6 Limitations

This project delivers laboratory-scale optimization and characterization of ternary blended cement using PFA and GGBS; therefore, recommended mix designs and performance results are valid only for the specific material sources, test procedures, and curing conditions used here. Numerous significant restrictions must be considered, and this issue may prevent the investigation from proceeding further. The limitations of doing this project are written below:

- **Long-term durability and environmental performance assessment:** The current study was mainly focused on the properties of fresh concrete and the properties of basic hardening of ternary blended cement; however, there is no thorough long-term durability investigation included in the experiment. There are several factors that affect durability, including sulfate resistance, acid resistance, chloride penetration, drying shrinkage, and high-temperature resistance, which have not been tested in this experiment. In spite of the fact that the optimized mix might perform well at an early age, its long-term strength, permeability, and resistance to chemical attack remain uncertain. Moreover, the environmental effect analysis in the experiment was mainly concentrated on the decrease of OPC content and CO_2 emissions. The experiment has not taken into account other factors like the whole lifecycle of the material and long-term effects after exposure. Therefore, the overall sustainability and durability of the ternary blended cement cannot be fully confirmed, highlighting the need for further long-term studies under realistic service conditions.

- **Microstructural or mineralogical analysis:** This study is limited by the absence of microstructural and mineralogical analyses such as SEM, XRD, FTIR, and TGA, which are commonly used to explain the hydration products, phase composition, pore structure, and bonding mechanisms in ternary blended cement. Even though the flow table test, flexural strength test, compressive strength test, water absorption test, density test, and porosity test have yielded informative results for the performance of the mixture, there is still no explanation regarding the reactions that occur between the three ingredients, namely the ordinary Portland cement (OPC), pulverized fuel ash (PFA), and ground granulated blast furnace slag (GGBS). As a result, the reasons behind the observed strength development and absorption behavior cannot be fully confirmed, and the changes in cement paste, interfacial transition zone, and pore refinement remain unclear. Therefore, further studies using microstructural and mineralogical techniques can better explain the material's performance and validate the interaction of the blended components.

- **Variation of alkali activator properties:** This research is restricted by the fact that the alkali activator composition was kept constant using only NaOH and sodium silicate, without varying important activator parameters such as NaOH molarity, sodium silicate-to-NaOH ratio, activator-to-binder ratio, or activator dosage. Because of this, this study being restricted to binder composition and not considering the effects of changing activator composition on parameters like workability, strength development, setting time, porosity, and durability. As a result, the optimum ternary blend identified in this research may not represent the best overall performance under different activator conditions, and the interaction between activator properties and the OPC–PFA–GGBS system remains unclear. Therefore, further research is needed to assess how different alkali activator proportions affect the fresh, hardened, and microstructural properties of ternary blended cement.

1.7 Significance of Study

Concrete used as a core material and its main binder, Ordinary Portland Cement (OPC), has been in use for a long time in the construction industry. This study is significant as it addresses the urgent need for sustainable alternatives to Ordinary Portland Cement (OPC), whose high carbon emissions and high costs of the raw materials have driven the search for replacer binders. By optimizing a ternary blended cement incorporating industrial by-products such as Pulverized Fuel Ash and Ground Granulated Blast-Furnace Slag, this research explores a pathway to reduce the carbon footprint of concrete production while also lowering the materials costs. Through a detailed investigation of the hardening rate and strength development under water curing, this work aims to determine the optimum synthesis of PFA and GGBS blends for use in mortar or concrete. The findings will contribute valuable insight for advancing low-carbon construction materials and promoting a more economical built environment. This study helps make concrete production greener and cheaper without sacrificing strength or durability, and produces the practical recipes and evidence needed for industry uptake.

The advantages of using blended materials as partial substitutes for Portland cement have been fully demonstrated. However, both types of blended materials applied in the ternary blended cement still exhibit certain shortcomings. Supplementary cementitious materials (SCMs) have been used since the 1970s to improve performance and minimize environmental effects by partially replacing OPC. Although binary blended cements, like Portland-slag or Portland-pozzolanic systems, are already standardized globally, new developments have shown that ternary blends, which combine two SCMs, have better durability and mechanical qualities than binary systems (Menéndez et al., 2003). Enhancing ternary blended cement with PFA and GGBS not only optimizes resource efficiency by valorizing industrial by-products and preventing landfill disposal, thereby augmenting resilience against price volatility, but also mitigates exposure to fluctuations in cement prices and energy or coal costs.

Ternary blended cement needs focus lies in advancing the development of resource-efficient ternary blended cement under ambient curing conditions. Since the middle of the 1990s, ternary systems have shown a great deal of potential in providing specific characteristics by utilizing the unique characteristics of each constituent to get around the limitations of traditional binary blends. However, real-world obstacles, including increased water use, fluctuating prices, and excessive heat production during hydration still prevent their wider use. Blending different types of ash resulted in improved the mechanical properties of the corresponding binary systems throughout the entire curing period (Antiohos et al., 2007). This study attempts to attain the best possible balance between performance, cost, and sustainability by refining the synthesis of PFA and GGBS ternary blends and assessing their rate of hardening and strength development at moisture temperature. The results will offer crucial direction for creating high-performance, low-carbon cementitious materials that can be used in mortar and concrete applications in the real-world industry.

The production of clinker and high-temperature calcination are the main causes of the cement industry's significant anthropogenic CO_2 emissions; hence, substituting some of OPC with SCMs like PFA and GGBS provides a practical way to reduce carbon emissions without requiring a total process change. Ternary blended cements skip the clinkerization stage, which is the source of the majority of process emissions, and promote the circular economy by valorizing industrial by-products, transforming waste streams into useful secondary raw materials. Well-designed ternary systems can enhance both fresh and hardened qualities such as workability, dimensional stability, long-term strength, durability, and resistance to sulfate or chloride attack, in addition to environmental benefits, which make them technically attractive as well as sustainable (Campagiorni et al., 2024). Enhancing ternary blended cements with PFA and GGBS diminishes reliance on OPC, but also elevates performance capabilities, as meticulously formulated blends can match or exceed OPC in terms of resistance to sulfate or chloride exposure, long-term strength, and durability, thereby promoting both circular economy principles and high-performance construction. Furthermore, it promotes practical application by offering explicit optimization strategies and implementation guidance, such as mix proportions, water-to-binder ratios, and processing steps, that support the extensive utilization of blended cements in actual construction projects.

1.8 Research Framework

The optimization of ternary blended cement by using PFA and GGBS

Problem Statement

- Emissions of carbon dioxide released from OPC
- Replacer of OPC
- Increase in the costs of materials

Limitations

- Long-term durability and environmental performance assessment
- Microstructural or chemical analysis
- Variation of alkali activator properties

i) To examine the best composition of ternary blended cement with PFA and GGBS.

ii) To evaluate the mechanical and durability properties of ternary blended cement with PFA and GGBS to get the applicable ratios.

Constant Variables

- W/B ratio = 0.5
- B/S ratio = 1:3
- NaOH solids = 2% of binder
- Na_2SiO_3 = 4% of binder

Manipulated Variables

- Cement: SCMs ratio = 4:6, 3:7, 2:8, 1:9

Examine the outcomes to determine whether they help to solve the problems and achieve the aim and objectives of the study.

1.9 Organization of the Report

The report is divided into chapters, each representing parts of the project, including introduction, literature review, methodology, results, and conclusions in a structured manner. The chapters are written in a logical order to ensure clarity and as concisely as possible.

Chapter 1: Introduction

This chapter presents the project description which contains a little bit of the background, problem statements, aims, objectives, limitations and project scope. It illustrates the updated challenges that the rise of the materials costs and highlights the environmental challenges posed by the overuse of Ordinary Portland Cement, particularly the carbon dioxide release during production of OPC poses to the environment. It mentions the need for solutions which use supplementary cementitious materials (SCMs) in cement and present a more economical and environmentally friendly method to solve them.

Chapter 2: Literature Review

In this chapter, existing literature review provides a comprehensive discussion of ternary blended cements and the role of SCMs in improving mechanical and durability properties while reducing environmental impact. It covers the materials properties in geopolymerization mechanisms of ternary systems, synergistic effects of PFA and GGBS, and previous studies on their optimal replacement levels. Key reactions such as pozzolanic reaction, latent hydraulic reaction, cement hydration are examined. The effects of PFA and GGBS on the mechanical and durability properties of ternary blended cement will be discussed. The review also highlights gaps in existing studies, particularly the lack of systematic optimization approaches for ternary blends in local contexts, thereby justifying the research.

Chapter 3: Research Methodology

This chapter mainly outlines the experimental approach adopted to optimize ternary cement blends. The methodology includes the selection of raw materials, application of alkali activator, mix design proportions, and preparation of test specimens. Laboratory testing procedures for fresh properties, mechanical properties, and durability characteristics are described. Experimental testing method, which consist of the flow table test, compressive strength test, flexural strength test, porosity test, and water absorption test, are employed to identify the optimum blending ratios. Mixing design, casting procedures, curing conditions, and the schedule of tests (3, 7, 14 and 28 days strength) are applied to ensure strength aligns with the same level or higher than OPC standards.

Chapter 4: Results and Discussions

The results chapter presents several results derived from the experimental work conducted on the tested ternary cement blends. It utilizes a comprehensive performance analysis of a ternary blended cement and compares it with the performance of the control mix of 100% Ordinary Portland Cement. Results will be evaluated based on the key performance metrics like compressive strength development, flexural strength, and durability performance. This chapter will more significantly examine these outcomes and the merits and demerits of the results.

This discussion chapter covers those experiments and evaluations in detail. It provides findings concerning how varying proportions of PFA and GGBS influence hydration kinetics and mechanical performance at different curing ages and demonstrates the synergistic benefits of combining PFA and GGBS, such as enhanced later-age strength and reduced permeability. Statistical optimization outputs are analyzed to determine the most effective blend ratio. The results are compared with academic journals, standards, and technical reports cited, and discuss where this ratio can be used, how it can be scaled and modified for real cases.

Chapter 5: Conclusions and Recommendations

The final chapter of the conclusion summarises the overall findings of the project, concluding whether ternary blends of OPC with PFA and GGBS can significantly enhance cement performance while reducing clinker dependency and environmental impact. The last chapter will outline whether the success of the project which the optimized mix demonstrates, is superior long-term strength and durability compared to OPC-only cement. It will also draw on practical implications for the construction industry to emphasizing cost-effectiveness and sustainability benefits. The challenges in large-scale applications, life-cycle assessments, and the exploration of other supplementary materials in ternary systems still need to be tackled in the construction industry. Recommendations will be given for the improvement and suggestions for future study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Construction and demolition waste are generated on a growing scale every year in developing nations. For instance, China produced more than 15 billion tons of construction and demolition debris in 2016, but the overall usage ratio was less than 10%. Conventional waste disposal methods such as landfilling or piling, will not only require space for storage but will also result in increased carbon dioxide emissions, which would pose severe environmental problems. The majority of construction and demolition debris really falls under the category of renewable materials, which includes leftover concrete, natural stone, brick, etc. As a result, employing construction and demolition wastes as recycled aggregates in concrete mixtures to partially or completely replace natural aggregates is a sustainable civil engineering solution (Xie et al., 2018).

In addition to the construction waste and demolition waste, the “air pollution” environmental effect due to the extensive use and production of ordinary Portland cement (OPC) is also increasing very fast. According to sources, the production of ordinary Portland cement (OPC) contributes to about 5% - 7% of the total carbon dioxide (CO_2) emissions globally. OPC replacements are necessary to minimize the impact of OPC concrete on CO_2 emissions. OPC paste has been partially substituted with fly ash, silica fume, and GGBS, which have proven to be more durable and physically robust than OPC (Xie et al., 2018).

This approach not only reduces OPC consumption but also improves long-term strength, durability, and sustainability. Optimization of these blends involves determining ideal replacement ratios to balance early-age properties like workability and setting time with later-age performance to examine their compressive strength and long-term durability. Current studies have concentrated on experimental evaluations of mixed proportions, mechanical properties, and price benefits, highlighting the potential for high-volume replacements in sustainable construction.

This literature review seeks to investigate the ternary blended cement by applying PFA and GGBS inside, providing insight into different ratios, challenges and solutions. This review paper synthesizes the most recent research results in this field and the test of examine the effect on mechanical and durability performance. This offers an extensive discussion of how ternary blended cement is revolutionizing the rise of materials costs and environmental impact in the construction industry, as well as opportunities for future research and development.

2.2 Definition of Ternary Blended Cement

Blended cements are cements where part of the clinker is replaced by other substances. Granulated slag from the production of pig iron, FA, and non-calcinated limestone play significant roles all around the globe. Moreover, an increasing amount of minerals is employed in cement compositions on the local level. At present, mixed cement application is experiencing growth on the global level. However, different countries make use of various types of cement, and there are differing industrial standards in different countries. To some extent, this situation is caused by differences between the standards themselves, and therefore, the standards are applied differently in different countries. Several methods have been proposed by the cement industry to reduce the amount of CO_2 emissions to tackle the global problem. One of the most effective and immediate solutions would be the development of low-CO_2 footprint cements produced by replacing traditional clinkers with alternative binders. In this context, a wide range of scientific works have addressed the properties of the so-called blended cement, where SCMs, including fly ash (FA), silica fume (SF), GGBS, and metakaolin, partly substitute OPC (Campagiorni et al., 2024).

Between the years 1980 and 1990, studies were done to produce models for predicting compressive strength of mortars containing OPC-GBFS-fly ash (FA). Ternary mixes' compressive strength could be predicted from the use of iso-strength contours. Since the beginning of the 1980s, some researchers have stated that ternary cements performed way better than binary cement and ordinary Portland cement (OPC). Malhotra emphasized at the early 1990s on the development of ternary cement and blending of these types of cement. St. Lawrence Cement produces ternary blend cement consisting of SF and FA, while Lafarge Cement produces ternary blend cement containing GBFS and SF. Quaternary and ternary cements had been intermittently available in several regions of Australia since 1966 (Nehdi, M., 2001).

The fly ash substitution in binary cements would reduce the water demand, while slag substitution in OPC would increase the water demand at the same consistency level. Therefore, one can say that fly ash helps in improving the flowability of concrete by being a water reducing material, but GGBS cannot do the same. Hence, a ternary cement would achieve the same flowability as OPC by using both slag and fly ash. Whatever the type of clinker, fly ash substitutions in binary cements would result in longer setting times, while slag substitutions in ternary cements would depend on the clinker type and would lengthen or shorten the setting times. Two types of setting times were observed for the ternary cements of Holcim and Lafarge. Holcim slag substitution in Holcim ternary cements does not result in delaying the paste setting times but, rather, reduces the increased setting times caused by fly ash. Contrary to the above case, the ternary cement shows an increased setting time with increased concentrations of SCM when 20% slag and 15% fly ash substitutions were made in Lafarge slag-blended cement (Kejin Wang & Zhi Ge, 2003).

