EXPERIMENTAL ANALYSIS OF FLY ASH BASED GEOPOLYMER CONCRETE INCORPORATING POTASSIUM HYDROXIDE FOR USE IN RIGID PAVEMENT CONSTRUCTION

Project submitted in partial fulfillment of the requirements for the degree

Of

BE CIVIL ENGINEERING

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This is to certify that the Final Year Design Project

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DEDICATION

This research paper is a heartfelt tribute to the unwavering backing and affection of our parents and siblings who have served as our guiding beacons throughout this educational voyage. Their perpetual motivation and unwavering faith in our capabilities have been the primary impetus propelling our quest for knowledge. This research paper is also dedicated to our instructors, whose expertise and unwavering dedication have played a pivotal role in shaping our research and fostering our academic development. Their profound knowledge and steadfast commitment have been crucial in molding our scholarly journey and expanding our horizons, their passion for respective fields and tireless efforts to impart knowledge have not only enhanced our understanding but also ignited a spark of curiosity that fuels our desire to delve deeper into the realms of learning.

DECLARATION

We hereby affirm that all the work undertaken for this final year design project has been solely executed by us and has not been previously submitted, either in its entirety or partially, for any degree program in any other institution. Any references to the work done by any other person, University or material used from other publications have been appropriately cited.

ACKNOWLEDGEMENTS

We extend our heartfelt appreciation to the Almighty for granting us the ability to successfully accomplish our degree and attain this significant milestone through the completion of this project. Our heartfelt appreciation goes to Dr. Arshad Ullah, our project advisor, whose invaluable guidance and expertise have guided us throughout the entire study. We are also thankful to the lab instructors and engineers who have provided us with valuable information and advice during the project's laboratory component. The insights and advice from our peers have been instrumental in shaping our project work, and we sincerely appreciate their contributions. Furthermore, we would like to acknowledge the researchers whose published works we have consulted, as their contributions have greatly influenced and supported the successful completion of this project.

ABSTRACT

The escalating menace of global warming and the skyrocketing expenses associated with raw materials in cement production, numerous researchers in the construction industry are actively seeking alternative, environmentally friendly (green), and economically viable materials to manufacture concrete. Cement is widely regarded as the second most used material in the world after water. One such method that has gained attention is the use of geopolymer concrete, specifically fly ash-based geopolymer concrete (FGPC). This research project focuses on the experimental analysis of fly ash-based geopolymer concrete (FGPC) and its applicability in highway construction. The aim is to explore environmentally friendly and cost-effective alternatives to traditional cement-based concrete. This study compares the mechanical properties of ordinary Portland cement concrete (OPCC) and FGPC. Three different batches of concrete are investigated: OPCC as the control mix, FGPC, and FGPC with 5% cement as an admixture. The mix proportions are kept similar to ensure a fair comparison. Mechanical strength tests, including compression strength, splitting, and three-point flexural tests, are conducted OPCC and FGPC samples. Potassium hydroxide with molarity 14 and Na_2SiO_3 solutions were used as alkaline activator in this study. The experimental results revealed that when FGPC is subjected to higher temperatures of 60°C (oven curing), a significant 8% enhancement in compressive strength is observed after 7 days, surpassing the performance of the control mix at 28 days. Moreover, incorporating a 5% cement admixture into FGPC leads to a notable 4% boost in compressive strength after 28 days, compared to the control mix. In terms of flexural strength, FGPC exhibits slightly superior values to the control mix after 7 days. However, FGPC with 5% cement as an admixture, when cured under ambient conditions, shows a significant 15% increase in flexural strength at 28 days compared to the control mix. Three-point flexural test was also conducted, the results indicate that FGPC pavements have similar thickness to OPCC pavements. However, when FGPC is combined with a 5% cement admixture and used in ambient curing, there is an 8% reduction in pavement thickness compared to OPCC pavements. This reduction suggests that FGPC with a cement admixture can optimize material usage and reduce overall construction costs. The cost analysis demonstrates the economic viability of using FGPC in pavement construction. FGPC pavements can reduce costs by 12% compared to OPCC rigid pavements. Furthermore, FGPC with a 5% cement admixture shows a cost reduction of 16% compared to OPCC pavements. These cost savings highlight the attractiveness of FGPC as a sustainable and cost-effective option for infrastructure development.

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CHAPTER 1

INTRODUCTION

1.1 General

Green concrete, which has gained attention due to its considerable environmental impact and the expensive raw materials required for its production, is facing scrutiny as it is the second most extensively utilized material globally, following water. With the increasing urgency of addressing global warming and the demand for sustainable and economically viable construction practices, experts in the field and industry pioneers are actively investigating alternative approaches to develop eco-friendly concrete.

The manufacture of OPC cement is energy-intensive, and estimates suggest that it takes approximately one ton of fuel to produce one ton of OPC (Vairagade et al. 2015). This makes OPC production one of the largest emitters of CO2, contributing to around 7% of global CO2 emissions each year (LK Turner and FG Collins-2013). The emissions from cement production are a significant contributor to climate change, and the use of OPC concrete has been linked to various health problems, such as asthma, bronchitis, and sinus infections (S anand-2012).

To address these environmental and health concerns, researchers and manufacturers are exploring alternative materials and technologies to reduce the carbon footprint of cement production and the use of OPC concrete (Nehdi and Yassine-2008). Some of the alternatives being investigated include blended cements, which combine OPC with other materials such as fly ash or slag, and geopolymer cements, which use industrial waste as a raw material (P Duxson and JL Provis-2017). In addition, researchers are investigating new manufacturing processes, such as carbon capture and utilization (CCU) (A Al-Mamoori and A Krishnamurthy - 2008) and carbon capture and storage (CCS) (J Gibbins, H Chalmers - 2020), to reduce emissions from OPC production.

A promising approach gaining momentum in the quest for sustainable and cost-effective concrete is the utilization of fly ash-based geopolymer concrete (FGPC), as highlighted by P. Nath and P. Sarker in 2013. FGPC offers a viable solution to the challenges associated with conventional concrete by incorporating fly ash, a byproduct of coal combustion, as a partial substitute for ordinary Portland cement (OPC) in the concrete mixture, as mentioned by K. Pasupathy in 2018. This innovative method aims to reduce the environmental impact and health concerns associated with traditional concrete while addressing the carbon footprint associated with OPC production. By harnessing the unique properties of fly ash and utilizing potassium hydroxide (KOH) as an activator, as explored by PA Khanna et al. in 2020, FGPC exhibits improved mechanical properties and shows promise for sustainable pavement construction, as demonstrated by X. Jiang et al. in 2017. This article delves into the various applications of FGPC using KOH as an activator, with a specific focus on its potential in pavement construction, as discussed by PA Khanna, D. Kelkar, and M. Papal in 2018.

In the 1980s, Joseph Davidovits played a pivotal role in the development of the geopolymer concept, introducing the idea that geopolymer binders could be created through a polymeric reaction involving alkaline liquids, silicon, and alumina sourced from materials like fly ash and rice husk ash. Geopolymers represent a category of inorganic polymers that form when an alkaline activator solution reacts with an alumino-silicate substance, as explained by E. Bonet et al. in 2004. By utilizing fly ash as the alumino-silicate material and incorporating an alkaline activator solution, a binder is formed that can serve as a substitute for ordinary Portland cement (OPC) in concrete production, as noted by D. Hardjito, S. E. Wallah, and D. M. J. Sumajouw in 2016. The reaction between the alkaline activator and fly ash generates a calcium-silicate-hydrate (C-S-H) gel, which serves as the primary binder in OPC concrete, as highlighted by G. F. Huseien et al. in 2020.

Research on geopolymers has shown that they have several advantages over OPC concrete, including higher compressive strength, better durability, and lower carbon footprint (CR Meesala, NK Verma and S Kumar-2005). In addition, geopolymers can utilize waste materials such as fly ash as a raw material, providing an opportunity to reduce waste and environmental impact (M Drechsler and A Graham, 2008). However, it is important to note that the production of geopolymers requires careful control of the reaction conditions and the quality of the raw materials (P Duxson and JL Provis, 2022). Variations in raw material quality or reaction conditions can result in variations in the properties of the resulting geopolymer binder, which can affect the performance of the concrete (FA Shilar et al.,2019). As such, further research and development is needed to optimize the production and use of geopolymers in concrete production.

1.2 Fly Ash (Class F) Based Concrete

Compared to OPC concrete, FGPC offers numerous advantages that contribute to its growing popularity (NK Verma et al.,2006). One significant benefit is its lower carbon emissions (ML Nehdi and A Yassine-2020). By utilizing fly ash as the primary raw material, the carbon footprint associated with traditional cement production is significantly reduced (A Naqi and JG Jang-2022). This reduction in carbon emissions aligns with global efforts to combat climate change and promote sustainability in the construction industry (J Sathaye et al.,2023).

FGPC is an innovative construction material that deviates from the conventional use of standard cement as a binding agent. Instead, it employs a geopolymer binder derived from **low-calcium** (ASTM Class F) fly ash. This alternative approach revolutionizes the way fine and coarse aggregates are bound together, whether they are in loose form or include admixtures (T Srinivas et al., 2017).

In addition to its environmental benefits, FGPC demonstrates superior durability and resistance to fire and chemicals (Y Li et al.,2016). These enhanced properties make it an attractive choice for various construction applications, where durability and safety are paramount. Furthermore, FGPC presents an opportunity for waste reduction (X Ge et al.,2021). By incorporating fly ash, which is often a byproduct of coal combustion in power plants, as a raw material, the need for virgin materials is diminished, fostering a more sustainable approach to concrete production (N Toniolo and AR Boccaccini, 2018).

The manufacturing process of fly ash-based geopolymer concrete (FGPC) closely resembles that of ordinary Portland cement (OPC) concrete, with a notable distinction in the type of binder used (Y Cui ,2016). The production begins by blending fly ash with alkaline activators to form the geopolymer binder. This binder is subsequently combined with the fine and coarse aggregates, creating the concrete mixture. The mixture is then poured into molds and allowed to cure, resulting in a robust and durable final product.

The utilization of fly ash as a major binding agent in concrete represents a significant advancement in sustainable construction practices. By harnessing the unique properties of fly ash and geopolymer technology, FGPC showcases improved performance, reduced environmental impact, and an opportunity for waste utilization. As research and development in this field continue to progress, fly ash-based concrete is poised to play a pivotal role in the transition towards greener and more sustainable construction practices, contributing to a more resilient and environmentally conscious future.

When considering the composition of FGPC, it is important to note that, like OPC concrete, the majority of its volume (around 70-75%) is occupied by aggregates. The key distinction lies in the binder material that binds these aggregates together. Fly ash, comprising silicon and aluminum, reacts with an alkaline solution containing sodium hydroxide and sodium silicate. This reaction results in the formation of a geopolymer paste, which acts as the binder to hold the aggregates in place, forming a cohesive and robust concrete structure.

1.3 Problem Statement

Cement, a vital ingredient in concrete, is responsible for significant environmental impact due to its energy-intensive production process. Roughly one ton of carbon dioxide is emitted into the atmosphere for every ton of cement manufactured.This highlights the urgent need for **environmentally friendly** alternatives to reduce carbon emissions and mitigate climate change. By exploring and implementing alternative materials, such as fly ash-based geopolymer concrete using **KOH as an activator**, the construction industry can reduce its dependency on cement, **improve cost-effectiveness**, and **enhance sustainability**.

1.4 Objectives of Project

As stated already, a lot of research has taken place on this topic both at international and national level, like the detailed long-term effects on durability of FGPC, behavior of beams and columns cast with FGPC. The main aim of this project was to compare three similar mix designed specimens of OPCC, FGPC and FGPC with cement admixture in normal field conditions and environment which prevails in Pakistan.

The objectives envisioned for the projects were as follows:

- **To evaluate the characteristics and attributes of the materials employed.**
- **To assess the mechanical properties** of concrete, including **compressive strength, split tensile strength,** and **flexural strength,** for both **FGPC** and **OPCC.**
- To carry out a **cost benefit analysis** of FGPC in utilization in rigid pavement construction.

1.5 UNGA Sustainable Development Goals

The United Nations General Assembly (UNGA) adopted a set of 17 Sustainable Development Goals (SDGs) in 2015, which aim to tackle diverse social, economic, and environmental issues to promote a sustainable future.

This research study will be focused on following sustainable development goals

1. **SDG-9**: Industry, Innovation and Economic Growth
2. **SDG-11**: Sustainable Cities and Communities
3. **SDG-13**: Climate Action

1.6 Scope of Work

The fly ash used for the production of FGPC was sourced from Faisalabad, while the alkaline liquids were obtained from a chemical manufacturer located in Rawalpindi. The fine aggregate was procured from Pizzu, and the coarse aggregate was obtained from a local crush plant in Mardan. The production method employed for FGPC was identical to that used for OPCC. The evaluation of concrete properties was focused on assessing their compressive strength, indirect tensile strength, and flexural strength.

1.7 Project Report0 Outline

The project report is arranged in following manner:

Chapter 2 contains a brief survey of the literature on geopolymer technology, concrete,and rigid pavements. Furthermore, the study explores alternative binders to traditional concrete and examines the utilization of low-calcium fly ash concrete (ASTM Class F) as a potential substitute.

Chapter 3 describes the research methodology adopted to investigate the topic. In this chapter the method of performing different test will be discussed and explained. The tests which are used to study the behavior of concrete will also be explained in this chapter.

In chapter 4 the results of the tests are compiled and discussed. The study delves into the impact of fly ash incorporation in concrete and the influence of temperature (curing conditions) on the mechanical properties of the concrete, which are thoroughly examined and discussed. The effects of use of FGPC in rigid pavement is also explained in terms of thicknesses achievedfor different mix under consideration in this study and their cost benefit analysis was also carried out.

Chapter 5 will have the summary and conclusion part of the project report and few recommendations will also be given.

The project report will end with a reference list.

CHAPTER 2

LITERATURE REVIEW

2.1 Effects of Concrete on Environment

The production and use of concrete has significant effects on the environment, particularly in terms of greenhouse gas emissions and energy consumption. Cement production, a key component of concrete, contributes to the release of large amounts of carbon dioxide (CO_2) into the atmosphere. For every ton of cement produced, approximately one ton of CO_2 is emitted, making the cement industry responsible for nearly 7% of global greenhouse gas emissions, (Bakhtyar & Nawaz, 2017). This substantial carbon footprint is a result of the energy-intensive process involved in cement manufacturing, which contributes to climate change and global warming.

Furthermore, concrete is known for its high energy requirements throughout its lifecycle. From the extraction of raw materials to the manufacturing process and transportation, significant energy inputs are needed. The reliance on fossil fuels for energy during these stages further exacerbates the environmental impact. The energy consumption associated with concrete production contributes to the depletion of natural resources and increases the demand for non-renewable energy sources, leading to further environmental degradation. (Mohamad, Nabilla, et al., 2022).

In addition to its carbon emissions and energy consumption, the extraction of raw materials for concrete production can have detrimental effects on ecosystems. The extraction of aggregates, such as sand and gravel, often involves the disturbance of riverbeds and habitats, leading to the loss of biodiversity and disruption of natural ecosystems. Moreover, the demand for these materials can contribute to unsustainable mining practices, causing soil erosion, deforestation, and habitat destruction.

Recognizing these environmental concerns, the concrete industry has acknowledged the need for sustainable development and has begun taking steps to mitigate its impact. Efforts are being made to reduce the carbon footprint of cement production by exploring alternative materials, such as supplementary cementitious materials and innovative manufacturing processes. Additionally, the industry is focusing on improving energy efficiency, promoting recycling and reuse of concrete waste, and investing in research and development of more environmentally friendly construction practices. By addressing these issues and adopting sustainable approaches, the concrete industry aims to minimize its environmental impact while continuing to provide a durable and versatile construction material.

2.2 Fly Ash

The According to the 2004 report by the American Concrete Institute (ACI) Committee 116R, fly ash is the residual material that remains after coal is ground and burned. It is carried along with the flue gases during the combustion process and then separated using a dust collector installed in the power plant's chimney before the gases are discharged into the environment. The separation can be accomplished either manually or through electrostatic methods. In contrast to ordinary Portland cement (OPC) and lime, fly ash particles generally have a spherical form and vary in size, ranging from 1 to 150 microns in diameter.

The chemical composition of fly ash varies depending on the type of coal utilized in its production. It mainly consists of silicon, aluminum, iron, and calcium oxides (CaO), with small amounts of magnesium, potassium, sodium, titanium, and sulfate also present. The physical and chemical properties of fly ash are influenced by factors such as the particle form, type of coal used, and the combustion process. For instance, efficient burning is achieved when coal with a higher iron content, such as bituminous coal, is employed, leading to specific characteristics of the resulting fly ash, as explained by V. Malhotra and Ramezanianpour in 1994.

When sub-bituminous coal, which has over 20% CaO in its ash, is burned, it produces Class C fly ash, also called high-calcium fly ash. On the other hand, bituminous and anthracite coals produce ASTM Class F fly ash, which contains very little calcium. The chemical composition and material content of fly ash determine its color. Further information on both Class F and C fly ash is provided in Table 2.1, as per V. Malhotra and Ramezanianpour (1994).

Table 2.1 Chemical Composition of Fly Ash as per ASTM C618-19

Chemical Composition	Class F	Class C
SiO_2	45 % (min)	20 % (min)
Fe_2O_3 (max %)	25	50
CaO (%)	15 % (max)	25 % (min)
SO_3 (max %)	5	5
MgO (max %)	6	12
Loss on Ignition (max %)	6.0	6.0
Moisture Content (max %)	3.0	3.0

Note: These values are general guidelines, and the actual composition of fly ash can vary depending on the specific source and production process.

Fly ash has following advantages over OPC as has been investigated by many researchers:

1. **Sustainability**: Fly ash promotes sustainability by utilizing a waste material, reducing the demand for OPC and minimizing resource consumption.
2. **Lower Carbon Footprint**: Compared to OPC, fly ash significantly reduces carbon emissions during concrete production, contributing to climate change mitigation.
3. **Enhanced Concrete Performance**: Fly ash improves workability, strength, durability, and resistance to chemical attack, resulting in longer-lasting concrete structures.
4. **Cost-Effectiveness**: Incorporating fly ash into concrete mixtures offers cost advantages, reducing the need for excessive water and expensive OPC.
5. **Waste Management Solution**: Fly ash utilization provides an environmentally friendly approach by converting a waste product into a valuable resource, minimizing landfill usage and environmental concerns.
6. Suitable for high temperature curing.

2.3 Use of Fly Ash in Concrete

To minimize the negative environmental impact of concrete, there are several ways to reduce the content of OPC in the concrete. One approach is to replace some of the cement in the concrete mix with fly ash. When used as a substitute for cement, fly ash acts as a synthetic pozzolan. The combination of silicon dioxide from the cement hydration phase and calcium hydroxide results in the formation of calcium silicate hydrate (C-S-H) gel (Hardjito & Rangan, 2005). Because of its small, spherical particle size, the use of fly ash can improve the workability of fresh concrete by filling the gaps between aggregates.