A crucial aspect of minimizing the effect of cement manufacturing on the environment, without compromising or enhancing building properties, is the application of cement systems made up of other cementitious materials besides those used in traditional Portland cements. The current review highlights the effectiveness of the synergies brought about by the combination of limestone together with Supplementary Cementing Materials (SCM), including ground granulated blast furnace slag (GGBS), silica fume, fly ash, and metakaolin. Each of these materials brings different benefits to construction processes through the development of more sustainable, durable, and low-CO_2 cementitious blends. Apart from reducing the amount of conventional Portland cements in the blends, which are known to emit a lot of carbon dioxide, the addition of SCMs enhances features like the workability and long-term strength of the mixture. Nevertheless, an issue worth noting is the inconsistency in their compositions and performances (Campagiorni et al., 2024).

A ternary blended cement is defined as a hydraulic cement that is made up of ordinary Portland cement (OPC) together with two supplementary cementitious materials (SCM). In this regard, the SCMs utilized in ternary blended cements are normally by-products from industries such as pulverized fuel ash (PFA) or GGBS (ground granulated blast-furnace slag). For instance, when referring to the ASTM standard for blended cements (ASTM C595), a “Type IT” of blended cement has two SCMs together with OPC. According to industry publications, “ternary cements are blends of two complementary supplementary materials such as fly ash, slag cement or silica fume.” (Blended Cement Supplier | Sustainable Cement Solutions | Heidelberg Materials) Therefore, “a tertiary blend is made by using OPC together with two mineral admixtures to replace part of the cement.” The use of OPC together with two mineral admixtures enables reduced clinker content in ternary blended cements while maintaining hydraulic reactivity (Glavind, 2009). The aim is to achieve performance in strength and durability comparable to that of pure OPC cement while lowering costs and carbon emissions.

2.3 Overview of Supplementary Cementitious Materials

The application of silicon-rich SCMs affects the quantity and nature of hydration products and their volume, porosity, and durability consequently. Due to the presence of SCMs at the usual substitution rates, the Ca/Si ratio in C–S–H gel becomes lower, and some part of portlandite gets consumed. Silica-rich SCMs enhance the incorporation of alumina into C–S–H gel and increase the amount of aluminate phases. The partial replacement of PC can be achieved effectively through the employment of certain types of SCMs, such as fly ash, produced during the combustion of coal, or blast-furnace slag, obtained as a result of the manufacture of pig iron. Apart from applying secondary raw materials, produced during different industries, the employment of such SCMs, which do not involve an additional clinker production stage, leads to the reduction of carbon dioxide emissions per ton of cementitious materials. This is possible since the energy costs of producing concrete through grinding, mixing, and transporting of concrete become lower than those of the clinkering process (Lothenbach et al., 2011).

Supplementary cementitious materials are increasingly being used in place of some of the cement, which affects the final mortar's or concrete's mechanical properties and environmental impact. Eco-mechanical properties of both binary and ternary blended cement mortars have been evaluated in a study. Fly ash and crushed granulated blast-furnace slag have been used for this purpose at various cement replacement levels. Ternary blended cements with cement replacement percentages ranging from zero to 40% displayed acceptable compressive strengths and flow behavior when compared with binary blended cements. Life cycle assessment revealed that cement replacement percentage, rather than replacement materials or mixing ratio, played a more critical role with regard to the main environmental impacts of fine particulate matter production and global warming potential. The same conclusion can be drawn regarding eco-mechanical performance with respect to the particulate matter to strength ratio and the global warming potential to strength ratio. Mortars with cement replacement percentages of 20% and 40% improved performance by around 20% and 40% on average (Radwan et al., 2020).

The significant improvement in the application of SCMs over the past two decades can be attributed to a number of factors that need to be considered together. The most important factor among these is that the SCMs have pozzolanic characteristics, which means that there is no need for pre-clinkerization and reduced CO_2 emissions on a per ton basis of cementitious material. Furthermore, many SCMs are byproducts of other industries and hence can be termed as secondary raw materials. This makes it possible to create a waste-to-resources green supply chain that adheres precisely to the circular economy's ideals. In addition to its positive effects on the environment, recent research has demonstrated that adding SCMs to hardened concrete can enhance its sustainability, improved strength, and eventually the material's workability and durability properties (Campagiorni et al., 2024).

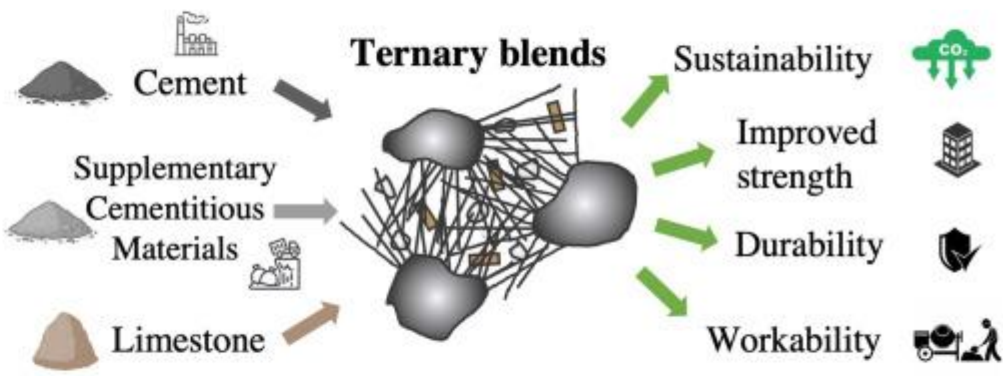

Figure 2.1: Overview of Ternary Blends (Campagiorni et al., 2024)

SCMs are finely divided materials that exhibit cementitious or pozzolanic properties in concrete. The most common SCMs in ternary blends are GGBS and PFA. These are chosen because they react with water and OPC hydration products (especially $Ca(OH)_2$) to form additional binding phases like C–S–H gel. Using SCMs in place of a portion of OPC brings economic and environmental benefits and often improves certain concrete properties. For example, GGBS and PFA as cement replacements can both reduce CO_2 emissions (by displacing OPC) and enhance long-term durability (Ahmad et al., 2022). Their effects on fresh and hardened properties depend on their specific characteristics and blend ratios, as described below.

2.3.1 Properties of SCMs using

2.3.1.1 Ground Granulated Blast-Furnace Slag

GGBS is the byproduct of the production of iron and steel. It is formed by the mixing of iron ore, coke, and limestone in a blast furnace operating at temperatures of about 1500°C. Under these temperatures, the iron ore forms molten iron, while the limestone serves as flux to clean the molten iron from any impurities. This results in molten slag, which floats to the top due to its lower density compared to molten iron. GBFS is formed through the fast cooling of molten slag using a high-pressure water jet. GGBS is made by grinding, drying, and pulverizing the slag into powder form using a revolving ball mill. GGBS is mainly used in the construction sector as supplementary cementitious material in concrete to partially replace Portland cement in concrete mix owing to a similar amount of CaO content that gets hydrated when reacting with water (Ban & Kang, 2019). Qiu et al. (2019) also reveal that the degree of calcium content has a considerable impact on the strength and structure formation of the geopolymer. C-S-H and C-A-S-H binding is encouraged by higher GGBS content, which also leads to higher levels of calcium. The bonding leads to geopolymer with better integration and a denser matrix, reducing its permeability and extending the life of the concrete (Qiu et al., 2019).

Chemically, GGBS is rich in CaO, SiO_2 and Al_2O_3 (its oxide composition is broadly similar to OPC clinker). The reason why GGBS exhibits pozzolanic properties lies in its glassy structure, which makes it a latent hydraulic binder. GGBS will undergo slow hydration in contact with water and react with calcium hydroxide to produce C-S-H gel. Compared to most fly ashes, GGBS exhibits stronger pozzolanic activity; hence, it will consume CH faster and contribute to the strength formation process more effectively. As an alternative binder to OPC, GGBS tends to produce less heat during hydration and increase set time due to slow reaction kinetics; however, using GGBS might enhance the ultimate strength. For instance, Ahmad et al. demonstrate that concrete produced by partial substitution of GGBS for OPC (usually 10-20%) develops higher mechanical strength and improved durability characteristics (Ahmad et al., 2022). Besides, GGBS usually demonstrates less water requirement compared to OPC and PFA, improving workability at certain W/B ratios. Overall, GGBS can be described as a supplementary cementitious material because it reacts both independently and through the pozzolanic reaction, producing additional C-S-H and C-A-S-H in alkaline environments (Oti et al., 2025).

2.3.1.2 Pulverized Fuel Ash (PFA)

The formation of coal fly ash occurs as a result of combustion in power stations in the production of electricity, and it is one of the coal combustion residuals. Some of the by-products resulting from the combustion of coal are flue gases, boiler slag, and fly and bottom ashes. FA has been collected together with flue gases following the burning of coal. It is chiefly composed of siliceous and aluminous glass, often low in CaO (Alterary & Marei, 2021). The pulverized fuel ash (PFA) or fly ash material is used in concrete mixture formulations because of its extremely fine particles and glass spheres that are similar in appearance to cement materials. The specific gravity of pulverized fuel ash (PFA) is 2.80, while its specific surface area is always within the range of 3000-5000 cm^2/g. Fly ash fineness results in improved bond creation in the concrete's microstructure. The use of fly ash enables a decrease in the w/b ratio without compromising workability since the rheology of the concrete mixture is enhanced (Ban & Kang, 2019).

The chemical composition of PFA consists mostly of SiO_2, Al_2O_3, and CaO, with a relatively low content of CaO compared to GGBS. The pozzolanic reaction is the dominant reaction of PFA, which results in the formation of extra C–S–H and C–A–S–H gels when it reacts with CH produced through OPC hydration reactions or an alkaline activator (Oti et al., 2025). The reaction rate of PFA is relatively slow compared to GGBS, and therefore blends containing PFA will exhibit slower strength development but may eventually catch up after day 28. The spherical nature of PFA particles makes it have a ball-bearing effect that helps improve the flowability of the wet mixture. In concrete, partial substitution of OPC by PFA will reduce early-age strengths but increase late strengths while decreasing permeability. Other properties that can be improved by using PFA include reduced heat generation due to the low OPC content, increased resistance to sulfate attack and alkali-silica reactions, and improved resistance to carbonation. However, too much PFA can result in low strengths if it is not properly activated or cured (Warrenty, 2026).

The large range of diversity in the FA composition makes it challenging to characterize. Fly ash was therefore categorized by the American Society for Testing and Materials (ASTM) into two categories: class C and class F. Class F fly ash is pozzolanic and is generated when bituminous or anthracite coal is burned. In addition, it is required that more than 70% be comprised of SiO_2, Al_2O_3, and Fe_2O_3. On the other hand, Class C ashes, obtained from the combustion of lignite or sub-bituminous coals, are cementitious and pozzolanic materials. The ASTM states that more than 50% of the mixture must consist of Fe_2O_3, Al_2O_3, and SiO_2. For FA classes C and F, the bulk content of metal oxides serves as a base for most characterisation techniques (Alterary & Marei, 2021). It is important to note that according to Bentz et al. (2011), FA containing calcium content less than 20% is class F, while FA with calcium oxide content exceeding 20% is class C. Moreover, it may differentiate between these two categories based on the percentage of CaO because class C is above 10%, and class F is less than 10%. FA is pozzolanic material that is silica or silica-alumina-based, hence enabling its use in concrete as a replacement of cement (Bentz et al, 2011).

2.3.2 Justifications and Advantages of Using SCMs

Incorporating SCMs like PFA and GGBS into cement yields multiple benefits. The environmental advantage is primary: replacing OPC with waste materials drastically cuts CO_2 emissions and energy use. For every ton of cement replaced by PFA or GGBS, roughly a ton of CO_2 emissions can be avoided. Ahmad et al. note that GGBS offers “a rational way to develop sustainable cement and concrete” and to “mitigate the economic impact” of cement production. SCM use also saves raw materials and diverts industrial by-products from landfills (Ahmad et al., 2022).

From a performance standpoint, SCMs often improve durability and long-term strength. Blended cements with GGBS or fly ash typically form a denser matrix with fewer capillary pores. For example, Oti et al. report that adding GGBS improves particle packing, creating a denser microstructure with less porosity. This densification reduces permeability and improves resistance to aggressive agents like chlorides or sulfates. In fact, blended cement concretes often gain strength beyond 28 days at a higher rate than pure OPC, and the permeability is significantly lower. SCMs also reduce the heat of hydration, mitigating thermal cracking in mass concrete (Oti et al., 2025).

Operational advantages include lower cost and improved workability. SCMs are generally cheaper than OPC clinker; replacing 15–35% of cement with PFA or GGBS can yield substantial material cost savings. The spherical PFA particles and smooth GGBS powder both improve flow, making concrete easier to mix and place (Al-Waked et al., 2024). In summary, SCMs make concrete greener and cheaper without sacrificing strength or durability by reducing clinker content and adding beneficial filler and reactive phases.

2.4 Geopolymerization

Geopolymerization is the alkali-activation process of aluminosilicate materials, distinct from ordinary cement hydration. In highly alkaline solutions (e.g. $NaOH/Na_2SiO_3$), glassy Si/Al oxides in precursors dissolve to form silicate ($(SiO_4)^{4-}$) and aluminate ($Al(OH)_4^-$) monomers. These monomers undergo polycondensation into a cross-linked aluminosilicate network, often referred to as N-A-S-H or C– A–S–H gels. Key factors control geopolymerization kinetics: alkali type/concentration, silicate modulus, temperature, and liquid/solid ratio. For example, higher NaOH molarity or $Na_2SiO_3/NaOH$ ratio enhances dissolution and early strength (Izadifar et al., 2026).

In practice, one study found NaOH plus Na_2SiO_3 activator drastically improved flowability: FA+GGBFS mixes flowed 16–26% more than OPC paste due to FA's "ball bearing" effect and fine slag packing (Wattanachai et al., 2025). The binder contains NaOH 2% and Na_2SiO_3 4% at a ratio of 2:1; most geopolymer solutions contain ~0.3 L/g solid (~30%) and have ratios that are roughly similar to ours. The strength developed may not be optimal for our ratio since a higher Si/Na ratio causes densification of the gel, but the ratio we have is still sufficient to dissolve.

Calcium-containing systems such as slag partially transform into C-(N-)A-S-H in an alkaline medium. Fly ash (rich in Si/Al) gives the N-A-S-H system. Geopolymer systems cure up to 20-50 MPa in 28 days. For instance, according to a study conducted by Nadarajah et al., mixtures of fly ash and ground-granulated blast furnace slag (80% SCM) developed a strength of ~30-35 MPa in 28 days (Nadarajah et al., 2024). Wattanachai et al. obtained ~93.5 MPa in 90 days with 40% GGBFS (Wattanachai et al., 2025). Generally, geopolymer compressive strength improves with optimized alkali content and moderate liquid/solid (our W/B=0.5 is on the high side, which may lower peak strength but improves workability). Many geopolymer studies use high-alkali (>6 M) or thermal curing; fewer examine ambient-curing ternary mixes with such low NaOH percentages. Long-term durability of alkali-activated cementitious blends also needs further study.

2.4.1 Alkali Activators

The type and dosage of alkali activator critically determine geopolymer/mortar behavior. Common activators include NaOH, KOH, sodium silicate, etc. NaOH increases pH and dissolution; higher molarity generally speeds the reaction but can cause rapid setting or efflorescence if excessive. In alkali-activated ternary blends (geopolymers), the reaction is governed by activator concentration, water content, and aggregate content. The alkali activators dissolve aluminosilicate species in the precursors, initiating polymerization. Their concentration and ratio critically influence the setting and strength. For instance, Jayajothi, P et al. found that a Na_2SiO_3/NaOH ratio of 2.5 yielded higher flexural strength and better workability compared to a ratio of 2.0 (Jayajothi, P. et al, 2014). In general, higher silicate content accelerates polymerisation and increases strength but can reduce workability. Conversely, higher NaOH molarity raises pH and dissolves more precursor, increasing early strength. Optimizing the activator mix (molarity, Na_2SiO_3/NaOH ratio and dosage) is therefore key to effective geopolymerization.

Sodium silicate (waterglass) provides soluble Si which accelerates polycondensation into a denser gel. In practice, the Na_2SiO_3:NaOH ratio (the SiO_2/Na_2O modulus) is tuned. Many studies find optimal silicate/hydroxide ratios in the 1:2 to 3:1 range. Literature notes that increasing Na_2SiO_3 (while keeping NaOH constant) often boosts strength and reduces setting time, at the cost of higher viscosity. One report found adding 5–10% Na_2SiO_3 improved early strength under ambient cure (Izadifar et al., 2026).

2.4.2 Water Content

Water content also plays a major role. In geopolymer mixes, extra water beyond the activator tends to stay as free water, increasing porosity. Studies show that a higher liquid-to-binder ratio increases porosity and water absorption, lowering density and strength. For example, Jayajothi, P. et al. reported that an alkaline liquid/binder ratio of 0.4 led to incomplete compaction and more voids, raising water absorption (Jayajothi, P. et al, 2014). Conversely, too little liquid can impede workability and reaction. Thus, the water content must be balanced; typically, a ratio around 0.4–0.6 is used to achieve flow without excessive porosity. In geopolymers, the liquid/binder ratio (L/B) includes activator solutions and any extra water. High L/B improves flow but yields more porosity. Conversely, too little liquid yields a dry, unworkable mix. Our fixed W/B=0.5 (plus activator) is moderate.

2.4.3 Fine Aggregate Content

Fine aggregate (sand) greatly influences mortar rheology and hardened properties. A higher sand-to-binder ratio reduces binder volume, thus raising internal voids and absorption. One study noted that increasing the S/B ratio (less binder) significantly boosted water absorption (by 31–186%) due to reduced paste volume (Prusty and Pradhan, 2022). Moreover, more sand can dry out mixes faster and hinder geopolymerization. In fresh mixes, fine sand increases abrasion and can stiffen the mix.

We fix binder: sand at 1:3, a common mortar proportion. At this level, pastes must coat sand surfaces well. An excess of sand would result in a lean mixture, making it difficult for the mixture to have good flow and cohesion. As indicated by the study conducted by Prusty and Pradhan, as the S/B ratio increased, it required higher activator content to maintain flow, and the absorption rate increased drastically (Prusty and Pradhan, 2022). At our end, maintaining the ratio at 1:3 will ensure that the absorption rate remains low.

2.5 Reaction of Ternary Blended Cement

2.5.1 Pozzolanic Reaction

A pozzolan is an aluminosilicate that reacts with $Ca(OH)_2$ (portlandite) in the presence of water to form secondary hydrates. In blended cements, FA (metakaolin, silica fume, etc.) are pozzolans. They do not hydrate on their own but consume CH from OPC hydration. The classic reaction is:

$$Ca\,(OH)_2 + \text{silica/alumina (from FA)} \rightarrow \text{C–S–H / C–A–S–H} \qquad (2.1)$$

Pozzolanic reaction thus requires a calcium-rich environment. Pozzolans accelerate overall C–S–H formation (after the normal OPC induction period) and fill pores. For example, a recent review notes that MK/FA/GGBFS in Ca-rich mixes produce calcium-silicate hydrates (C–S–H) and calcium-alumino-silicate hydrates (C–A–S–H) as primary binding phases. These products are nearly indistinguishable from OPC hydrate. Hence, pozzolans indirectly increase later-age strength and reduce porosity (Izadifar et al., 2026).

Reactivity depends on glass content, particle fineness, and CH availability. Highly reactive pozzolans (e.g. metakaolin) form C–S–H faster; slower pozzolans (Class F FA) build strength over months. Studies often measure pozzolanic activity by CH consumption or strength gain. In practice, partial FA replacement (5–20%) typically improves 28d strength by up to ~20–40% (Fode, Jande and Kivevele, 2023); however, at very high FA levels (50%+), early strength can drop due to dilution. For example, Gholampour and Ozbakkaloglu report that compressive strength drops sharply as FA increases from 50% to 90% (Gholampour and Ozbakkaloglu, 2017).

Class F PFA is using, which is low in CaO (often <5%) and high in SiO_2+Al_2O_3 (~75%). It relies entirely on OPC's CH. Given W/B=0.5 and our alkali activators, CH will also be partially consumed to activate the FA. Significant late-age gain is expected: e.g. a 50% FA mix might reach near OPC strength by 28 d. Pozzolans also refine pore structure, reducing permeability. In our binder: sand=1:3 mortar, FA's spherical particles should boost flow and packing. Many ternary mix studies observe improved workability and comparable strength at moderate FA levels. One test reported a 75:25 FA: GGBFS mix achieving ~40 MPa at 28 d. Conversely, too much FA (e.g. >75%) tends to reduce early strength and increase absorption (Gholampour and Ozbakkaloglu, 2017).

Most SCM reports focus on concrete; fewer characterize mortar-specific metrics (flow table vs slump). Also, alkali-activated blends behave differently from portlandia-pozzolan mixes. There is a need for systematic data on how W/B, alkali %, and high FA contents interact.

2.5.2 Latent Hydraulic Reaction

Ground granulated blast-furnace slag (GGBFS) is latent hydraulic: it contains reactive glassy CaO–SiO_2–Al_2O_3 that will hydrate similarly to cement once activated. Unlike pozzolans, slag does react with water even without OPC, but very slowly. In a blended mix, the high pH and Ca $(OH)_2$ from cement "activate" slag. Early on, OPC's alite/belite hydration produces CH and C–S–H. After a brief dormant period, $Ca(OH)_2$ and alkalinity initiate slag hydration. The result is additional C–S–H and more strength.

As found in calorimetry studies, adding GGBFS lowers the peak heat release of hydration (PC/GGBS mixes have smaller initial heat than pure cement). The latent nature means the hydration curve is extended: OPC supplies early CH which "turns on" slag after the induction period. An analysis by Noor Azline Mohd Nasir notes: "GGBS is a latent hydraulic material that reacts similarly to PC once in contact with water, but the initial reaction between GGBS and water occurs over a short period, as it results in the formation of an impermeable layer". Ultimately, the total heat at 28 days is the sum of OPC's reaction and slag's secondary reaction (Noor Azline Mohd Nasir, Farah N.A.Abd Aziz and N.A. Safiee, 2014).

Substituting slag typically slows early strength but boosts later strength. Up to ~50% GGBFS replacement can maintain or even improve 28d strength (since slag continues to hydrate). For example, Gholampour & Ozbakkaloglu found 90% GGBFS mixes had 28d strengths comparable to OPC (though early-age strength was lower). Slag also densifies the matrix, reducing permeability and shrinkage. In one study, partial GGBFS replacement increased 28d modulus and decreased capillary pores (Gholampour and Ozbakkaloglu, 2017). Conversely, in pure OPC/GGBFS blends, very high slag (>70%) can limit CH availability and slow hydration.

The ternary mixes include GGBS up to 75% of the SCM fraction. With only 10% OPC, CH may be scarce; however, alkali activators (NaOH) will also help activate slag. We expect compressive strengths on par with OPC if slag≥50% of binder, as seen by Wattanachai et al. (40% GGBFS+20%FA gave 93.5 MPa at 90d). However, a potential gap: the latency of slag means our 7d strengths may be low (Wattanachai et al., 2025). Research gaps remain in determining the optimal NaOH dosage, the effect of the sodium silicate-to-NaOH ratio, and the long-term strength and CH stability beyond 90 days in low-OPC alkali-activated systems.

2.5.3 Cement Hydration

Ordinary Portland Cement hydration is well-known: the principal clinker minerals (C_3S, C_2S, C_3A, C_4AF) react with water. Overall, alite (C_3S) and belite (C_2S) dissolve, precipitating C–S–H gel and crystalline $Ca(OH)_2$ (portlandite). Portlandite and C–S–H provide the paste's strength. Hydration proceeds in stages (dissolution, induction, acceleration, deceleration) as ions saturate and diffusion barriers form (Cuesta et al., 2018). Early-age set is largely driven by C_3A and gypsum (ettringite formation), but long-term strength comes from C–S–H.

In blended systems (with FA/GGBFS), OPC hydration is modified. Slag and FA consume CH (via pozzolanic/latent reactions), lowering the $Ca(OH)_2$ peak; this can alter heat release. A mixed OPC–slag calorimetry study found total heat is reduced and spread out when slag is added (Noor Azline Mohd Nasir, Farah N.A.Abd Aziz and N.A. Safiee, 2014). Pozzolans (FA) similarly smooth the hydration curve by CH uptake. Adding $NaOH/Na_2SiO_3$ (as in alkali-activated cement) further accelerates dissolution of silicates, often reducing setting time. For instance, adding 5% NaOH boosted early binder strength (≤7 d) but excessive NaOH later created non-uniform products. In general, hydration in alkali-activated blends is faster (higher pH) but can become less uniform with too much activator (Izadifar et al., 2026).

In the mixes ($NaOH+Na_2SiO_3$ with OPC), accelerated initial reactions and a higher pH are expected. The OPC portion will hydrate and form CH, which the FA and GGBFS will then consume. We should see a relatively rapid strength gain to a certain point, but also look for signs of unevenness (e.g. efflorescence from excess alkali or ettringite in the presence of sodium). The CH also aids the latent activation of slag. Research gap: detailed heat-metry of such triple-activated blends is scarce; standard hydration models do not apply directly when alkali silicate is present.

2.6 Effects of PFA and GGBS on the Mechanical Properties of Ternary Blended Cement

2.6.1 Compressive Strength Test

The compressive strength of ternary blends depends on the SCM proportions and age. Generally, moderate SCM replacement (often ≤30%) yields concrete strengths similar to or slightly above pure OPC at later ages. For example, Zhou et al. found that GGBS mixes up to 30% cement replacement had compressive strengths comparable to OPC, while PFA mixes showed lower early strengths (Zhou et al., 2012). In many studies, the optimum is achieved when both GGBS and PFA mixes are utilized together. Thus, Al-Waked et al. discovered that the maximum compressive strength was obtained when 30% GGBS and in ternary blends of 10% PFA and 20% GGBS were employed (Al-Waked et al., 2024). This means that GGBS is responsible for strength, because of its hydraulicity, whereas a little PFA is capable of improving the mixture. At levels above an optimum, strength may tend to be lower due to excessive replacement of cement without adequate reaction. Regarding the situation, it can be anticipated that some ratios of ternary mixes (75% PFA and 25% GGBS, or vice versa) will demonstrate equal compressive strength to OPC, since the literature data show that up to 50-60% SCM mixtures can be used (Al-Waked et al., 2024).

2.6.2 Flexural Strength Test

Flexural strength trends usually mirror compressive strength, though absolute values are lower. Studies indicate that adding GGBS tends to increase flexural and splitting tensile strength up to an optimum. For instance, Jayajothi, P. et al. observed that flexural strength "increases with an increase in GGBS content" in a fly ash and GGBS geopolymer mortar (Jayajothi, P. et al, 2014). In the Oti et al. geopolymer study, mixes with 60–80% GGBS gave flexural strengths 20–40% above the control. Conversely, high PFA levels alone tend to reduce flexural strength early on due to slower curing. Thus, ternary mixes with balanced PFA–GGBS often show improved bending strength: small PFA content (10–20%) with higher GGBS yields flexural strengths exceeding pure OPC (Oti et al., 2025). In summary, the literature suggests that appropriately proportioned PFA and GGBS blends can achieve flexural performance comparable to or better than OPC, provided the mix is well optimized.

2.7 Effects of PFA and GGBS on Durability Properties of Ternary Blended Cement

2.7.1 Flow Table Test

The flow table test measures fresh mix consistency. SCMs generally improve workability: the spherical PFA particles and smooth GGBS powder act like ball bearings, reducing internal friction. Al-Waked et al. found that replacing cement with PFA and GGBS "significantly improved" concrete workability, with the highest flow at 30% PFA replacement (Al-Waked et al., 2024). However, in low-water alkali-activated systems, high GGBS can stiffen the mix. Jayajothi, P. et al. reported that increasing GGBS content decreased flow percentage in geopolymer mortars (Jayajothi, P. et al, 2014). In my mixes (with fixed w/b = 0.5), we expect that intermediate SCM ratios will yield higher flow due to PFA, while extremely high-GGBS mixes may become less workable. In all cases, workability must meet the target consistency spread while using minimal extra water.