The development of high-volume fly ash concrete (HVFA) has been a significant achievement in reducing the environmental impact of concrete. By replacing up to 60% of OPC with FA, HVFA concrete has demonstrated good mechanical properties and increased durability. In fact, in some cases, HVFA concrete has even outperformed OPC concrete in terms of resource efficiency and durability. This innovative concrete technology has gained popularity in several regions, especially in India, where it has been utilized in pavement development projects to varying degrees of OPC replacement with FA (Deasai, 2004).

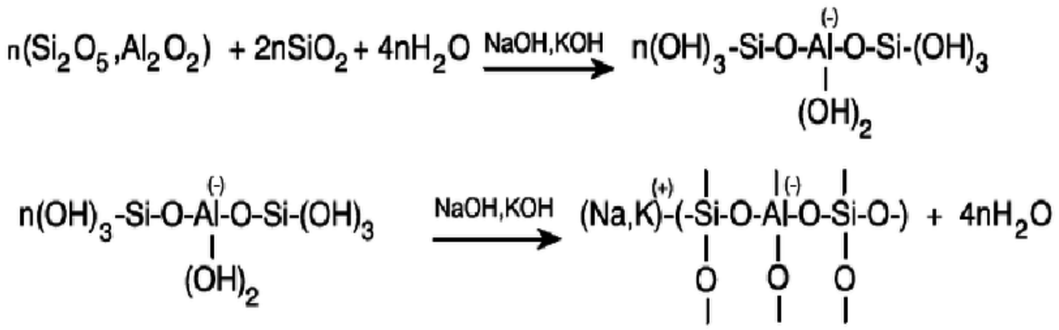
2.4 Geopolymers

David Ovitz suggested that an alkaline liquid could be used to create binder materials by bonding with silicon and aluminum in any source material, whether from a geological location or an industrial process like fly ash or crushed granulated blast furnace slag (Hardjito & Rangan, 2005). These binders were named geopolymer by Davidovits, who described the polymerization process that takes place during their creation (Davidovits, 1999).

Geopolymers are a type of inorganic polymer that have a chemical composition similar to that of conventional zeolitic minerals, but they have an amorphous microstructure instead of a crystalline one. The process of polymerization occurs rapidly in an alkaline environment on Si-Al minerals. This process leads to the formation of three-dimensional polymeric chains and rings of Si-O-Al-O links.

$$Mn\ [-(SiO_2)\ z–AlO2]\ n.\ wH_2O \qquad (1)$$

“Where: M = alkaline element or cation such as potassium, sodium, or calcium; the symbol - indicates the presence of a link; n represents the degree of polycondensation or polymerization; z is 1,2,3 or higher, up to 32; and an is a positive integer between 1 and 32” (Hardjito & Rangan, 2005). Following equations explain the graphical development of geopolymer material (Van Jaarsveld, Van Deventer, & Lorenzen, 1997):



(2)

Figure 2.1 Schematic Equation of Geopolymer Material

As seen in eq 2 of figure 2.1, water gets liberated during the synthesis of geopolymers. Ejected water from the geopolymer substrate after curing leaves intact intermittent very small-pores in the matrix, which enhance the geopolymer's performance. In contrast conventional OPC concrete, in which water is required for the chemical reaction that leads to the hydration of cement in concrete, geopolymer solution does not need water for any chemical processes (Hardjito, 2005).

Table 2.2 Geopolymer applications offered by Davidovits based on the molar ratio of Si to Al.

Si/Al	Application
1	Bricks, ceramics, fire protection
2	Low CO_2 cements, concrete, radioactive & toxic waste encapsulation
3	Heat resistance composites, foundry equipment, fiber glass composites
>3	Sealants for industry
20<Si/Al<35	Fire resistance and heat resistance fiber composites

2.5 Source Materials for Geopolymers

Geopolymers can be produced using any Si-Al-containing amorphous substance as a source material. Researchers have explored a range of minerals and industrial byproducts for this purpose, including metakaolin or calcined kaolin, low calcium ASTM class F fly ash, a combination of calcined and non-calcined materials, and a combination of granulated blast furnace slag and metakaolin (Teixeira-Pinto, Fernandes, & Jalali, 2002; Palomo et al., 1999; Xu & Vans Deventer, 2002; Cheng & Chiu, 2003).

Many geopolymer product manufacturers like metakaolin due to its relative ease of dissolution in the chemical mixture and more control over the Si/Al ratio. (Gourley, 2003). However, making concrete on a large scale it is too costly.

To ensure that the polymerization of concrete is not hindered by the presence of large amounts of calcium, class F fly ash is preferred to class C fly ash. (Gourley, 2003).

2.6 Alkaline Liquids

A probable blend of “sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate or potassium silicate” is the most prevalent alkaline liquid used in geopolymerization (Barbosa, MacKenzie, & Thaumaturgo, 2000).

According to Palomo et al. (1999), the polymerization process in geopolymer production is significantly influenced by the type of alkaline liquid used. The use of sodium or potassium silicate in an alkaline solution leads to faster reactions compared to other alkaline hydroxides. Xu and Vans Deventer (2000) also found that combining sodium silicate solution with sodium hydroxide solution increases the reaction between the source material and the solution. Moreover, they observed that the KOH solution dissolves more material than the NaOH solution, on average.

2.6.1 Potassium Hydroxide

Potassium hydroxide (KOH) is a strong alkali compound that is commonly used in various applications. Here are some key points about KOH:

1. **Chemical Properties:** KOH is an inorganic compound with the chemical formula KOH. It is a white, odorless solid that readily dissolves in water, producing a highly alkaline solution.
2. **Alkali Properties:** It is highly caustic and has strong alkaline properties. It is classified as a strong base and can react exothermically with acids.
3. **Industrial Applications:** KOH has diverse industrial applications. It is used in the manufacturing of soaps, detergents, and other cleaning products. It is also employed as a pH regulator in various industries, including the production of food and beverages.
4. **Catalyst:** It is used as a catalyst in several chemical reactions. It can promote reactions such as esterification and transesterification, making it valuable in the production of biodiesel and other organic compounds.
5. **Alkaline Activator**: In the field of construction materials, KOH is utilized as an alkaline activator in the production of **geopolymer materials**, including geopolymer concrete. It aids in the geopolymerization process of materials like **fly ash,** promoting the formation of a hardened, durable material.

Potassium hydroxide (KOH) is commonly used as an alkaline activator in the production of fly ash-based geopolymer concrete. Geopolymer concrete is an alternative to traditional Portland cement-based concrete and is known for its lower carbon footprint and improved durability. KOH is added to the mixture of fly ash, aggregates, and water to initiate the geopolymerization process. It serves as an alkali source, providing the necessary alkalinity for the activation of the fly ash. The alkaline activator reacts with the silica and alumina in the fly ash, resulting in the formation of a three-dimensional polymeric network, known as the geopolymer gel.

The concentration of KOH used as an activator can vary depending on the specific requirements of the geopolymer concrete mix. Typically, concentrations ranging from 6% to 14% by weight of the fly ash are used. The exact concentration is determined based on factors such as the reactivity of the fly ash, desired strength development, and workability of the mix.

KOH plays a crucial role in determining the properties of fly ash-based geopolymer concrete, including compressive strength, setting time, and durability. The concentration and proportion of KOH influence the activation process and subsequently affect the development of the geopolymer gel network. Therefore, careful consideration and optimization of the KOH concentration are essential to achieve the desired performance of geopolymer concrete.

2.7 Overview of Fly Ash (FA) Modified Concretes

2.7.1 Concrete Incorporating High Volumes of ASTM Class F Fly Ash

Giaccio and Malhotra (1988) conducted research on the mechanical properties of high-volume fly ash (HVFA) concrete utilizing Types I and III cements. They prepared a total of twelve batches of concrete, consisting of eight different combinations, each with a volume of 0.06 m3 and a water-to-cement (w/c) ratio of 0.32. In these concrete mixtures, 60% of the cement content was replaced with fly ash while keeping the other constituents constant.

This inquiry evaluated "12 x (152 by 305 mm cylinders), 192 x (102 by 203 mm cylinders), and 40 x (76 by 102 by 406 mm) prisms." Table 2.4 shows compressive, flexural, splitting-tensile, and elasticity test results.

Table 2.3 Mechanical Properties of HVFA Hardened Concrete, Giaccio and Malhotra (1988)

ASTM Type Cement	Mixture No	Densit yat 1 Day kg/m3	Compressive Strengths of 102 by 203 mm Cylinders, MPa			28-day Flexural Strength of76 by 102 by 406 mm Prisms, MPa	28-day Splitting Tensile Strength of 102 by 203 mm Prisms, MPa	28-day Modulus of Elasticity of 152 by 305 mm Cylinders, GPa
			1-d	7-d	28-d			
I	1 (Batch A)	2420	8.4	18.3	30.7	4.6	3	
	1 (Batch B)	2440			31.6			34.4
	2 (Batch A)	2400	9.3	17.6	32.5	4.9	3.3	
	2 (Batch B)	2420			33.3			35.5
	3 (Batch A)	2430	8.4	17.1	28.9	4.3	3.1	
	3 (Batch B)	2420			30.5			34
	4 (Batch A)	2410	9.6	17.5	29.2	5.2	3.2	
	4 (Batch B)	2420			31.9			35
III	5	2430	14.3	22.9	34.3	5.6	3.1	
	6	2425	13.8	24.0	34.8	5.6	3.2	
	7	2450	15.3	25.0	37.3	5.8	3.4	
	8	2435	14.8	26.3	37.7	6.2	3.6	

The maximum compressive strength of concrete made with Type I cement was found to be 9.6 MPa after one day and 33.3 MPa after 28 days. These results were attributed to the low concentrations of C3S and C2S in Type I cement, which are known to contribute to early strength. In contrast, concrete made with Type III cement showed much higher compressive strengths after one day, with a maximum value of 15.3 MPa, which is 37% higher than that of Type I cement.