2.7.2 Water Absorption Test

Water absorption by immersion in water indicates open porosity. Blends with high SCM content can behave differently: in principle, a denser C–S–H matrix from pozzolanic reaction should lower absorption. Indeed, studies show SCM concretes often have lower capillary absorption than OPC. However, Al-Waked et al. observed that in a fly ash/GGBS alkali blend, absorption increased as GGBS content rose. But poorly consolidated mortar (e.g. too little activator) can lead to higher absorption (Al-Waked et al., 2024). They attributed this to incomplete compaction in high-GGBS mixes, which created more voids. More generally, literature notes that adding GGBS refines the pore structure, resulting in fewer large capillaries (Oti et al., 2025), which should reduce permeability. It concludes that if mixes are well-compacted, moderate GGBS/PFA should reduce absorption via pore refinement. We will measure water uptake to verify how each SCM ratio affects open porosity compared to OPC.

2.7.3 Porosity Test

Porosity test underpins durability by indicating how much void space exists. High-volume GGBS and PFA tend to refine the pore network. For example, Oti et al. report that adding GGBS “creates a denser microstructure with less porosity” (Oti et al., 2025). Likewise, research on silica fume/GGBS blends shows a marked reduction in microcapillary pores (Chen, Wu and Liang, 2024). These findings suggest that properly proportioned ternary mixes can achieve porosity and permeability at least as low as OPC. However, the porosity benefit depends on good compaction and curing. In planned tests, it is expected that ternary mixes will show lower total porosity than the OPC control, as long as the binders fully react. Elevated porosity might appear if SCMs are overused or the activator is insufficient. Measuring porosity will allow us to quantify the environmental impact by diffusion and strength-related implications of each blend.

2.8 Summary and Conclusion of Literature Review

The literature indicates that ternary blended cement typically OPC partially replaced with PFA and GGBS can meet or exceed the performance of plain OPC when properly designed. By definition, ternary cement contains OPC plus two SCMs. GGBS (a glassy Ca-rich slag) and PFA (siliceous fly ash) complement each other: GGBS hydrates and pozzolanically reacts relatively quickly, while PFA slowly develops strength and improves workability (Warrenty, 2026). Blended mixes yield sustainability gains: lower carbon footprint and cost due to reduced clinker content (Ahmad et al., 2022). Strength-wise, moderate blends (e.g. 20–30% total SCM) often match OPC by 28 days (Oti et al., 2025); optimal combinations (e.g. 10% PFA + 20% GGBS) may even outperform OPC in 28-day compressive and flexural tests (Al-Waked et al., 2024). Durability is generally enhanced: SCMs densify the pore structure, reduce permeability and shrinkage, and improve resistance to chemical attack. Factors such as activator dosage, water/binder ratio, and aggregate content critically influence the alkali-activation process and final properties (Jayajothi, P. et al, 2014).

In summary, the literature indicates that well-designed ternary blends of OPC, fly ash, and GGBFS can match or even exceed the mechanical and durability performance of plain cement mixes while substantially lowering carbon footprint and cost (Wattanachai, P. et al., 2025). Geopolymerization and pozzolanic/latent reactions are the core mechanisms: high-alkali activation dissolves FA/slag particles to form binding gels (Izadifar, M. et al., 2026), while residual OPC hydrates concurrently to provide CH and additional C–S–H. Studies consistently show that moderate SCM ratios (e.g. ~40% cement replaced by SCM) achieve the best balance of early strength and long-term gain (Gholampour and Ozbakkaloglu, 2017). Workability is generally good at these levels, thanks to SCM particle effects. Research also research supports the feasibility of developing a ternary cement with PFA and GGBS that achieves OPC-equivalent strength and durability, while offering economic and environmental benefits.

Research Gaps: Despite extensive studies, gaps remain in high-SCM cements under high-alkali, moisture conditions. Microstructural analyses (e.g. QXRD, NMR of gels) are sparse. Long-term durability (beyond 1 year) and performance under freeze-thaw or real environmental conditions warrant further work. There is also a need for standardized mix-design protocols for triple blends with alkali activation. Our study will contribute new data on these fronts. In conclusion, the literature strongly supports that ternary blended cements with PFA and GGBS can match conventional OPC performance if optimized. Our study's alkali-activated ternary mixes (with 2% NaOH, 4% Na_2SiO_3, W/B=0.5, B: S=1:3) should therefore aim for the ranges identified above.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

This chapter outlines the laboratory methodology used to develop and evaluate ternary blended cement mixes incorporating Pulverised Fly Ash (PFA) and Ground Granulated Blast-Furnace Slag (GGBS) as partial replacements for Ordinary Portland Cement (OPC). The study addresses increasing concrete costs and environmental concerns by investigating whether industrial by-products can reduce OPC consumption while maintaining comparable mechanical and durability performance. The methodology focuses on identifying the optimum ternary blend ratio capable of achieving maximum performance while supporting sustainability objectives. Emphasis is placed on detailing the materials used, mix design development, specimen preparation and experimental procedures carried out to achieve the aims and objectives of the study.

This research employs a combination of experimental testing and statistical analysis to evaluate the mechanical and durability properties of ternary blended cement. A series of mix designs consisting of a 100% OPC control mix and various proportions of PFA and GGBS replacements were prepared, cast and cured under standard conditions. Each mix was tested in replicate to ensure the reliability and consistency of the results. The experimental programme included flow table tests to assess workability and fresh properties, compressive and flexural strength tests at selected curing ages to evaluate mechanical performance, and water absorption and porosity tests to examine durability characteristics. The collected data were analysed statistically to compare the blended mixes against the OPC control and across different replacement levels, enabling the identification of the optimum ternary blend composition.

3.2 Materials

Supplementary Cementitious Materials (SCMs) will be employed for the purpose and testing of this study, including Pulverized Fly Ash (PFA) and Ground Granulated Blast-Furnace Slag (GGBS). Ordinary Portland Cement as the main binder will be used, along with fine aggregate and water. Additionally, alkaline activators will also be applied, which are sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3).

3.2.1 Ordinary Portland Cement (OPC)

Figure 3.1: Ordinary Portland Cement

Ordinary Portland Cement is a high-strength Portland cement which is specially formulated for early demoulding, handling and use. It is ideal for high-strength concrete applications where time is of the essence and certified to MS EN 197-1. OPC is suitable for the high strength needed to improve productivity. It is the main binder that is used in ternary blended cement, which is responsible for hydration and early strength to improve performance and sustainability. Besides that, OPC was used as the main reference material in the methodology to provide a control mix for comparison with the ternary blended cement mixes. It was partially replaced by Pulverised Fly Ash (PFA) and Ground Granulated Blast-Furnace Slag (GGBS) in different proportions to assess how much cement could be reduced without significantly affecting performance. This allowed the study to evaluate the strength, workability, and durability of the blended mixes against the 100% OPC mix and identify the most effective replacement ratio.

3.2.2 Pulverized Fuel Ash (PFA)

Pulverized Fuel Ash (PFA) is a fine grey by-product obtained from coal-fired power stations and is widely used as a supplementary cementitious material in concrete production. Rich in silica and alumina, PFA exhibits pozzolanic properties that promote the formation of additional calcium silicate hydrate (C-S-H), improving the long-term strength and durability (Cheah et al., 2019). In this study, PFA complying with BS EN 450-1 requirements was used as a partial replacement for Ordinary Portland Cement (OPC) at selected replacement levels. The PFA was dry-mixed with the binder components before water and activators were added to ensure uniform distribution throughout the mix. The influence of the pulverized fuel ash on the fresh and hardened properties of the mix was determined using different tests.

Figure 3.2: Pulverized Fuel Ash (PFA)

3.2.3 Ground Granulated Blast-Furnace Slag (GGBS)

Ground Granulated Blast-Furnace Slag (GGBS) was used in this study as a supplementary cementitious material in the concrete mixture with the standard MS EN 15167-2. GGBS is a by-product of the iron manufacturing process produced through the rapid quenching and grinding of molten blast-furnace slag (*What is GGBS? - CSMA - The Cementitious Slag Makers Association*, 2018). It is supplied as a fine white powder with high calcium, silica, alumina, and magnesium oxide content, which contributes to its cementitious properties. The GGBS used possessed suitable fineness and specific gravity for concrete applications, making it effective as a partial replacement for OPC (Cheah, Tan and Ramli, 2020). In this study, GGBS was incorporated into the binder system at selected replacement levels to evaluate its influence on the workability, strength, and durability performance of ternary blended cement mixes.

Figure 3.3: Ground Granulated Blast-Furnace Slag (GGBS)

3.2.4 Fine Aggregate

Fine aggregate was used as the main granular material in the mortar mixture. Fine aggregates are preferred over coarse aggregates in producing the mortar. It will improve the volume stability, workability, and durability of mortar compared to hydrated cement paste alone. According to BS 882: 1992, fine aggregates typically pass through a 4.75 mm and remain on a 0.075mm sieve. The shape and texture of fine aggregate particles contribute to better interlocking between the cement paste and aggregate, which enhances the strength and compactness of the mortar (Donza et al., 2002). In addition, fine aggregates help reduce voids and air pockets by filling spaces between particles, resulting in a denser mortar mix with improved bonding and structural integrity. As a result, fine aggregates can give mortar strength and workability.

Figure 3.4: Fine Aggregate

3.2.5 Water

Water was used in this study as an essential component in the mortar mixture to initiate the hydration process between cementitious materials and form a binding paste that holds the mixture together. The amount of water used was carefully controlled because the water-to-binder ratio significantly affects the strength, density, and durability of the hardened mortar. Sufficient water is required for proper hydration, while excessive water may create voids that reduce the overall performance of the cementitious material.

Figure 3.5: Source of Water

3.2.6 Alkaline Activator

Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) were used in this study as the alkaline activator for the geopolymer mixture. NaOH was supplied in solid pellet form and dissolved in distilled water one day before mixing to prepare the activator solution. The solution was then left to cool and sealed overnight to avoid reaction with atmospheric carbon dioxide. Sodium silicate was supplied in liquid form and combined with the prepared NaOH solution at the required mixing proportion before use. This alkaline activator was used to promote geopolymerization and improve the overall performance of the binder system.

When water was added to NaOH pellets, a portion of heat was released due to the exothermic reaction, as shown in Equation 3.1 (Oti et al., 2025). The concentration of NaOH was fixed at 10 M.

$$NaOH(s) + H_2O(l) \rightarrow NaOH(l) \quad (3.1)$$

Secondly, adding sodium silicate speeds up the polymerization process and enhances the creation of geopolymer precursors. Sodium hydroxide solutions were combined to make the sodium silicate at predetermined mix proportions using Equation 3.2. (Oti et al., 2025).

$$2SiO_2 + 2NaOH(s) \rightarrow NaO(SiO_2)_2(l) + H_2O(l) \tag{3.2}$$

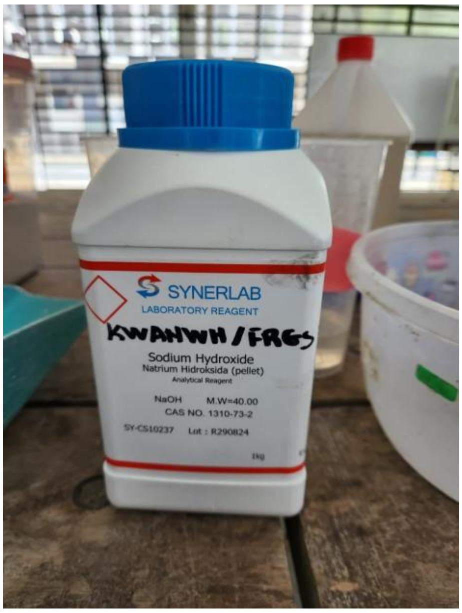

Figure 3.6: Sodium Hydroxide (NaOH)

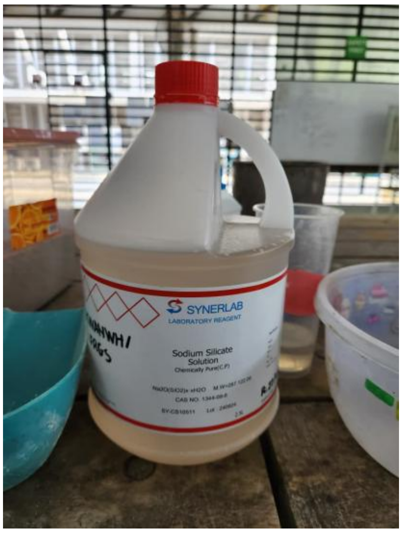

Figure 3.7: Sodium Silicate (Na_2SiO_3)

3.3 Preparation Mixture Design

Table 3.1 presents the mix proportions used in this study for the preparation of ternary blended cement mortar. The binder system consisted of Ordinary Portland Cement (OPC), Pulverised Fly Ash (PFA), and Ground Granulated Blast-Furnace Slag (GGBS), with the total binder content kept constant at 2.2560 kg for each batch. Different mix IDs were assigned based on the cement-to-supplementary cementitious material (SCM) ratio, ranging from 4:6, 3:7, 2:8, and 1:9, while a 100% OPC mix was used as the control. For each ternary mix, the OPC content was reduced and replaced by varying proportions of PFA and GGBS, while the total binder, water, sand, sodium hydroxide, and sodium silicate contents remained unchanged. This allowed the effect of binder composition on mortar performance to be assessed under consistent mix conditions.

In the methodology, the mix design was prepared by maintaining a fixed water-to-binder ratio of 0.5 and a binder-to-sand ratio of 1:3 for all mixes. Sodium hydroxide and sodium silicate were used as alkaline activators at 2% and 4% of the binder mass, respectively. The ternary binder was produced by blending OPC, PFA, and GGBS in the prescribed proportions shown in the table, with PFA and GGBS varying to produce different replacement levels, while the control mix contained only OPC. All materials were measured accurately before mixing to ensure uniformity and comparability across samples. This mix design enabled the study to evaluate the influence of ternary binder composition on the fresh, mechanical, and durability properties of the mortar.

Table 3.1: Mixture design of Ternary Blended Cement

Mix ID (Cement: SCM)	OPC (kg)	PFA (kg)	GGBS (kg)	Water (kg)	Sand (kg)	NaOH (kg)	Na_2SiO_3 (kg)	Total (kg)
4:6	0.9024	0.3384	1.0152	1.2004	4.7997	0.048	0.096	8.40
4:6	0.9024	0.6768	0.6768	1.2004	4.7997	0.048	0.096	8.40
4:6	0.9024	1.0152	0.3384	1.2004	4.7997	0.048	0.096	8.40
3:7	0.6768	0.3948	1.1844	1.2004	4.7997	0.048	0.096	8.40

3:7	0.6768	0.7896	0.7896	1.2004	4.7997	0.048	0.096	8.40
3:7	0.6768	1.1844	0.3948	1.2004	4.7997	0.048	0.096	8.40
2:8	0.4512	0.4512	1.3534	1.2004	4.7997	0.048	0.096	8.40
2:8	0.4512	0.9024	0.9024	1.2004	4.7997	0.048	0.096	8.40
2:8	0.4512	1.3534	0.4512	1.2004	4.7997	0.048	0.096	8.40
1:9	0.2256	0.5076	1.5228	1.2004	4.7997	0.048	0.096	8.40
1:9	0.2256	1.0152	1.0152	1.2004	4.7997	0.048	0.096	8.40
1:9	0.2256	1.5228	0.5076	1.2004	4.7997	0.048	0.096	8.40
100%OPC	2.2560	-	-	1.2004	4.7997	0.048	0.096	8.40

3.4 Preparation of Specimens

The preparation of the ternary blended cement mortar began with the accurate weighing of the raw materials, including Ordinary Portland Cement (OPC), Pulverized Fuel Ash (PFA), Ground Granulated Blast-Furnace Slag (GGBS), fine aggregate, water, and alkali activators. The solid pellets of sodium hydroxide (NaOH) were slowly added to water and stirred constantly. The solution was lately placed for cooling down and sealed afterwards. Sodium hydroxide was diluted into a 10-mole liquid solution and mixed with sodium silicate (Na_2SiO_3) one day before the mixing process. The required equipment, including 50 mm × 50 mm × 50 mm cube moulds, 40 mm × 40 mm × 160 mm prism moulds, 45 mm x 40 mm cylindrical moulds, mixer, vibrating machine, and flow table apparatus, was prepared beforehand. Before casting, the fine aggregate was washed, dried and sieved through a 4.75 mm sieve, while the binder materials were weighed according to the required mix proportions. The moulds are cleaned and greased with demoulding oil to ensure the ease of demoulding hardened specimens and prevent any damage to the specimens.

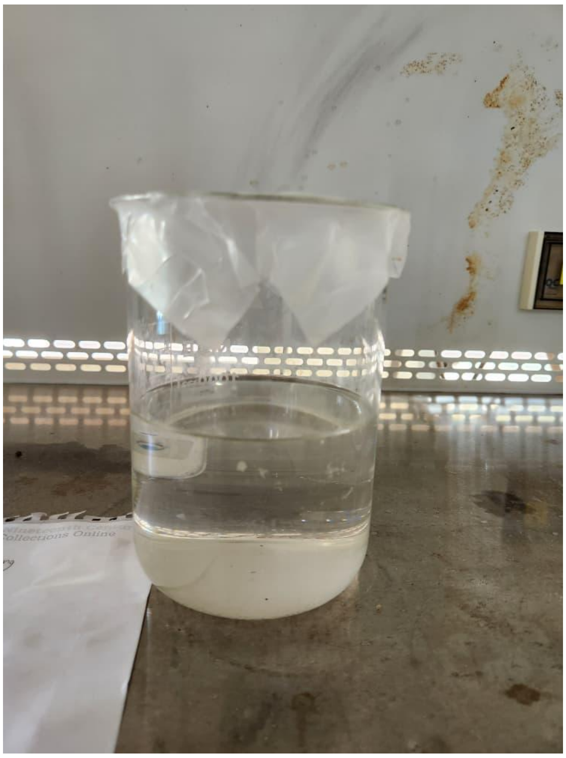

Figure 3.8: 10 mol of Sodium Hydroxide Diluted with Water

Figure 3.9: 4.75mm Sieve

3.5 Process of Casting, Moulding, and Demoulding

The casting process was started by first thoroughly mixing the dry materials using a cement blender, followed by the gradual addition of water and the alkaline activator solution until a uniform, workable mortar was obtained. This freshly mixed mortar was then subjected to a flow table test to assess its flow rate and workability before being poured into the moulds. For the casting process, the fresh mortar was poured into the moulds in three layers. Each layer was compacted by vibration to remove entrapped air and to prevent honeycombing, ensuring a dense and uniform specimen. The surface of the mortar was then levelled smoothly after filling the mould completely.

Depending on the test requirement, the mortar was cast into either 50 mm × 50 mm × 50 mm cube moulds for compressive strength, 45 mm x 40 mm cylindrical moulds for porosity test and water absorption tests, and 40 mm × 40 mm × 160 mm prism moulds for flexural strength tests. After casting, the moulds were left undisturbed at room temperature for 24 hours. The specimens were then carefully demoulded and transferred to the curing process for the required testing age. The steps were later continued with another mix of proportions using the preliminary step as well as casting, moulding, demoulding, and curing for 24 hours.

Figure 3.10: Prism Mould

Figure 3.11: Cube Mould

Figure 3.12: Cylindrical Mould

3.6 Process of Curing

The hardened mortar specimens were demoulded after 24 hours and then cured using the water curing method. Each specimen was fully immersed in a water tank at ambient temperature, with the water maintained at approximately 25°C to 29°C to provide adequate moisture for continued strength development. The specimens were kept under water until the designated testing ages of 3, 7, 14 and 28 days. Water curing was selected to ensure sufficient moisture availability throughout the curing period, allowing for an increase in long-term strength and further binder reaction to proceed, thereby improving the mechanical and durability properties of the mortar.

Figure 3.13: Water Tank for Curing

3.7 Experimental Testing Method

Several experimental tests were conducted in this study to evaluate the mechanical and durability properties of the ternary blended cement mortar. The workability of the fresh mortar was assessed using the flow table test. The mechanical properties of the hardened mortar were evaluated through compressive strength and flexural strength tests. In addition, durability performance was examined using water absorption and porosity tests. These tests were carried out to determine the suitability and performance of the ternary blended cement mortar with different mix proportions of PFA and GGBS.

3.7.1 Flow Table Test

The workability of fresh ternary blended cement mortar will be determined using the flow table test in accordance with ASTM C230/C230M. The test measures the horizontal flow and consistency of mortar after repeated drops on a flow table. First, the flow table will be levelled and the conical mould will be placed at the centre of the table. Fresh mortar will be filled into the mould in two layers, with each layer compacted using 25 strokes of a tamping rod. Excess mortar will be struck off flush with the top of the mould. The mould will then be lifted vertically to allow the mortar to spread freely. The flow table will subsequently be dropped 15 times in a controlled manner. After the drops, the spread diameter of the mortar will be measured in two perpendicular directions, and the average value will be recorded as the flow value. A larger spread diameter indicates higher workability and flowability, while a smaller spread indicates a stiffer mortar mix.

$$\textbf{Flow (\%)} = [(D_1 - D_0)/ D_0] \times 100$$

Where,

D_1 = Average Diameter of the spread, mm

D_0 = Original Base Diameter (100 mm)

Figure 3.14: Flow Table Test Apparatus

3.7.2 Compressive Strength Test

The compressive strength of the ternary blended cement mortar will be determined using 50 mm × 50 mm × 50 mm cube specimens in accordance with ASTM C109/C109M-21. The test will be used to evaluate the ability of the mortar to withstand applied loads and to determine its maximum compressive strength in MPa. After casting, the specimens will be cured and tested at 3, 7, 14, and 28 days. Each cube will be removed from curing and placed at the centre of the compression testing machine to ensure uniform load distribution. The load will then be applied steadily until failure occurs. The maximum load recorded at failure will be used to calculate the compressive strength of the specimen. For each age, the compressive strength will be taken as the average of three specimens. Higher compressive strength indicates better mechanical performance of the ternary blended cement mortar.

Compressive Strength (MPa)= Maximum Compressive Load (N)/ Surface Area (mm^2)

Figure 3.15: Compressive Strength Test Machine

3.7.3 Flexural Strength Test

The flexural strength of the ternary blended cement mortar will be determined using prism specimens with dimensions of 40 mm × 40 mm × 160 mm. The test will be carried out at 3, 7, 14, and 28 days to evaluate the ability of the mortar to resist bending forces and to determine its modulus of rupture. The specimens will be tested using a universal testing machine in accordance with ASTM C78/C78M. During testing, each prism will be placed on the loading supports and subjected to a three-point bending load at the centre of the specimen. The load will be applied gradually until fracture occurs. The maximum load at failure will be recorded and used to calculate the flexural strength. Three specimens will be tested for each curing age, and the average value will be reported as the flexural strength of the mix. A higher flexural strength indicates better resistance to bending and improved performance of the ternary blended cement mortar.

$$\textbf{Flexural Strength (N/mm}^2\textbf{)} = 3FL / 2bd^2$$

Where,

F = Maximum Load (force) at fracture (N)

L = Length of the span between supports (mm)

b = Width of the sample(mm)

d = Thickness of the sample(mm)

Figure 3.16: Flexural Strength Test Machine

3.7.4 Water Absorption Test

The water absorption of the ternary blended cement mortar will be determined in accordance with ASTM C1403-22a. The test will be conducted using cylindrical samples of 45 mm x 40 mm specimens at 3, 7, 14, and 28 days of curing to evaluate the durability and ability of the mortar to absorb water. Each specimen will be oven-dried at 100°C for 24 hours and then weighed to obtain the dry mass. The specimen will then be immersed in water for 30 minutes. After immersion, the sample will be removed, surface water will be wiped off, and the wet mass will be recorded. The percentage of water absorption will be calculated from the difference between the dry and wet masses. This test will be repeated for all specimens, and the average value will be reported. Lower water absorption indicates a denser mortar with better durability and reduced permeability.

$$Water\ absorption\ (\%) = (Ww - Wd)\ /Wd \times 100$$

Where,

Ww **= Weight of wet sample, g**

Wd **= Weight of dry sample, g**

Figure 3.17: Water Absorption Test

3.7.5 Porosity Test

The porosity of the ternary blended cement mortar will be determined using cylindrical samples of 45 mm x 40 mm specimens in accordance with the RILEM standard method, with reference to ASTM C1754/C1754M-12. The test will be conducted at 3,7, 14 and 28 days of curing age. This test is used to evaluate the internal pore structure of the mortar, as higher porosity generally indicates a greater ability to absorb water and lower material density. After curing, each specimen will be oven-dried and its dry mass recorded. The specimen will then be placed in a vacuum desiccator or vacuum-pressure vessel and vacuumed for approximately 15 minutes to remove entrapped air. The vacuuming process may be repeated after a 2-hour interval, after which the specimen will be left immersed for 24 hours to achieve full saturation. Following saturation, the specimen will be weighed in air and then weighed while immersed in water. These three mass measurements will be used to calculate the porosity of the mortar. The test will be repeated for all specimens, and the average porosity will be reported. A lower porosity value indicates a denser mortar with improved durability and reduced permeability.

Porosity (%) = [(Saturated Mass−Dry Mass)/ (Saturated Mass - Weight Immersed in Water)] X 100

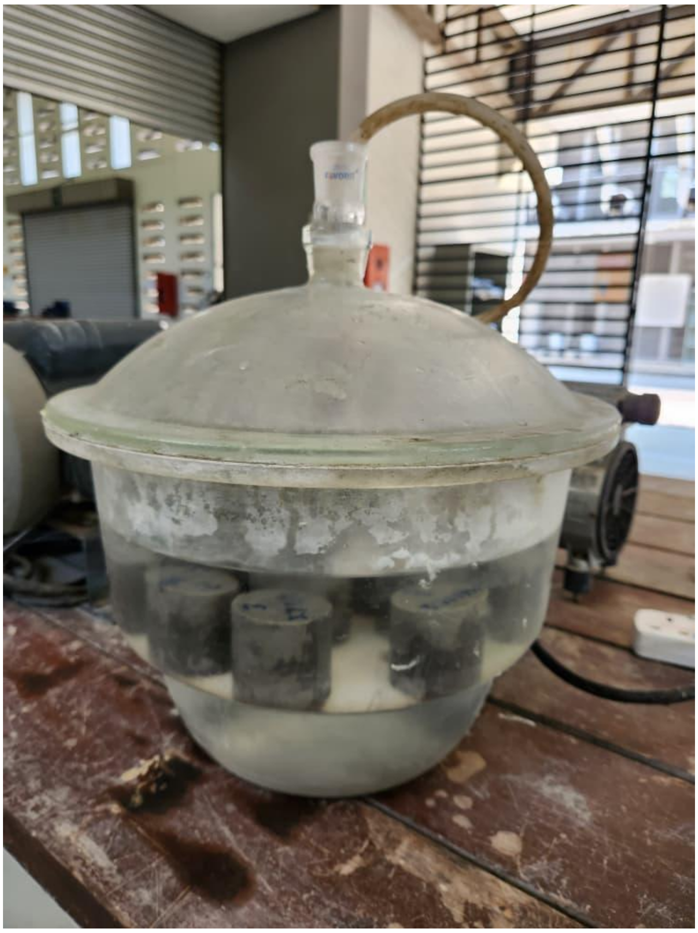

Figure 3.18: Porosity Test

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter will introduce and discuss the experimental results that have been conducted on the blended cement mixes that contain OPC, PFA, and GGBS. This chapter will analyze the impact of the binder mixture on the characteristics of the mortar, particularly its flowability, compressive strength, flexural strength, water absorption, and porosity. The experimental results will be interpreted in comparison to the performance of the binder mixes compared to the pure OPC. Thus, it will become possible to determine the efficiency of using PFA and GGBS as partial substitutes for OPC in regard to both the functionality of the resulting materials and their sustainability.

Moreover, this chapter will also discuss the impact of the control variables that were used during the experimentation process, which include the OPC-to-SCM ratio and the PFA-to-GGBS ratio. Mixes that include different replacement ratios will be analyzed, and it will become possible to define the optimal composition of the ternary blended cement. The experimental findings that are presented in this chapter will be used to prove whether the proposed ternary blended cement can serve as an effective substitute for the traditional OPC.

4.2 Flow Table Test

The flowability of the fresh mortar was determined by conducting a test known as the flow table test. In this test, the mortar was lifted gently 15 times on a horizontal surface. The spread distance of the mortar is illustrated in Table 4.1.

Table 4.1: Results of Flow Table Test

Variables	Spreading Width (cm)	Flow (%)
C40-P15G45	14.55	45.50
C40-P30G30	16.50	65.00
C40-P45G15	17.00	70.00
C30-P17.5G52.5	19.00	90.00
C30-P35G35	19.65	96.50
C30-P52.5G17.5	18.80	88.00
C20-P20G60	21.25	112.50
C20-P40G40	19.75	97.50
C20-P60G20	21.15	111.50
C10-P22.5G67.5	20.25	102.50
C10-P45G45	21.40	114.00
C10-P67.5G22.5	23.25	132.50
C100	14.00	40.00

A flow table test is performed to determine the workability of the mortar. The slump value represents the average spread of the mortar. A high average spread indicates high workability, while a low average spread signifies low workability. The data above indicate that increasing the total replacement of OPC generally increases the spread. At the 4:6 binder ratio (40% OPC, 60% SCM), the spreads were 14.55, 16.50 and 17.00 cm for PFA/GGBS = 25/75, 50/50 and 75/25, respectively. At the 3:7 ratio, they increased to 19.00, 19.65 and 18.80 cm. At the 2:8 ratio, they were 21.25, 19.75 and 21.15 cm. At the 1:9 ratio, they were 20.25, 21.40 and 23.25 cm. So, compared with the 100% OPC control at 14.00 cm.