There are no significant differences between both the concrete's 28-day flexural strengths when created with Type I cement and those of other similar-strength concrete when prepared with Type III cement. Also, these values are equivalent to those reported by experts for OPCC of a similar strength.

The highest splitting tensile strength achieved by concrete produced with Type I cement after 28 days was 3.3 MPa, whereas concrete made with Type III cement had a maximum tensile strength of 3.6 MPa. It is worth noting that published data indicates that the splitting tensile strength values are around 10% of the 28-day compressive strength results. These tensile strengths are similar to those of regular OPC concrete with similar mix proportions.

Using only Type I cement, a Youngs modulus of elasticity of 35 GPa has been determined. Typical limestone concrete of the same strength has a modulus of elasticity roughly 20% greater than this. E values are high because of the densification effect of concreteparticles at 28 days, when there is little pozzolanic interaction between low-calcium fly ash andPortland cement.

The research conducted by Giaccio and Malhotra (1988) on concrete made with class F fly ash indicates that it exhibits exceptional mechanical properties and holds great potential for use in structural concrete components, especially in large sections. To achieve adequate workability in the initial stages of the construction process, the use of ASTM Type III cement and superplasticizers is deemed crucial when creating structural concrete with a high proportion of fly ash.

2.7.2 Durability Characteristics of Steel Fiber Reinforced Geopolymer Concrete

Ganesan, Abraham, and Raj (2015), conducted detailed research on the 100 % replacement of concrete with fly ash and its effects on mechanical properties of concrete as compared with OPCC.

To prepare the alkaline liquid component for the FGPC, NaOH in 10 molar concentration was utilized, and the ratio of sodium silicate to sodium hydroxide was kept at 2.5. The FGPC specimens were subjected to dry curing in an oven at 60 C for 24 hours, followed by curing at ambient conditions until the day of testing. Various mechanical tests, including slump, compressive strength, split tensile strength, modulus of elasticity, and flexural strength tests, were conducted to assess the mechanical properties of FGPC and compare them with OPCC.

After the slump test it was observed that FGPC had a slump of 123 mm and OPCC had a slump of 128 mm. Both are almost similar which shoes that FGPC and OPCC can have identical workability conditions during their fresh states. But it is important to note that a plasticizer of 2.5 % by weight of FA was also used in FGPC whereas OPCC had none.

Mechanical properties of FGPC also showed better results as compared to OPCC. The compressive strength of FGPC showed a **6 %** increase from that of OPCC. Split tensile strengthof FGPC showed a **12 %** increase from that of OPCC. Similarly, the modulus of elasticity of FGPC was higher than that of OPCC by **29 %.** The flexural strength of FGPC was also greater than that of OPCC by **8 %**.

Ganesan et al. (2015) concluded that FGPC had comparable and in most cases higher mechanical properties than OPCC. It was entirely possible to use FGPC as a substitute of OPCC in general construction work.

2.7.4.1 Influence of Concentration of Potassium Hydroxide (KOH) Solution on mechanical properties

2.7.2.1 Workability

In their research, M M Abdelmoamen et al. (2020) investigated the impact of KOH (AA) on the mechanical characteristics of concrete under normal temperature conditions. They altered the molarity of KOH within the range of 8 molar to 16 molar. Various tests were conducted to evaluate the mechanical properties of the concrete. The decrease in the effectiveness of GP is was observed as the molarity of KOH increases.

Change of molarity of KOH from 8 M to 10 M had no effect on slump. But slump of FGPC reduced by "**10.5%, 11.7% and 6.6%** when molarity of KOH was changed from 10 M – 12 M, 12 M – 14 M and 14 M – 16 M respectively" (M M Abdelmoamen et al., 2020). This decrease in slump due to increasing KOH molarity can be explained by the fact that KOH solution has more viscosity than water and with increasing molarity the solutions become more viscous.

2.7.2.2 Compressive Strength

Increasing the KOH molarity within the specified range (10 M to 18 M) resulted in significant percentage improvements in compressive strength, strength increased slightly by 11% when we increased molarity from 10M to 12M, then it increased significantly by 70% when molarity is increased from 12M to 16M. it is greatly reduced by 37% with increasing concentration to 18M (M M Abdelmoamen et al., 2020). It's important excessively high molarity beyond the specified range may not result in proportionally higher increases in compressive strength. In fact, there may be diminishing returns or even adverse effects on workability and other properties.

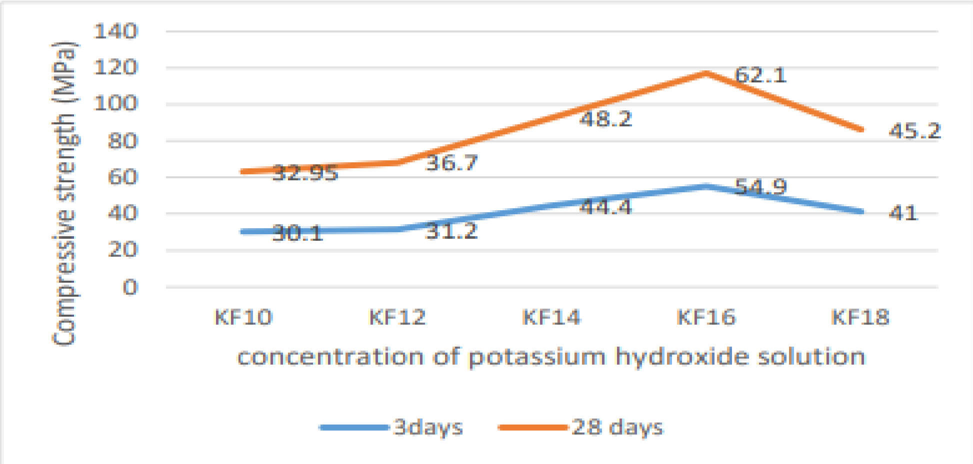


Figure 2.2: Compressive strength of concrete with different molarity of KOH solution. (M M Abdelmoamen et al., 2020)

2.7.2.3 Flexural Strength

Similarly, it was observed that with increasing molarity flexural strength also increased. At 8 M KOH there was 5% increase, at 12M 10% increase, at 14 M 20% increase was observed strength. (Moraes Pinheiro et all.2018). Similarly to compressive strength, excessively high molarity beyond the specified range will not result in proportionally higher increases in flexural strength. The influence of KOH molarity on flexural strength can vary based on factors such as the specific composition of fly ash, activator-to-fly ash ratio, curing conditions, and other mix design parameters.

2.7.5 Effects of Salient Parameters

2.7.5.1 Curing Temperature

It appears that increasing the curing temperature of the fly ash-based geopolymer concrete (FGPC) led to an increase in compressive strength for mixture 2 and mixture 4. However, it was observed that the compressive strength did not significantly increase beyond a curing temperature of 60°C.

Additionally, it was noted that the FGPC reached its optimum strength at a curing temperature of 90°C. Despite this observation, most researchers have chosen to cure FGPC at 60°C due to the rapid gain in compressive strength observed up to that temperature.(Ahmad, Shamsad,et al.)

2.8 Feasibility study of ambient cured geopolymer concrete – A review

The curing process of FGPC differentiates it from conventional concrete. Unlike conventional concrete, water curing is not used in FGPC. Heat curing i.e., steam curing and dry curing is generally used for activating the chemical reactions for polymerization of concrete (Badar, Mohammad Sufian 2014). Nath and Sarker (2015) _ investigated the effects of different admixtures when added to FGPC mechanical properties if ambient curing is carried out. A lot of researches has been done on the topic which have suggested that low calcium FGPC shows better mechanical properties when heat cured (Lloyd & Rangan, 2010) but it does not depict good mechanical properties at ambient temperature curing conditions (Sharma & Jindal, 2015).

FGPC cured at ambient temperature has shown poor compressive strength (Sharma & Jindal, 2015). At ambient temperature curing, many studies have concentrated on improving the mechanical strength and endurance of FGPC by mixing OPC, GGBS, nano-silica, and Alccofine.

Cured geopolymer concrete containing low-calcium fly ash has weak compressive strength at room temperature (Sharma & Jindal, 2015). Jindal et al. (2017) reported that FGPC could achieve ultimate strength of 20 MPa in 28 days with ambient curing in their report. Heat curing at 90 C resulted in a compressive strength of 42 MPa.

Most geopolymer concrete that has been tested so far has been heated to a higher temperature in order to improve its strength properties. The geopolymer concrete that was cured at room temperature was not strong enough. While GPC can be used in the precast industry, the heat curing process restricts its use in general construction.

Therefore, it was felt necessary to develop FGPC which can gain required sufficient strength in ambient curing condition which can further help in use of FGPC for general construction purposes at normal temperature. It would also further economise the use of FGPC instead of OPCC.

Nath and Sarker (2015) in their research showed that up to 12 percent of the total binder in FGPC mixtures in ambient curing conditions contained OPC as a component. Geopolymerization reaction was hastened and workability and setting time were altered by the presence of OPC, as indicated in Fig. 3. After 28 days, the compressive strength of geopolymer concrete containing 5% OPC was 40 MPa. OPC can be substituted for binder in cost and energy efficient FGPC at ambient curing conditions, resulting in a setting time that is comparable to that of conventional OPC concrete.

2.9 Conclusions form Literature Review

After detailed analysis of literature on the topic by different researcher's certain parameters regarding the production and curing of FGPC were observed. These parameters were set as guidelines for the production of FGPC for this research.

It was found that average molarity of KOH in alkaline solution should be between 8 M – 16 M, with **14 M** concentration giving the optimum compressive strength. The ratio of sodium silicate to sodium hydroxide at **2.5** gives the best results in terms of mechanical properties of FGPC. There are two methods of curing the FGPC, one is the dry curing in an oven with an optimum temperature of **60 C for 24 hours** and other way is to perform curing of FGPC at ambient temperature by addition of an admixture. Usually, a little cement between5% - 12% is added to FGPC to facilitate the attainment of target strength values at ambient curing temperatures. Addition of at least 5 % of cement is enough for FGPC to achieve its target strengths.(Al Bakri et al.2011).