In the first place, as the amount of OPC content is still high at 40%, as the amount of PFA increases, the value of flow also increases: 45.50% → 65.00% → 70.00%. Secondly, for a lower OPC content (30%), the values of the three mixtures' flow are almost equal (88.00% -96.50%). It means that these three mixtures possess more stable and balanced rheological properties. Thirdly, for an even lower OPC content (20%), the effect on spreadability is already nonlinear: the 25/75 and 75/25 mixtures perform well while the 50/50 mixture displays a minor deterioration. Lastly, as the OPC content falls to only 10%, the spreading becomes more pronounced again with the increase of PFA content, and the spreading width becomes significantly larger: 102.50% → 114.00% → 132.50%. Consequently, these can conclude that higher percentages of total Supplementary Cementitious Materials (SCM) replacement positively affect workability, and at the highest rates of substitution, PFA is more efficient in improving workability than GGBS. This conclusion supports published research. Zhou et al. claimed that Ordinary Portland cement can be efficiently replaced by both PFA and GGBS, and the efficiency of PFA in improving workability is higher than GGBS' efficiency (Zhou et al., 2012). This is in line with the overall pattern, particularly the shift from the OPC control group to mixtures with high substitution ratios, as well as the particularly wide range of variations observed in the PFA-rich 1:9 mixture.

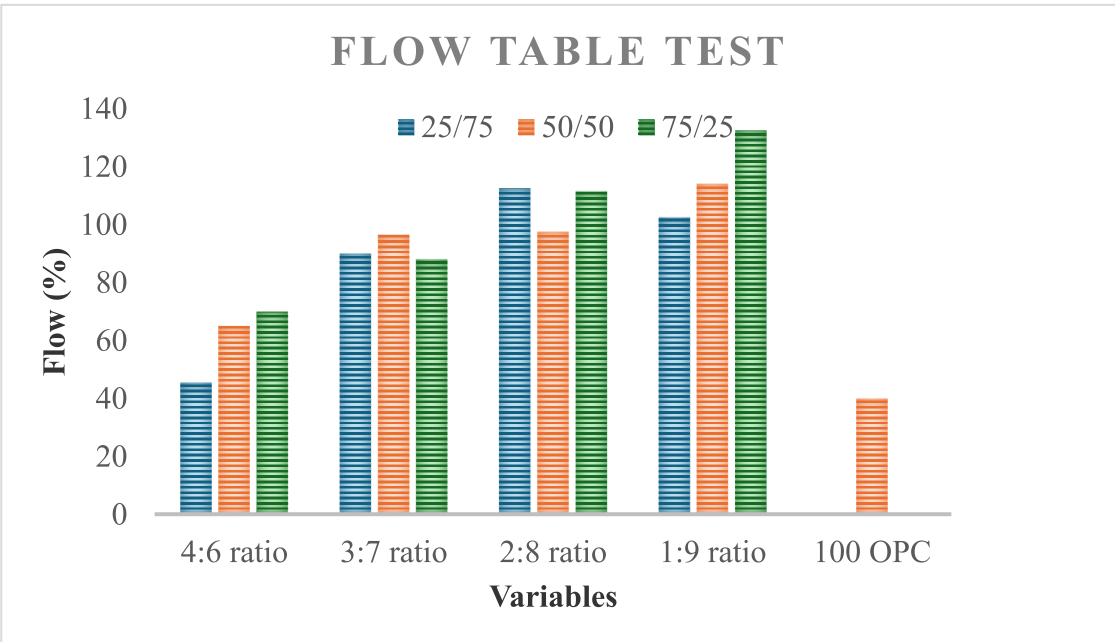

Figure 4.1: Flow of Different Variables

PFA enhances the workability of cement-based mixes mainly because of the morphology of the particles. The spherical shape of the particles makes them function as tiny ball bearings, reducing friction and minimising water requirements, thereby improving workability (Nayak et al., 2022). GGBS also plays an essential role in improving workability by lowering yield stress and plastic viscosity. The relatively smooth surfaces of the GGBS particles make the fresh mixes flow smoothly (Akhlaq et al., 2025). It is for this reason that PFA contents with higher levels provide better spread values in the experimental data. Moreover, mixes with high slag contents have excellent workability in some cases, like C20-P20G60, where a spread value of 21.25 cm was recorded.

This non-linear outcome is logical since the binder made of three components of OPC, PFA, and GGBS does not normally exhibit linearity in its behaviour. Workability involves particle size and shape, packing ability, water requirement, and binder interaction (Cheah et al., 2019). In summary, it can be concluded that both PFA and GGBS played an important role in enhancing flow when they were used in place of OPC. Best flow values were achieved in the case of 90% replacement with a PFA/GGBS ratio of 75/25, meaning that PFA had the most significant impact on flow enhancement than GGBS.

4.3 Compressive Strength Test

Table 4.2: Results of Compressive Strength Test

	Compressive Strength (MPa)			
Variable	**3 days**	**7 days**	**14 days**	**28days**
C40-P15G45	6.11	11.24	13.84	16.99
C40-P30G30	6.13	12.01	13.80	14.46
C40-P45G15	4.50	8.35	10.58	12.21
C30-P17.5G52.5	7.22	9.23	12.88	13.10
C30-P35G35	7.49	9.48	12.29	13.43

C30-P52.5G17.5	6.70	11.19	11.30	12.29
C20-P20G60	8.36	10.94	12.14	14.88
C20-P40G40	11.78	12.45	13.75	14.69
C20-P60G20	9.01	10.08	10.90	12.01
C10-P22.5G67.5	10.08	11.98	14.44	15.28
C10-P45G45	8.55	10.47	11.62	12.22
C10-P67.5G22.5	6.67	6.88	8.60	10.78
C100	16.91	17.77	27.50	33.06

The major observation is that the strength of all ternary combinations is lower than the 100% OPC strength at all ages tested, although they continue to develop strength with increasing curing period. In the current investigation, the measured strength of the control mixture at the ages of 3, 7, 14, and 28 days is 16.91 MPa, 17.77 MPa, 27.50 MPa, and 33.06 MPa, respectively, while the strength of the ternary mixture at 3 days varies from 4.5013 MPa to 11.779 MPa, and at 28 days between 10.78 MPa to 16.99 MPa. In the latter case, the best ternary mix for 28 days was found to be C40-P15G45 = 16.99 MPa, followed by C10-P22.5G67.5 = 15.28 MPa. Therefore, the results indicate a reduction in absolute compressive strength resulting from substituting OPC with a higher proportion of PFA and GGBS, but strength will still develop progressively with age.

Based on the available literature, ternary cementitious systems containing fly ash and slag typically exhibit a reduction in strength during the early stages due to the longer reaction time of fly ash and the slow rate of hydration reactions associated with slag. Nevertheless, studies have proven that through the production of more C-S-H and C-A-S-H gels, strength gain can be attained through curing. Studies also report that mixes with more fly ash often lose more compressive strength, while GGBS can improve later-age development (Cheah et al., 2021).

The results indicate that ternary mixtures having a high replacement ratio exhibit a lag in gaining strength. On the other hand, the optimized blends having a low replacement ratio were formulated to achieve a strength after 28 days equivalent to that of the ordinary portland cement. This explains the lower strength attained by the ternary mixtures compared to the control mixture after 28 days, although there was an increase in strength from day 3 to 28 days. In terms of academic consideration, this can be accepted because according to scientific literature, some ternary concrete mixes have strength that is below the control group at 28 days, which is normally dependent on clinker content, replacement level, fineness, and strength grade (Rivera et al., 2021).

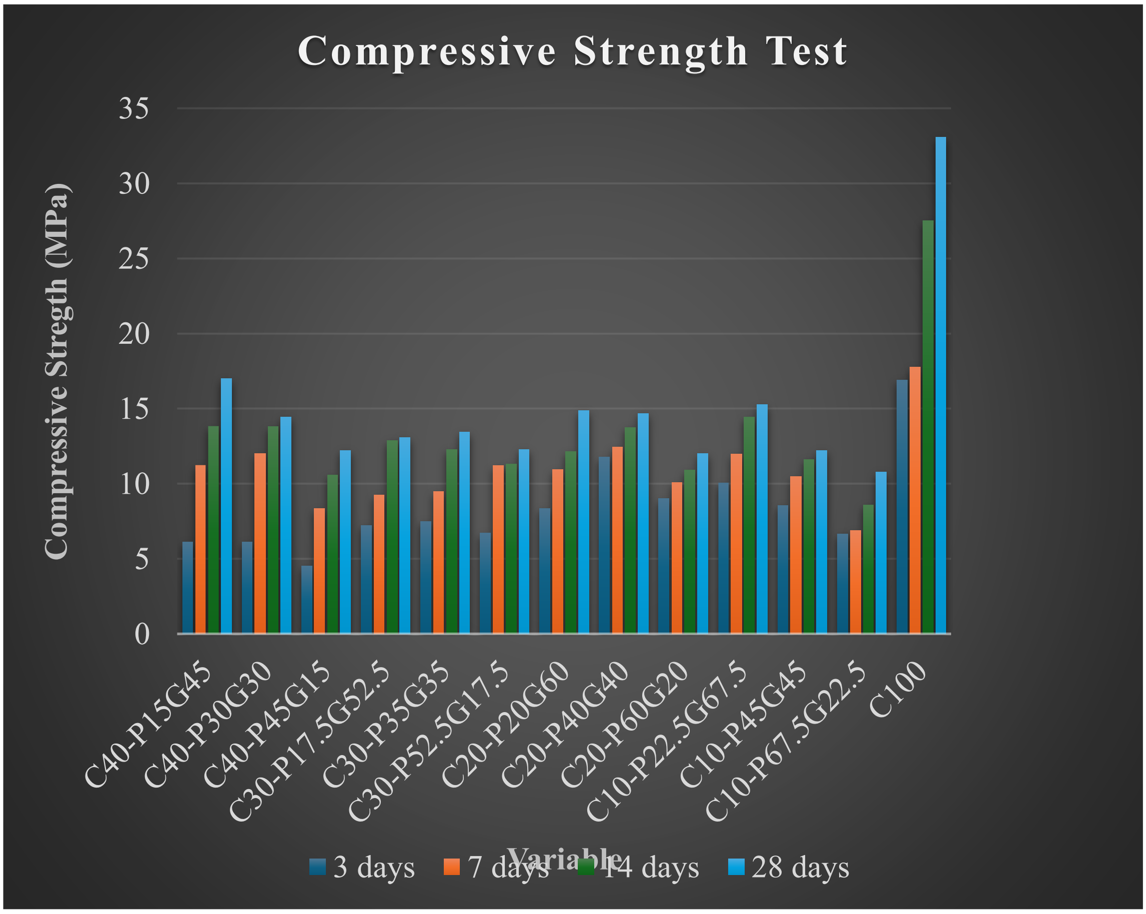

Figure 4.2: Compressive Strength of Different Variables

Within each OPC content group as well, there exists an internal trend that can be seen. With an OPC content of 40%, the higher the PFA content, the weaker the mixture becomes; thus, C40-P15G45 > C40-P30G30 > C40-P45G15 at 28 days. With 20% OPC content, the same trend is evident: C20-P20G60 > C20-P40G40 > C20-P60G20. In the case where the OPC content is 10%, the GGBS-enriched mixtures have performed better again; C10-P22.5G67.5 > C10-P45G45 > C10-P67.5G22.5. However, in the case where the OPC content is 30%, slight variations have been found such that C30-P35G35 = 13.427 MPa was stronger compared to C30-P17.5G52.5 = 13, but the PFA-rich mix is still the weakest. These results generally support the statement that higher PFA content tends to reduce compressive strength more severely, while balanced or GGBS-richer blends perform better (Cheah et al., 2021).

One of the other important parameters is the strength gain rate. For instance, within the period of 3 days to 28 days, the strength gain of C40-P15G45 changed from 6.1063 MPa to 16.991 MPa, while C40-P45G15 changed from 4.5013 MPa to 12.213 MPa. Even though the final strength value may not be as high as that of ordinary Portland cement (OPC), the increasing values signify that there are reactions and secondary pozzolanic reactions happening during the hydration process. This is due to the admixtures causing dilution of the ordinary Portland cement and decreasing its early strength. (Cheah et al., 2021). That explanation that the SCMs diluted the initial OPC content, which depressed early strength, but ongoing reactions still improved the matrix over time.

4.4 Flexural Strength Test

Table 2.3: Results of Flexural Strength Test

	Flexural Strength (MPa)			
Variable	**3 days**	**7 days**	**14 days**	**28days**
C40-P15G45	1.91	3.39	3.65	5.44
C40-P30G30	2.21	3.76	4.00	4.23
C40-P45G15	1.31	2.85	3.33	4.20
C30-P17.5G52.5	2.34	3.11	3.75	3.89
C30-P35G35	1.88	3.80	4.15	4.30
C30-P52.5G17.5	1.65	2.92	3.47	3.59
C20-P20G60	2.33	3.69	3.72	6.29
C20-P40G40	3.32	3.77	3.98	5.79
C20-P60G20	2.75	2.77	3.61	4.16
C10-P22.5G67.5	2.32	3.03	3.83	5.59
C10-P45G45	2.01	2.81	3.21	4.15

C10-P67.5G22.5	1.62	2.03	2.99	3.24
C100	4.16	4.44	5.15	6.86

The ternary-blend mortars all showed steadily increasing flexural strength from 3 to 28 days, as expected for cementitious materials, indicating continued hydration and alkali-activated reaction over time. However, every blended mix remained lower in flexural strength than the 100% OPC control at all testing ages. For example, the 100% OPC mortar reached 6.86 MPa at 28 days, whereas the blended mortars ranged from 3.24 to 6.29 MPa at 28 days. The highest 28-day flexural strengths were found in the slag-rich mixes: C20-P20G60 (6.29 MPa) and C10-P22.5G67.5 (5.59 MPa), both of which contain only 20% or 10% OPC but high GGBS. In contrast, mixes with higher fly ash content showed lower flexural strength, confirming that increasing GGBS content generally improves performance while increasing PFA reduces it. This trend was consistent within each OPC level, where mixes with higher slag replacement always outperformed the corresponding fly ash-rich mixes. By contrast, mixes with higher amounts of fly ash (PFA) were less effective. For example, for mixes containing 40% OPC, the order was C40-P15G45 (5.44 MPa) > C40-P30G30 (4.23 MPa) > C40-P45G15 (4.20 MPa). The same applies to mixes with 30%, 20%, and 10% OPC; mixes with higher GGBS (fewer PFA) exhibited higher strength. This pattern agrees with known behavior which suggests that slag (GGBS) tends to contribute more to strength development than fly ash.