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

This chapter outlines the manufacturing process of (ASTM Class F) FGPC, which is fly ash-based geopolymer concrete. Currently, there is no widely accepted standard method for calculating the mix proportion of FGPC by organizations such as ACI, AS, and IS. Researchers have primarily relied on trial and error approaches to determine the appropriate mix proportion for desired parameters.

In this study, the mix proportion for FGPC was adapted from a previous work by Hardjito and Rangan in 2005, which closely resembled the control concrete (OPCC) used in the experiment. This decision was made to simplify the testing and manufacturing process and evaluate the suitability of FGPC when employing existing field practices.

To ensure a smoother introduction of FGPC into the construction industry in Pakistan, the study adopted the established practices utilized in the manufacturing and testing of OPC concrete. This approach aimed to reduce complexity and facilitate the integration of the new material.

Among the various materials available for geopolymer concrete production, ASTM Class F fly ash was chosen due to its accessibility in Pakistan. The cement used was obtained from the local market. To minimize the impact of aggregate qualities on fly ash parameters, the testing of fly ash was conducted using aggregates from a single source, namely the PRC lab.

By following established OPC concrete practices and utilizing locally available materials, the study aimed to pave the way for the future implementation of FGPC in the construction sector of Pakistan.

3.2 Materials used in this study

3.2.1 Fly Ash

The Fly Ash (FA) for this project was sourced from the Faisalabad Coal Power Plant in Punjab, Pakistan. It was utilized as a complete replacement for cement in order to produce FGPC. The chemical composition of the fly ash was obtained from Abdullah's research conducted on fly ash sourced from the same location. The fly ash used in this study shared similar texture with cement and had a light grey color. Analysis of the fly ash revealed a CaO content of approximately 14.12%, confirming its classification as Class F fly ash, which was a requirement for the study. The major minerals present in the fly ash were found to be SiO2 (59.96%) and Al2O3 (14.02%).

Table 3.1 Chemical Composition of Fly Ash (ASTM 2011)

SiO_2 (%)	**Al_2O_3 (%)**	**Fe_2O_3(%)**	**CaO (%)**	**SO_3 (%)**	**MgO (%)**	**LOI[a] (%)**
59.96	14.02	6.29	14.12	2.84	0.41	0.445
(59.96+14.02+6.29=80.27 >50)			14.12 ≤ 18	2.85 ≤ 5	0.41 ≤ 6	0.445 ≤3

Figure 3.1 Fly Ash

The results clearly indicate that the composition of the fly ash consisted of 80.27% SiO_2, Al_2O_3, and Fe_2O_3 combined. The amount of CaO present was 14.12%, while the content of SO_3 was 2.85%. Additionally, the loss on ignition value was measured at 0.445. The relatively low CaO content (14.12%), which falls below the 18% threshold, confirms that the fly ash used in the study was classified as class F fly ash

3.2.2 Fine Aggregates

In this study, the fine aggregates used were obtained from the concrete laboratory. These aggregates had a loose bulk density of around 1600 kg/m3. The results of the sieve analysis conducted on the fine aggregate are presented below.

Figure3.2 Fine Aggregate

Table 3.2 Sieve Analysis of Fine Aggregate

Sieve No.		**Weight retained**	**% Retained**	**Cumulative % Retained**	**% Passing**
No.	**mm**	**(g)**	**(%)**	**(%)**	**(%)**
#4	4.75	3	0.57	0.57	99.43
#8	2.36	5	0.94	1.51	98.49
#16	1.18	57	10.75	12.26	87.74
#30	0.6	132	24.91	37.17	62.83
#50	0.3	249	46.98	84.15	15.85
#100	0.15	58	10.94	95.09	4.91
#200	0.75	12	2.26	97.35	3.02
Pan	0	14	2.64	99.99	0

3.2.3 Coarse Aggregate

The coarse aggregate used in this study was obtained from the concrete laboratory and was treated similarly to the fine aggregate. It had a bulk density of 1794 kg/m3 and a particle size range of 20 mm to 7 mm. The aggregate sample had an aggregate impact value of 22.73 percent and an aggregate crushing value of 22.55 percent. The sieve analysis results for the coarse aggregate can be found in Table 3.3.

Table 3.3 Coarse Aggregate Sieve Analysis

Sieve No.	Weight retained	% Retained	Cumulative % Retained	% Passing
No.	(kg)	(%)	(%)	(%)
3/8	1.2	0.84	0.84	99.16
½	2.3	1.61	2.45	97.55
¾	5.1	3.56	6.01	93.99
1	9.7	6.78	12.79	87.21
$1^{1/2}$	15.2	10.63	23.42	76.58
2	21.17	14.80	38.22	61.78
$2^{1/2}$	25.70	17.97	56.19	43.81
3	30.13	21.07	77.26	22.74
$3^{1/2}$	35.76	22.57	99.83	0.17
Pan	0.24	0.17	100	0

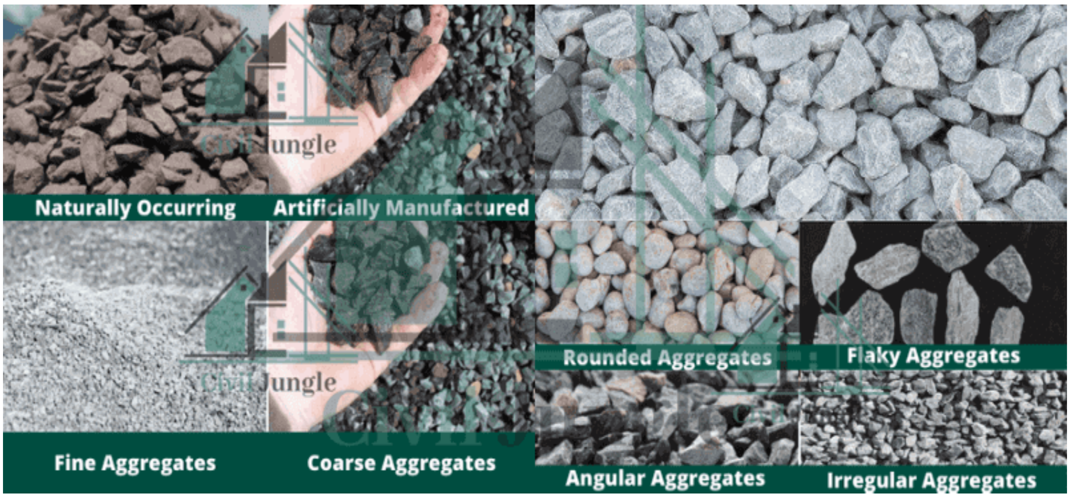


Figure 3.3 Coarse Aggregat

3.2.4 Alkaline Liquid

To prepare the alkaline liquids required for FGPC production, a solution consisting of sodium silicate (Na_2SiO_3) and potassium hydroxide (KOH) was utilized. Potassium-based activators were chosen due to their easy availability in the local market and cost-effectiveness.

The KOH solution was prepared by dissolving KOH pellets in water. The mass of the dissolved KOH particles is determined by their Molarity (M). With a molecular weight of 56.10 g/L for KOH, a 14 M concentration of KOH solution contains 785.54 g/L of the compound. It is important to note that the majority of the KOH solution is composed of water rather than KOH solids, which should be taken into account when calculating the mass of the solution.

The sodium silicate solution was locally sourced from a chemical supplier in Rawalpindi. It was obtained in a solution form with a concentration of 14.7% Na_2O and 29.4% SiO_3, with the remaining concentration consisting of water.

3.2.5 Super Plasticizer

The incorporation of "Ultra Super Plast 470," an organic polymer-based superplasticizer, was observed to enhance the workability of fresh FGPC concrete.

3.3 Mixture Proportions

In order to establish a baseline for comparison, a control mixture of OPCC (Ordinary Portland Cement Concrete) was initially prepared. The mixture proportion for FGPC (Fly Ash-based Geopolymer Concrete) was **1:1.5:3**. The FGPC mixture proportion chosen was similar to that of the control mixture. Calculations are as follows:

- **Cement**:

  Density of cement = 1440 kg/m³

  Dry volume of cement = 0.1818 m³ x 1.54 = 0.2799 m³

  Weight of cement = 0.2799 m³ x 1440 kg/m³ = 403.91 kg

- **Fine Aggregate (Sand)**:

  Density of fine aggregate = 1600 kg/m³

  Dry volume of fine aggregate = 0.2727 m³ x 1.54 = 0.4200 m³

  Weight of fine aggregate = 0.4200 m³ x 1600 kg/m³ = 672.00 kg

- **Coarse Aggregate (Gravel):**

  Density of coarse aggregate = 1794 kg/m³

  Dry volume of coarse aggregate = 0.5455 m³ x 1.54 = 0.8399 m³

  Weight of coarse aggregate = 0.8399 m³ x 1794 kg/m³ = 1506.94 kg

- **Fly Ash:**

  Density of fly ash = 860 kg/m³

  Dry volume of fly ash 0.1818 m³ x 1.54 = 0.2799

  Weight of fly ash = 0.1818 m³ x 860 kg/m³ = 240.71 kg

Additionally, a third mixture was prepared, which included an admixture of 5% cement in the FGPC mixture. The mixture proportion for this particular mixture was identical to that of FGPC, with the only difference being the addition of 5% cement by weight of FGPC. This resulted in a quantity of 12.04 kg/m^3 of cement in the mixture. The mixture proportions for all three mixtures are provided below

Table 3.4 Mixture Proportion of Control and Modified Batches

Materials	OPCC (kg/m^3)	FGPC (kg/m^3)	FGPC + 5% Cement (kg/m^3)
Cement	403.2	-	12.04
Fly ash	-	240.71	240.71
Coarse Aggregate	1507	1507	1507
Fine Aggregate	672.0	672.0	672.0
Sodium Silicate (SiO_2/ Na_2O=2)	-	44.125	44.125
Potassium Hydroxide Solution	-	17.65	17.65
Water	241.92	22.5	22.5
Super Plasticizer	-	6	6

3.4 Manufacturing Process

The manufacturing process of OPCC (Ordinary Portland Cement Concrete) is widely understood, and standard practices were followed to produce the control batch for comparison purposes. The manufacturing process of FGPC (Fly Ash-based Geopolymer Concrete) is similar to that of OPCC with a few exceptions. The production steps involved in manufacturing FGPC are as follows:

- **Preparation of liquids**: This step involves the preparation of alkaline liquids used in FGPC, such as the sodium silicate and sodium hydroxide solutions mentioned earlier. These liquids are prepared according to the required concentrations and specifications.
- **Mixing of materials and casting**: In this step, the dry materials, including the fly ash, fine aggregate, coarse aggregate, and any additional additives, are combined in appropriate proportions. The liquids prepared in the previous step are then added to the mixture, and the materials are thoroughly mixed to achieve a homogenous consistency. The resulting FGPC mixture is then cast into molds or formwork, where it is allowed to set and harden.
- **Curing of test specimens:** Once the FGPC is cast into the desired shapes or forms, it undergoes a curing process to promote hydration and strength development. Curing conditions, such as temperature and humidity, are carefully controlled to optimize the performance of the FGPC. Test specimens, such as cubes or cylinders, are typically cured under specific conditions to assess the properties and performance of the FGPC.

By following these manufacturing steps, the FGPC is produced and prepared for further testing and evaluation.

3.4.1 Liquid Preparation

According to Davidovits (2002), it is recommended to prepare the alkaline liquid for fly ash concrete a day before mixing and pouring the concrete. The reason behind this is that the process of dissolving potassium hydroxide pellets in water is exothermic, meaning it generates a significant amount of heat due to the reaction taking place. To account for this, the sodium silicate solution and sodium hydroxide solution were mixed a day in advance, prior to preparing the solid elements of the concrete mix.

The amount of potassium hydroxide pellets used to prepare the solution depended on the selected molarity, as explained in section 3.2.4. For example, to achieve a concentration of 14 M, 785.54 grams of KOH was dissolved per liter of water to prepare the potassium hydroxide solution.

After the potassium hydroxide solution was prepared, it was mixed with sodium silicate, the required amount of water, and the superplasticizer. This mixing method was adopted from the research conducted by Wallah and Rangan (2006). The mixing process generated a significant amount of heat. Therefore, as suggested by existing literature, the solution was left to cool down overnight in the laboratory.

Figure 3.4 Preparation of Alkaline Liquid

3.4.2 Mixing of Materials and Casting

The solid components of the mixture were combined in a concrete drum mixer and mixed for approximately 2-3 minutes. Then, the liquid part of the mix was added, and the constituents were mixed for an additional 5 minutes to ensure thorough blending.

After the mixing process, the resulting concrete was poured into cylindrical molds measuring 150 mm x 300 mm. The pouring was done in three layers, and after each layer, it was compacted manually using a rod for 25 blows. Additionally, to improve compaction and consolidation, each layer was placed on a vibrating table for 10 seconds.

Similarly, for casting prisms, molds measuring 100 mm x 100 mm x 400 mm were used. The casting was performed in two layers, with each layer being compacted with 25 blows to ensure proper compaction. Furthermore, to aid in the consolidation of the concrete, each layer was placed on a vibrating table for 10 seconds

By following these steps, the concrete was effectively mixed, poured into molds, and compacted to achieve the desired shape and density for testing and evaluation.

Figure 3.6 Mixing of Concrete

3.4.3 Curing

It is essential to highlight that FGPC (Fly Ash-based Geopolymer Concrete) does not require traditional water curing, as mentioned in section 2.7.4. Instead, it undergoes a dry or heat curing process to accelerate the geopolymerization process and achieve the necessary strength development (Jindal, 2018).

Two types of curing methods were employed in this study to investigate their effects on the properties of FGPC. The first method was dry curing in an oven. After the specimens were cast, they were left in their molds at room temperature for one day. Subsequently, the specimens were removed from the molds and placed in an oven located in the structural dynamics laboratory at MCE (mention the specific temperature and duration if available). The specimens were subjected to a temperature of 60°C for 24 hours in the oven. Following this, the specimens were returned to ambient curing conditions for an additional 7 days.

The second curing method was ambient curing, which involved the addition of 5% cement as an admixture to the FGPC mixture. This admixture was used to accelerate the geopolymerization process during ambient curing at room temperature. For this type of curing, the specimen was left in its mold for 24 hours, after which it was removed and placed in a location within the laboratory where sufficient sunlight was available during the day for curing. The specimen remained under ambient curing conditions until the time of conducting tests.

It is crucial to exercise caution and ensure accurate data entry into the industrial oven interface present in the structural dynamics laboratory at MCE. Any negligence or incorrect input of data into the machine could compromise the curing process of FGPC, leading to a lack of requisite strength gain in the concrete

3.5 Test Matrix

Table 3.5 Number of Specimens for Tests

Tests	**Specimens**			**Age (days)**	**Type**
	OPCC	FGPC	5%Cement FGPC		
Compressive Strength	3	3	3	7	Cylinders
	3	-	3	28	Cylinders
Splitting Tensile Strength	3	3	3	7	Cylinders
	3	-	3	28	Cylinders
Three Point Loading	3	3	3	7	Prisms
	3	-	3	28	Prisms

3.5.1 Compressive Strength Test

The compressive strength tests of the specimens were conducted using a 3000 KN automatic servo plus machine available in the structural dynamics lab at MCE. The testing procedure followed the guidelines specified in ASTM C39. The specimens used for testing were cylindrical in shape, with dimensions of 150 mm x 300 mm.

For the control batch of OPCC, the cylinders were removed from the curing tank on the 7th and 28th days of curing. These specimens were immediately taken for testing, as per ASTM standards, which require testing on moist specimens.

In the case of FGPC specimens, which underwent dry curing, the tests were conducted on the 7th day only. For the FGPC specimens undergoing ambient curing, the tests were performed at both the 7th and 28th days of curing.

The compressive strength tests were carried out at standard room temperature. Due to the rough surface of the FGPC specimens, sulphur capping was applied to the top and bottom faces of the cylinders. After the application of sulphur, the specimens were allowed to cure for 5 hours before testing.

During the testing process, the specimens were placed in the machine, and the relevant testing mode was selected from the menu on the machine interface. The tests were stress-controlled, with the load being applied at a rate of "0.25 MPa/s" according to ASTM C39. The machine automatically stopped the application of load once the ultimate strength of the specimen was reached. The results of the compressive strength tests were then recorded from the machine interface.

3.5.2 Splitting Tensile Test

The splitting tensile tests of the specimens were conducted using the same 3000 KN automatic servo plus machine that was used for the compressive strength tests. The testing procedure followed the specifications outlined in ASTM 496. The specimens used for testing were cylindrical in shape, with dimensions of 150 mm x 300 mm.

For the control batch of OPCC, the cylinders were removed from the curing tank on the 7th and 28th days of curing. These specimens were immediately taken for testing, as per ASTM standards, which require testing on moist specimens.

In the case of FGPC specimens, which underwent dry curing, the tests were conducted on the 7th day only. For the FGPC specimens undergoing ambient curing, the tests were performed at both the 7th and 28th days of curing.

The splitting tensile tests were performed at standard room temperature. The specimens were placed in a steel jig to ensure the correct alignment of the bearing surface of the specimen. The jig, along with the specimen, was then placed in the machine, and the relevant test mode was selected.

The test was stress-controlled, with the load being applied at a rate of "0.7 - 1.4 MPa/min" according to ASTM 496. The machine automatically stopped applying the load once the ultimate tensile strength of the cylinder was achieved. The results were then recorded from the interface of the machine.

3.5.2 Three Point Loading Test

The three-point loading tests of the specimens were conducted on prisms, following the guidelines of ASTM C293. The prisms had dimensions of 100 mm x 100 mm x 400 mm.

For the control batch of OPCC, the prisms were removed from the curing tank on the 7th and 28th days of curing. These specimens were immediately taken for testing, as per the ASTM standard requirement of testing on moist specimens.

In the case of FGPC specimens, which underwent dry curing, the tests were performed on the 7th day only. For the FGPC specimens undergoing ambient curing, the tests were conducted at both the 7th and 28th days of curing.

The tests were carried out at standard room temperature. Supporting blocks, which acted as supports for the prism, were attached to the machine. The prism was then placed on the supporting blocks, leaving a 25 mm space between the point support and the end face of the prism, as specified by ASTM standards.

The load-applying block was applied to the upper face of the prism at the center point. The load was applied to the specimen smoothly, without any abrupt changes, and the rate of loading was maintained at 1 MPa/s, which fell within the range specified in ASTM standards.

3.6 Summary

This chapter provides a comprehensive discussion on the materials and preparation methods for manufacturing FGPC concrete. It highlights that FGPC can be produced using the same manufacturing process employed for OPCC. The mixture proportions for the control and modified batches are also presented.

Furthermore, a testing matrix is described, outlining the tests conducted in this research to evaluate the mechanical properties of the concrete. These tests will provide valuable insights into the performance of FGPC, particularly in rigid pavement applications. Additionally, the flexural strength data obtained from the tests may offer additional observations regarding the use of FGPC in this context.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

In this chapter, the results and analysis of the experimental tests conducted on the mechanical properties of concrete are presented. The tests included

- Compressive Strength Test
- Splitting Tensile Test
- Three Point Loading Test.