The flexural strength trends obtained in this study agree with previous research on ternary blended mortars. Increasing fly ash content generally reduced flexural strength, especially at high replacement levels above 40–50%, which explains the lower strengths observed in PFA-rich mixes such as C10-P67.5G22.5 and C40-P45G15 (Ali *et al.*, 2023). In contrast, higher GGBS content improved flexural performance due to the formation of additional calcium-rich hydration products that densified the mortar matrix (Jayajothi, P. et al, 2014). This was evident as slag-rich mixes consistently achieved higher strengths than fly ash-rich mixes within the same OPC level. Overall, the results followed the expected trend of OPC > high-GGBS > balanced blends > high-PFA mixes, which is consistent with findings reported in the literature.

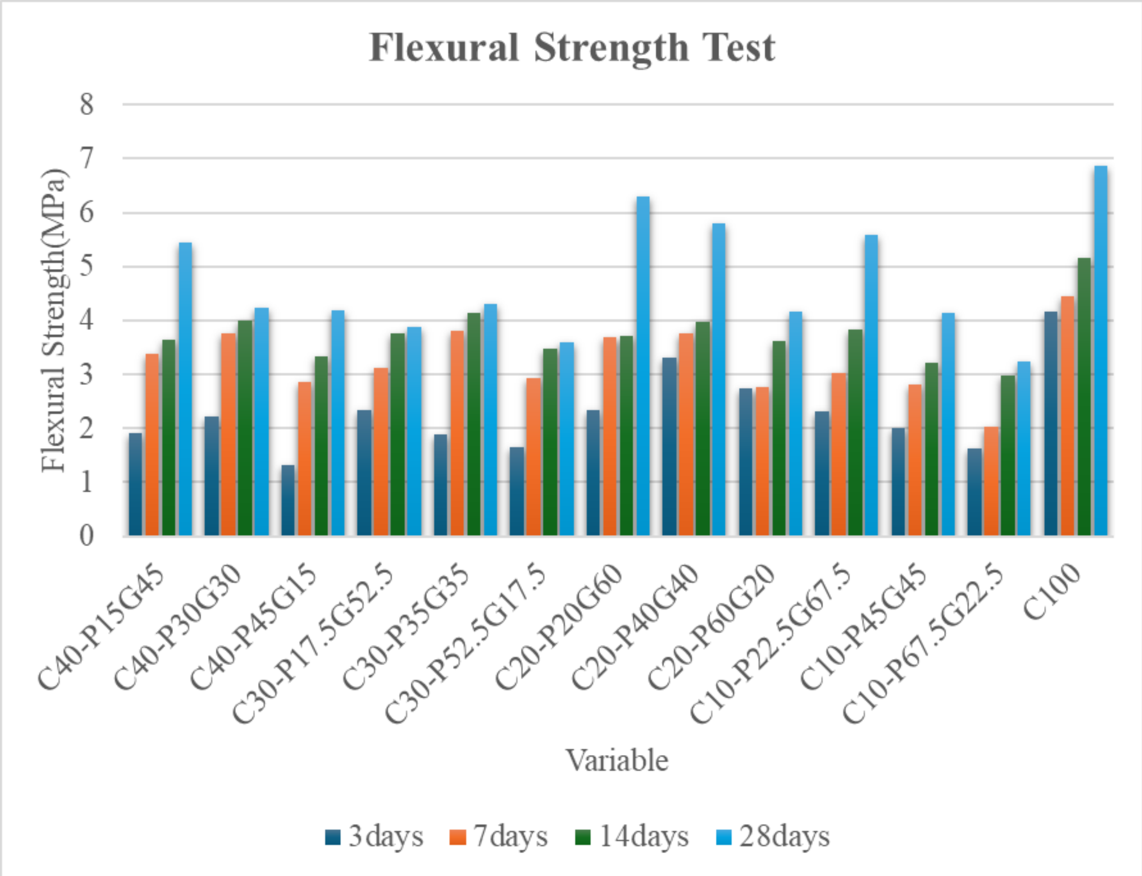

Figure 4.3: Flexural Strength of Different Variables

The use of alkaline activators consisting of NaOH and Na_2SiO_3 in this study likely enhanced the reaction of fly ash and GGBS by increasing the solution pH and silica availability, which promoted the formation of additional C–S–H and N–A–S–H gels (Sasui *et al.*, 2024). Previous studies reported that alkali activation improves the dissolution of aluminosilicate materials and accelerates the polymerization reaction, resulting in higher strength development (Phoo-Ngernkham *et al.*, 2016). This effect was observed in the present study, where slag-rich mixes such as C20-P20G60 and C10-P22.5G67.5 showed significant strength increases from 14 to 28 days, indicating continued late-age reaction under alkali activation. The results also show that mixes containing only 10–20% OPC were still able to achieve flexural strengths of approximately 3–6 MPa at 28 days, suggesting that the alkali solution contributed to additional cementing gel formation and improved flexural performance compared to non-activated ternary blends, although the strengths remained lower than the OPC control.

Overall, the flexural strength data are rational and consistent with the data found in literature sources, where strength increases with the curing time and the mixture with higher percentages of slag is stronger than the mixture with higher fly ash percentage. The majority of mixtures were showing an increase in their strength values from 3 days to 28 days, implying the presence of ongoing hydration and alkali activation process. Nevertheless, there is one case that deserves special attention, namely the C20-P20G60 mixture, which has a much larger increase in its strength value from 3.72 MPa to 6.29 MPa between 14 days and 28 days. In addition, its strength value at 28 days was greater than some other mixtures, which had a higher percentage of OPC. It can be explained by a very intensive reaction that took place at a later age due to the presence of a high percentage of GGBS and alkali activation, though the value can be considered an anomaly or an outlier. A similar but more reasonable increase was observed for C10-P22.5G67.5, which also contained high GGBS content. Despite this anomaly, the overall trend remains clear and credible, confirming that higher GGBS and lower PFA contents contribute to improved flexural strength, while the alkaline solution further enhances later-age strength development through continued gel formation and hydration reactions.

4.5 Water Absorption Test

Table 4.4: Results of Water Absorption Test

	Water Absorption Rate (%)			
Variable	**3 days**	**7 days**	**14 days**	**28days**
C40-P15G45	11.03	6.71	6.26	5.34
C40-P30G30	11.09	6.84	5.47	4.73
C40-P45G15	11.47	8.41	7.55	5.45
C30-P17.5G52.5	12.70	8.25	7.68	7.56
C30-P35G35	11.54	8.26	8.07	7.79

C30-P52.5G17.5	10.96	9.29	9.10	9.01
C20-P20G60	9.86	3.59	3.65	3.55
C20-P40G40	9.83	4.43	4.34	4.20
C20-P60G20	9.88	7.15	7.03	6.97
C10-P22.5G67.5	8.24	6.50	5.63	5.43
C10-P45G45	10.32	7.52	6.70	4.50
C10-P67.5G22.5	11.30	10.44	7.2	6.2
C100	8.32	5.30	5.27	5.05

The water absorption results showed a consistent reduction from 3 to 28 days for all mortar mixes, indicating continued hydration and pore refinement with curing age. The 100% OPC control mix recorded a reduction from 8.32% at 3 days to 5.05% at 28 days. Similarly, all ternary blended mortars demonstrated lower absorption over time, suggesting that the ongoing hydration and alkali-activated reactions gradually densified the internal pore structure. At 28 days, nearly all mixes achieved water absorption values below 10%, which is generally considered acceptable for durable mortar (GS and N, 2011). This indicates that the incorporation of supplementary cementitious materials (SCMs) together with alkali activators successfully improved the impermeability of the mortar matrix.

The results also showed that the binder composition significantly influenced water absorption performance. Mixes containing higher GGBS content generally recorded lower absorption values compared to fly ash-rich mixes. The lowest 28-day absorption was obtained by C20-P20G60 at 3.55%, followed by C20-P40G40 at 4.20% and C10-P45G45 at 4.50%. These results suggest that GGBS contributed to the formation of additional calcium-silicate-hydrate (C–S–H) gel, which refined the pore structure and reduced water penetration. In contrast, mixes with higher PFA content, such as C30-P52.5G17.5, recorded the highest 28-day absorption value of 9.01%. This may be due to the slower pozzolanic reaction of fly ash and insufficient calcium content, which can leave residual porosity within the mortar matrix. Overall, mixes with balanced or slag-rich PFA: GGBS ratios demonstrated better impermeability than high-PFA blends.

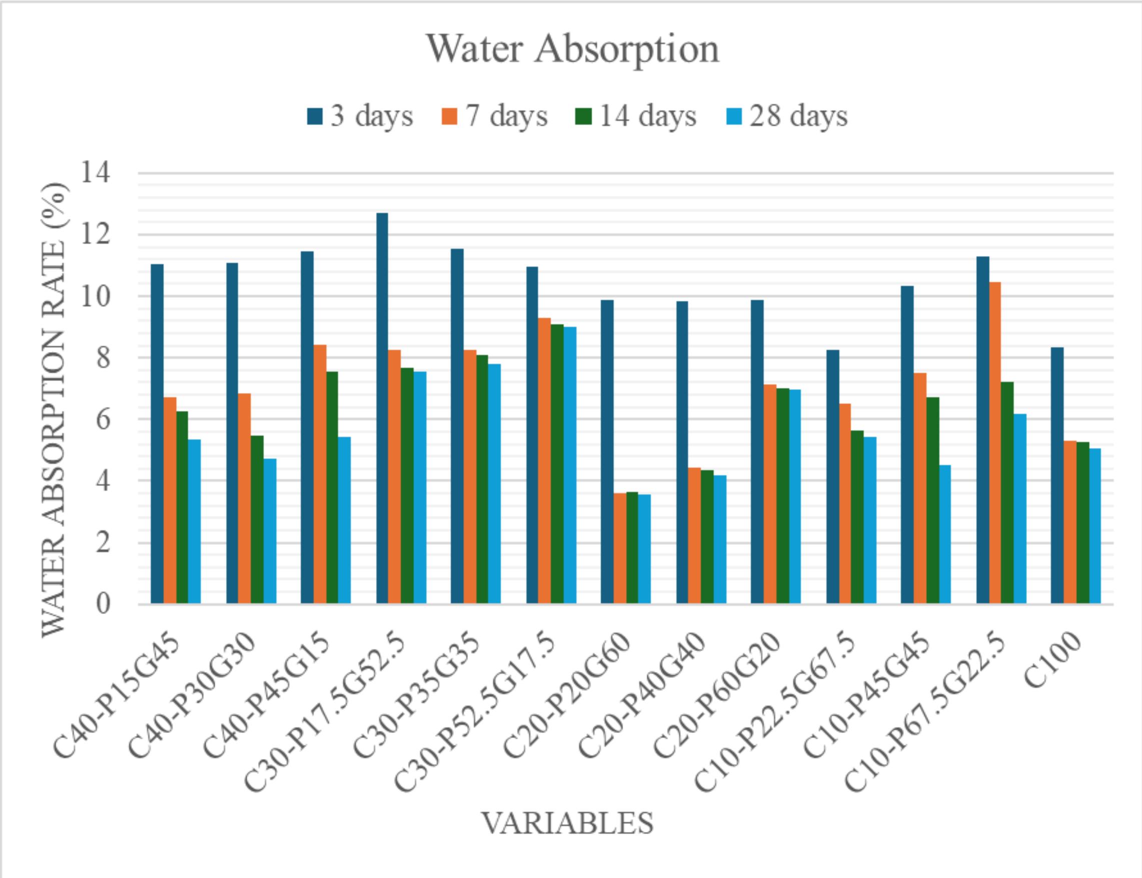

Figure 4.4: Water Absorption Rate of Different Variables

Previous studies show that both PFA and GGBS can improve mortar impermeability, but the effect depends on their proportion. PFA alone can refine pores through its filler effect and slow pozzolanic reaction, with moderate replacement levels often giving better absorption performance (GS and N, 2011). GGBS is even more effective in reducing permeability because it forms dense C–S–H and calcium-aluminate hydrate products that fill capillary pores, which explains why the GGBS-rich mix in this study, C20-P20G60, recorded the lowest water absorption. In ternary blends, the combined use of OPC, PFA and GGBS often produces a synergistic effect, and studies have shown that well-balanced binary or ternary SCM mixtures can achieve lower porosity and absorption than OPC alone. This matches the present results, where the 25:75 and 50:50 PFA: GGBS mixes generally performed better than the high-PFA 75:25 mixes, showing that sufficient calcium from OPC and GGBS is needed to react effectively with fly ash and produce a denser microstructure (Ban and Kang, 2019).

The combined alkali activator used in this study, NaOH and Na_2SiO_3, likely influenced water absorption by changing the pore structure of the mortar. NaOH helps dissolve aluminosilicate materials and promotes early reaction, but if used at too high a concentration it may create excess Na-rich phases or microcracks that can increase water uptake (Huseien et al., 2016). In contrast, sodium silicate generally improves impermeability by forming additional silicate-based gels and C–S–H products that fill pores and densify the matrix (Wang, 2018). The relatively low absorption values in this study, especially in the GGBS-rich mixes, suggest that the activator system was effective in producing a compact microstructure, while the slightly higher values in some mixes may be due to an imbalance in the activator ratio or incomplete curing.

The findings are consistent with previous studies reporting that ternary blends containing PFA and GGBS can improve durability and reduce water absorption compared with plain OPC mortar. Literature shows that GGBS enhances the formation of dense hydration products, while moderate amounts of fly ash contribute filler and pozzolanic effects that further refine pores. In addition, the alkali activators used in this study, namely NaOH and Na_2SiO_3, likely accelerated the dissolution of aluminosilicate materials and promoted additional gel formation, resulting in a denser microstructure. Sodium silicate particularly contributed to pore blocking and reduced permeability, while the selected NaOH concentration appeared sufficient to activate the SCMs without causing excessive microcracking. Therefore, the overall water absorption results confirm that well-balanced ternary blended mortars, especially those with higher GGBS content, can achieve improved impermeability and durability performance compared to conventional OPC mortars.