After presenting the data, the effects of different concrete batches are studied. Thickness for a standard length of rigid pavement is calculated based on the data collected during the testing, and a cost-benefit analysis is carried out for all types of concrete batches used to find their respective thicknesses.

4.2 Results and Discussions

4.2.1 Compressive Strength Test

Table 4.1 Compressive Strength Test Data

Compressive Strength (psi)			
Sample	**7 Days**	**28 Days**	**Remarks**
OPC (Control)	3250	4550	Water Cured
FGPC	4785	-	Oven Cured at 60º for 24 hours
FGPC + 5% Cement	2675	4620	Ambient Cured

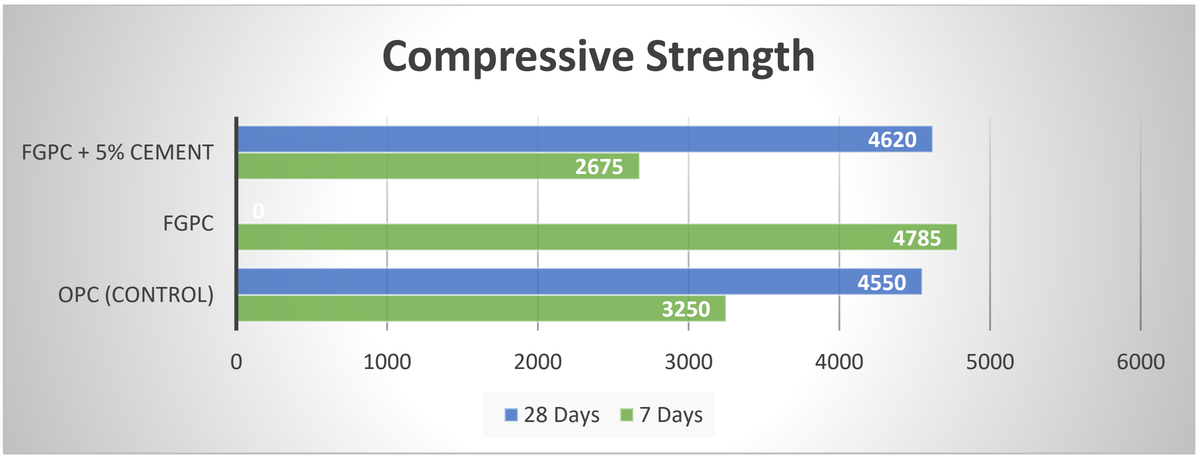


Figure 4.1 Comparison of Compressive Strength at 7 & 28 days of all Batches

The data presented in figure 4.1 indicates that FGPC exhibited the highest 28-day compressive strength among all batches, reaching 4800 psi. This value was about 5% higher than the control group and 3.5% higher than the 5% cement + FGPC batch. The second-highest 28-day compressive strength was observed in the 5% cement + FGPC concrete, which recorded 4620 psi, about 2.5% higher than the control group. Overall, the results demonstrate that both fly ash-containing batches achieved higher compressive strength values compared to OPCC, indicating the effectiveness of fly ash as a binding agent.

4.2.2 Splitting Tensile Test

Table 4.2 Splitting Tensile Strength Data

Split Tensile Strength (psi)			
Sample	**7 Days**	**28 Days**	**Remarks**
OPC (Control)	1585	1890.4	Water Cured
FGPC	1930	-	Oven Cured at 60^{o} for 24 hours
FGPC + 5% Cement	1035	1290	Ambient Cured

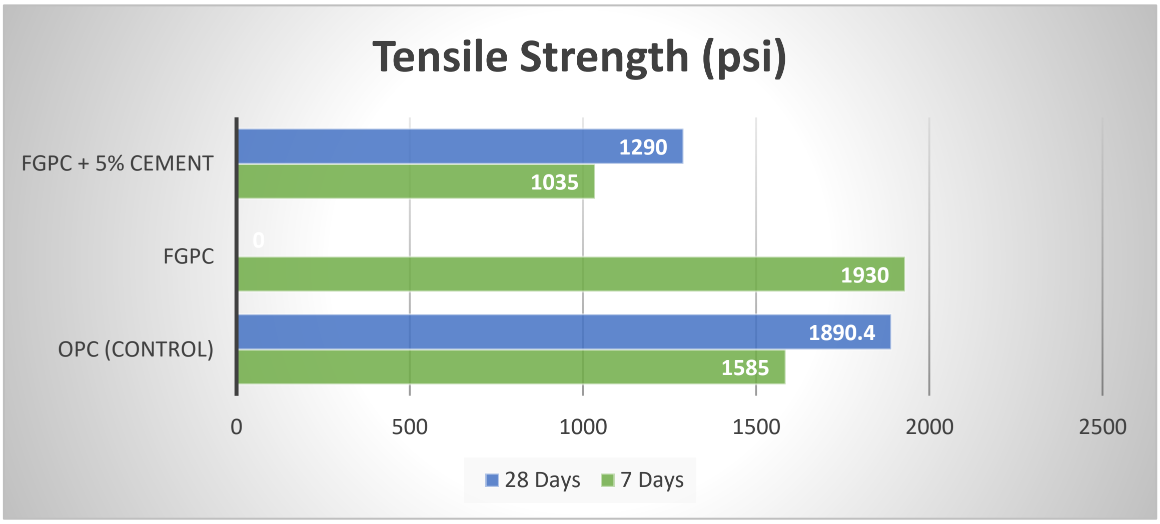


Figure 4.2 Comparison of Splitting Tensile Strength at 7 & 28 days of all Batches

The data shows that FGPC exhibited the highest tensile strength among all batches, with OPCC and 5% Cement + FGPC falling behind. As can be seen in the comparison chart presented in Figure 4.2.

4.2.3 Three Point Loading Test

Table 4.3 Three-Point Loading Test Data

Three Point Loading Test (Modulus of rapture) (psi)			
Sample	7 Days	28 Days	Remarks
OPC (Control)	715	980	Water Cured
FGPC	1005	-	Oven Cured at 60° for 24 hours
FGPC + 5% Cement	756	1145	Ambient Cured

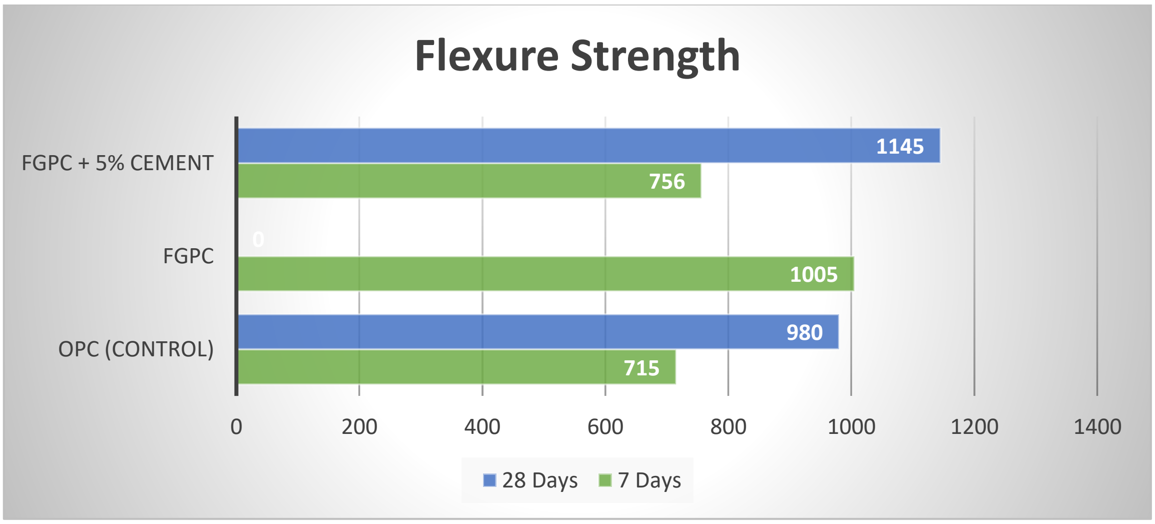


Figure 4.3 Three-Point Loading Test (Modulus of Rupture) at 7 & 28 days of all Batches

Based on the test data and graph, it is evident that the flexural strength of OPCC and FGPC batches is nearly equal. However, the 5% Cement + FGPC batch exhibited the highest flexural strength, recording a 12.2% and 14.5% increase over FGPC and OPCC, respectively. This may be attributed to the presence of cement as an admixture in the mix.

4.3 Structural Design Thickness of Rigid Pavement

The thickness calculation for pavement was conducted utilizing the AASHTO road test parameters. The AASHTO Design Guide, which was developed after the AASHTO road test completed in the 1950s, is presently the foundation for current pavement design techniques. Despite being several years old, the AASHTO Design Guide is still extensively used in the industry for determining pavement thickness design. To design pavement using the AASHTO method, several design parameters must be either determined or presumed.