4.6 Porosity Test

Table 4.5: Results of Porosity Test

	Porosity (%)			
Variable	**3 days**	**7 days**	**14 days**	**28days**

C40-P15G45	24.41	23.63	22.37	22.04
C40-P30G30	23.50	22.15	21.84	21.34
C40-P45G15	23.83	22.61	22.43	19.35
C30-P17.5G52.5	27.92	24.99	24.77	24.80
C30-P35G35	24.32	24.21	24.21	20.72
C30-P52.5G17.5	23.44	23.58	23.43	23.52
C20-P20G60	21.87	19.38	18.51	17.50
C20-P40G40	22.16	21.81	21.43	18.28
C20-P60G20	23.33	23.28	22.45	22.98
C10-P22.5G67.5	23.32	22.23	20.35	20.02
C10-P45G45	24.25	22.98	22.06	21.53
C10-P67.5G22.5	23.13	22.85	21.83	20.54
C100	21.21	21.73	21.71	21.30

The porosity results show that most ternary blended mortars experienced a reduction in porosity from 3 days to 28 days, indicating progressive pore refinement with curing age. This behaviour suggests continued hydration and alkali-activated reactions between OPC, PFA and GGBS, which helped fill capillary pores and produce a denser mortar matrix. In contrast, the OPC control remained almost unchanged at around 21.21% to 21.30%, showing very limited pore refinement over time compared with several blended mixes. Overall, this indicates that the ternary blends were more effective than plain OPC in improving microstructural densification.

Among all mixes, C20-P20G60 gave the best porosity performance, decreasing from 21.87% at 3 days to 17.50% at 28 days, making it the lowest porosity value in the study. This suggests that the combination of 20% OPC, 20% PFA and 60% GGBS provided the most effective balance for pore reduction, likely because the high GGBS content supplied more reactive calcium for gel formation while the alkali solution enhanced the activation of both GGBS and PFA. The second-best mix was C20-P40G40, which decreased to 18.28% at 28 days, further showing that the C20 series generally produced the densest microstructure among the blends tested.

For the other mix groups, the results were less uniform but still showed the same general pattern of porosity reduction with age. The C40 series showed moderate improvement, with C40-P45G15 performing best at 19.35% at 28 days. The C30 series gave the poorest overall results, especially C30-P17.5G52.5, which remained the highest at 24.80%, suggesting a less effective balance of PFA and GGBS or slower gel formation. The C10 series also reduced porosity over time, but its final values remained around 20% to 21.5%, which is reasonable for a low-OPC system but not as strong as the C20 blends. Overall, the results confirm that a suitable balance of PFA and GGBS, especially with higher GGBS content, improves porosity performance, while the alkali solution supports pore filling and matrix densification.

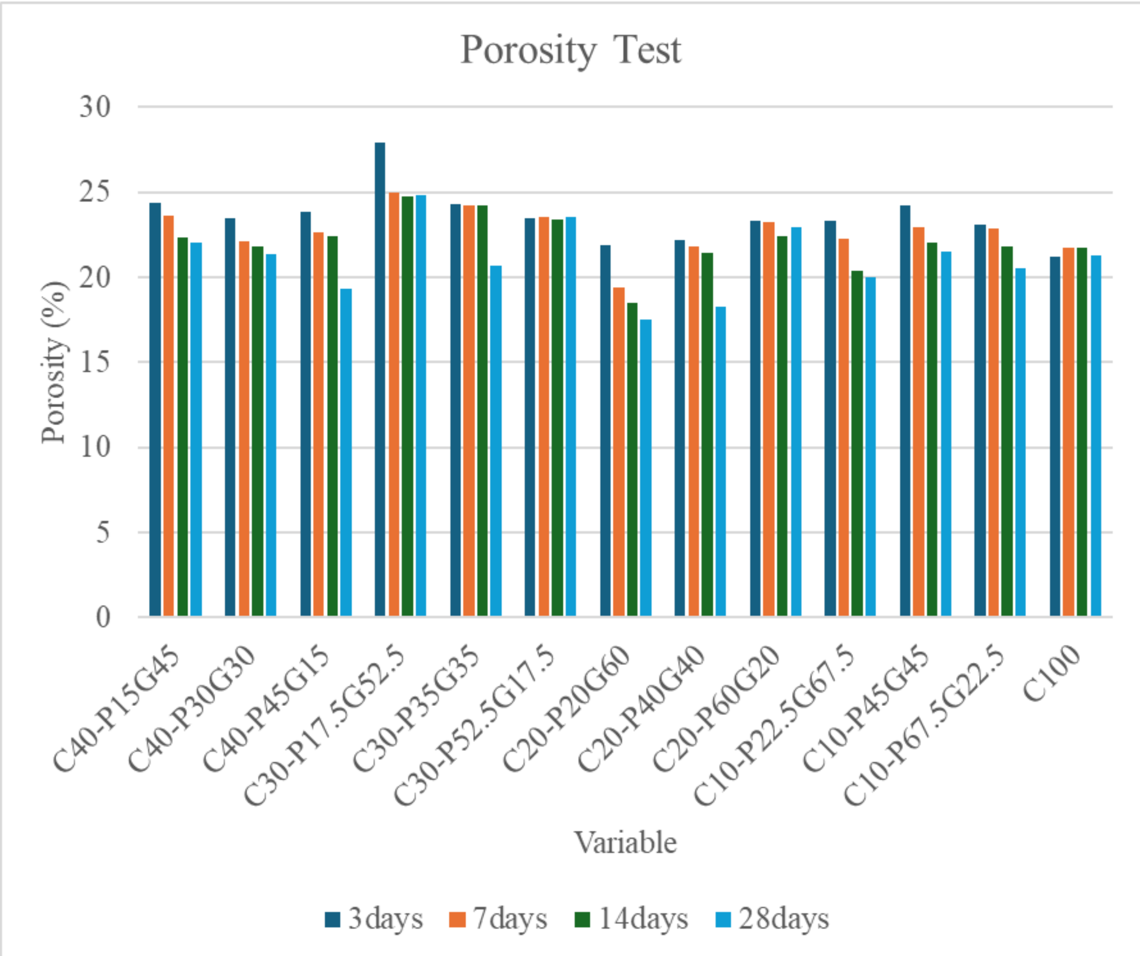

Figure 4.5: Porosity of Different Variables

These observations agree with published studies showing that increasing slag content generally reduces porosity, while increasing fly ash content tends to raise water absorption and void volume. In ternary blended systems, high SCM replacement can produce a much denser microstructure than OPC alone because the slag contributes more reactive calcium for gel formation, while fly ash helps refine the matrix when used in a suitable proportion. This matches the present results, where the high-replacement mixes showed lower porosity than the OPC control, especially in mixes with higher GGBS content (Mohamed *et al.*, 2023).

The alkali activators, NaOH and Na_2SiO_3, also play an important role in reducing porosity by accelerating the reaction of PFA and GGBS and promoting the formation of C–S–H and C–A–S–H gels. A higher sodium silicate to hydroxide ratio is generally reported to produce denser gel and lower water absorption, while increasing NaOH concentration can improve reactivity up to an optimum level and reduce sorptivity. In this study, the presence of NaOH and sodium silicate likely helped refine the pore structure and improve durability by producing a more compact mortar matrix.

Porosity is an important durability indicator because it influences water absorption, permeability and the overall long-term performance of mortar. In general, the results showed that mixes with higher GGBS content tended to produce lower porosity due to improved gel formation and pore refinement, while excessive PFA content resulted in higher porosity because of slower reaction rates. Overall, the porosity data are consistent with findings reported in the literature, showing that properly balanced ternary blended systems can achieve lower porosity than conventional OPC mortar through the combined effects of SCM reaction and alkali activation.

4.7 Summary of Experimental Results

The five tests show a clear overall pattern: increasing OPC replacement by PFA and GGBS improved fresh workability, but it reduced early strength compared with the 100% OPC control, while later-age curing and alkali activation helped the ternary blends continue improving in strength and durability. In the flow table test, the control mix had the lowest spread at 14.00 cm (40% flow), whereas higher replacement mixes showed much greater flow, with the 90% replacement mix C10-P67.5G22.5 giving the highest spread of 23.25 cm, indicating that PFA and GGBS both improved workability and that PFA had the stronger effect at high replacement levels.

In compressive strength, the OPC control remained the strongest at all ages, reaching 33.06 MPa at 28 days, while the ternary blends increased steadily from 3 to 28 days but stayed lower overall, ranging from 10.78 to 16.99 MPa at 28 days. The best ternary mix was C40-P15G45 at 16.99 MPa, and within each OPC group, the mixes with more GGBS generally performed better than the PFA-rich mixes, showing that higher slag content supported later-age strength development. The flexural strength results followed a similar trend of continuous gain with curing age, but all blended mixes remained below the OPC control, which reached 6.86 MPa at 28 days. Among the blends, slag-rich mixes performed best, especially C20-P20G60 at 6.29 MPa and C10-P22.5G67.5 at 5.59 MPa, confirming that higher GGBS content improved flexural strength more effectively than higher PFA content. The data also showed a strong late-age increase in some mixes, suggesting the benefit of alkali activation in sustaining gel formation and strength growth.

For water absorption, almost all mixes showed a clear reduction with age, which indicates progressive pore refinement. The 28-day values were mostly below 10%, with C20-P20G60 recording the lowest absorption at 3.55%, followed by C20-P40G40 at 4.20% and C10-P45G45 at 4.50%, while C30-P52.5G17.5 had the highest value at 9.01%. The OPC control reached 5.05% in 28 days, meaning several ternary blends performed as well as or better than plain OPC in terms of impermeability. The porosity test showed the same overall pattern of microstructural densification with curing time. The OPC control remained nearly unchanged at about 21.21% to 21.30%, while the ternary blends generally reduced porosity more noticeably, with C20-P20G60 giving the lowest 28-day porosity at 17.50% and C30-P17.5G52.5 giving the highest at 24.80%. Overall, the results show that a balanced ternary system, especially with higher GGBS content, can improve pore structure, reduce water movement, and enhance long-term durability when combined with NaOH and Na_2SiO_3 activation.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study investigated the optimization of ternary blended cement incorporating Pulverized Fuel Ash (PFA) and Ground Granulated Blast-Furnace Slag (GGBS) as partial replacements for Ordinary Portland Cement (OPC). PFA mainly enhanced the flowability of the mortar, whereas GGBS contributed to strength development and improved durability. Overall, the findings show that ternary blended cement can improve the workability and durability performance of mortar, while also reducing the amount of OPC used.

In terms of fresh properties, the ternary mixes generally showed better workability than the OPC control, with higher replacement levels producing greater flow values. For mechanical performance, all ternary mixes recorded lower compressive and flexural strengths than the OPC control at 28 days, but strength continued to develop with curing age, showing that the mixes remained reactive over time. Among the ternary mixes, C40-P15G45 achieved the highest compressive strength, C20-P20G60 showed the best overall durability performance and highest flexural strength among the ternary blends. This means the study successfully identified the best composition depending on the target performance. From these results, the applicable ratios were established, especially mixes with higher GGBS and moderate PFA, which gave better overall performance.

Overall, the study confirms that ternary blended cement using PFA and GGBS can serve as a more sustainable alternative to conventional OPC, particularly for applications requiring better workability and durability. Nevertheless, further optimization of mix design and curing conditions is necessary to achieve compressive strength comparable to OPC. The scope of this study was limited to the selected replacement levels, curing ages, and laboratory test conditions. Future research should explore broader mix proportions, higher alkali activator, longer curing periods, and microstructural analysis to better understand the strength development and durability mechanism of ternary blended cement systems.

5.2 Recommendations

Based on the findings of this study, the results of the study with SCMs did not guarantee full representation of overall performance, especially in the strength development. Therefore, several recommendations are proposed to further improve the performance of ternary blended cement and support future research.

I. Refine the ratios of PFA and GGBS to achieve a better balance between strength and durability based on ‘higher GGBS content with moderate PFA content may give better overall performance.’

II. Future studies should include longer curing ages beyond 28 days, such as 56 days and 90 days to better assess long-term strength development, particularly for slag-rich mixes.

III. Tests such as SEM, XRD, and FTIR should be carried out to better understand hydration products, pore structure, and the bonding behind strength and durability improvements.

IV. Different alkali activators or alternative activators should be explored to evaluate their effects on performance, cost, and environmental impact.

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APPENDICES

Appendix A: C10-P22.5G67.5 Flow Test

Appendix B: C10-P45G45 Flow Test

Appendix C: C10-P67.5G22.5 Flow Test

Appendix D: C20-P20G60 Flow Test

Appendix E: C20-P40G40 Flow Test

Appendix F: C20-P60G20 Flow Test

Appendix G: C30-P17.5G52.5 Flow Test

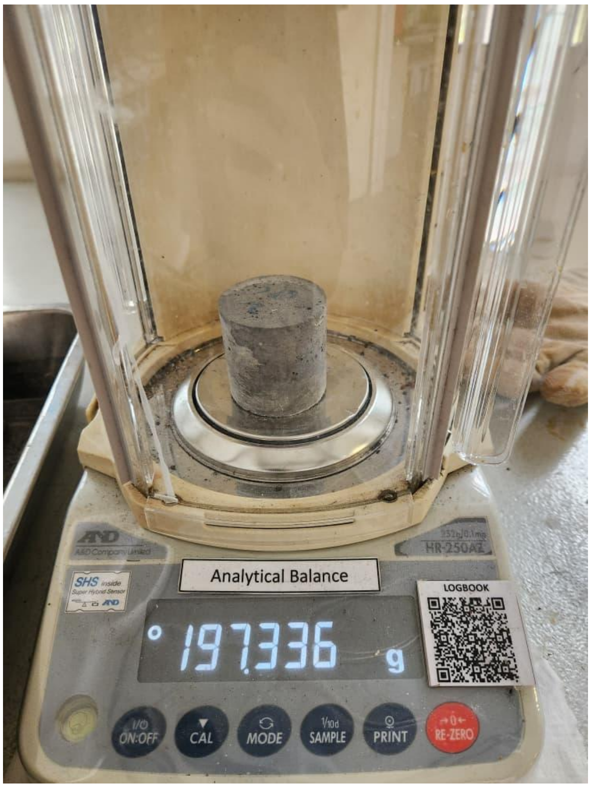
Appendix H: C30-P35G35 Flow Test

Appendix I: C30-P52.5G17.5 Flow Test

Appendix J: C40-P15G45 Flow Test

Appendix K: C40-P30G30 Flow Test

Appendix L: C40-P45G15 Flow Test



Appendix L: Analytical Balance for Weighing