4.3.1 Design Parameter Values

To conduct a comparison between the three sample compositions and determine the pavement thickness, we utilized the 1993 AASHTO Design Guide, which includes fixed values for AASHTO design parameters

- Design Traffic, W_{18} (highways) - 5×10^6 ESALS
- Overall Standard Deviation, S_0 - 0.30
- Load Transfer Coefficient, J - 3.2
- Reliability, R - 95% ($Z_R = -1.645$)
- Coefficient of Drainage, C_d - 1.10
- Performance Criteria (Serviceability Indexes), ΔPSI - 4.5 – 2.5 = 2
- Modulus of Subgrade Reaction, K - 72 psi (assumed)
- Soil Resilient Modulus, M_R - 5000 psi

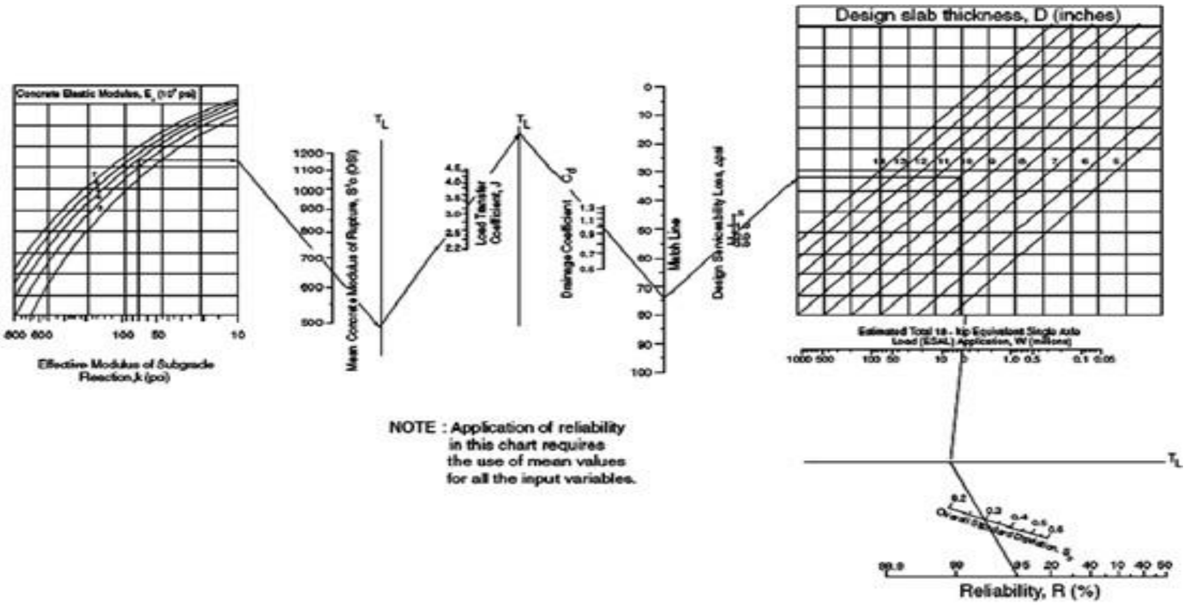
4.3.2 Design Parameters

We conducted tests on the three samples under consideration to determine their Modulus of Elasticity (E) and Modulus of Rupture (Sc). Assuming standard traffic and AASHTO test conditions, we kept the variables constant and varied only the Modulus of Elasticity and Modulus of Rupture. Using the empirical formula and nomograph, we calculated the pavement thickness for each sample.

Design Equation of Rigid Pavement

$$\log_{10}(W_{18}) = Z_R \cdot S_o + 7.35\log_{10}(D+1) - 0.06 + (4.2 - 0.32p_t)\log_{10}\left[\frac{S_c \cdot C_d \cdot (D^{0.75} - 1.132)}{215.63 \cdot J \cdot \left(D^{0.75} - \frac{18.42}{\left(\frac{E_c}{k}\right)^{0.25}}\right)}\right] \quad \textbf{(4.1)}$$

Figure 4.4nRigid Pavement Nomo graph



4.3.3 Results

Table 4.4 Thicknesses of Pavements for Various Batches

Sample	Modulus of Elasticity (Psi)	Modulus of rapture Sc (Psi)	Slab Thickness D (in) Calculated
Cement	3.8 x 10^6	980	6.5
FGPC*	3.96 x 10^6	1005	6.5
FGPC + 5% Cement	3.88 x 10^6	1145	6

* 7 Days

The thickness of the OPCC and FGPC for rigid pavements was found to be nearly equal as their Modulus of Rupture values were similar. However, the pavement thickness for the FGPC + 5% Cement batch was 7.6% less, as its Modulus of Rupture was greater than both concrete batches.

4.3.4 Comparison of Stress and Deflection

Using the calculated slab thicknesses, we can determine the stress and deflection that they would experience. Assuming standard tire loads and spacing, we can deduce the interior stress caused by the loading of a dual tire arrangement.

4.4 Cost Benefit Analysis

A thorough cost analysis was performed for all three batches after determining the thickness of rigid pavements for a standard road dimension of 1000 m length and 3.65 m width. The thickness varied according to the type of batch used for the construction of the road patch, we analyzed cost with an increased depth of FGPC to determine whether it is economically feasible to increase the depth where more strength of pavement is required.

The cost analysis considered the prices of all materials except for the alkaline liquids, which were not readily available in the local markets of Pakistan. Due to the limited availability of sodium silicate and potassium hydroxide, their prices were relatively high when compared to other materials. However, if these chemicals were purchased in bulk quantities, their costs would be significantly reduced. According to Hardjito and Rangan (2005), the cost of chemicals required to react with one ton of fly ash was approximately AU $50 in 2005, which is equivalent to approximately AU $85 today or Rs 24650. This indicates that the production of low calcium FGPC concrete would be less expensive than OPCC.

4.4.1 OPCC rigid pavement cost analysis

OPCC is the reference sample according to standard procedures, and the cost of its composition is given in the tables below. The rates in the tables represent the prevailing market rates at the time of acquiring the samples, which may differ slightly due to changes in the inflation rate. One table presents the cost of each cubic meter of the sample, while the other table shows the cost of a 577.85 m^3 (1000m x3.5m x 0.1651m) (6.5 in) patch of rigid pavement.

Table 4.7 OPCC Cost per cubic meter

Constituents	Quantity (Kg/m^3)	Cost Per Unit (Rs)	Total Cost (Rs/m^3)
Cement	403.2 kg	30 / kg	12096
Coarse aggregate	1507 kg (29.66 ft^3)	130 / ft^3	3856
Fine aggregate	672 (14.9 ft^3)	190 / ft^3	2831
Super Plasticizer	6 kg	350	2100
Total			**Rs 20973**

Table 4.8 OPCC Total Cost for 1 lane kilometer Rigid Pavement Slab

Constituents	Material Quantity for road ($577.85\ m^3$)	Total Cost (Rs)
Cement	232.99 Ton	6.99 Mn
Coarse aggregate	17139 ft^3	2.23 Mn
Fine aggregate	8610 ft^3	1.64 Mn
Super Plasticizer	3.5 ton	1.23 Mn
Total		**12.09 Mn**

4.4.2 FGPC and 5 % Cement+ FPGC Rigid Pavement Cost Analysis

The composition of this FGPC batch follows standard SOPs and is made entirely of fly ash. The cost of the sample composition is provided in the table below, with rates reflecting standard market rates at the time of sample procurement. These rates may vary slightly due to inflation. Table 4.9 displays the cost per cubic meter of the sample and table 4.10 shows total cost with column 5 showing cost of constructing a 623 m^3 (1000m x 3.5m x 0.178m) (7 in) and the last column showing the cost of constructing a 577.5 m3 (1000m x 3.5m x 0.165m) (6.5 inch) patch of rigid pavement.

Table 4.9 FGPC and 5 % Cement+ FPGC Cost Per Cubic Meter

Constituents	Quantity(m^3) FGPC	Quantity(m^3) 5 % Cement+ FPGC	Cost Per Unit (Rs)	Total Cost FGPC	Total Cost 5 % Cement+ FPGC
Cement	-	12.04	30		361
Fly Ash	240.71 Kg	240.71 Kg	25/ Kg	6017	6017
Coarse aggregate	29.66 ft^3	29.66 ft^3	130 / ft^3	3856	3856
Fine aggregate	14.9 ft^3	14.9 ft^3	190 / ft^3	2831	2831
Super Plasticizer	6 Kg	6 Kg	350	2100	2100
Na_2SiO_3	44.125 Kg	44.125 Kg	50 / Kg	2206	2206
KOH	17.65 kg	17.65 kg	65 / Kg	1147	1147
Total				**Rs 18157**	**Rs 18518**

Table 4.10 FGPC and 5 % Cement+ FPGC Total Cost 1 lane kilometer Rigid Pavement Slab

Constituents	Material quantity for road (623 m^3)	Material quantity for road (577.8 m^3)	Road Construction Cost FPGC H=7 in	Road Construction Cost FPGC H=6.5 in
Cement	-	6.96 Tons	-	.21 Mn
Fly Ash	150 Ton	138.64 Ton	3.75 Mn	3.46 Mn
Coarse aggregate	18478 ft^3	17139 ft^3	2.4 Mn	2.23 Mn
Fine aggregate	9282 ft^3	8610 ft^3	1.76 Mn	1.64 Mn
Super plasticizer	3.7 Ton	3.6 Ton	1.3 Mn	1.2 Mn
Na_2SiO_3	27.5 Ton	25.5 Ton	1.37 Mn	1.27 Mn
KOH	1.06 Ton	1.02 Ton	.07 Mn	.066 Mn
Total			**Rs 10.65 Mn**	**Rs 10.06 Mn**

4.4.3 Comparison between Costs of Different Batches

The table below presents a comparison of the sample cost, which indicates that the sample composed of 100% fly ash has the lowest cost among all the batches. Although the FGPC pavement does not have the same thickness as the OPCC pavement, it is still **12%** cheaper than the OPCC pavement. Moreover, the data shows that the 5% Cement + FGPC pavement is **17%** cheaper than the OPCC pavement. When comparing both fly ash concrete pavements, it becomes evident that the FGPC pavement is **6%** costlier than the 5% Cement + FGPC pavement due to difference in depth of pavement. The chemicals used in this process can only be obtained at a given cost when procured in bulk quantities, i.e., in tons. The significant cost reduction between FGPC and OPCC mixtures indicates that a huge amount of capital can be saved on large-scale transportation rigid pavement projects.

FGPC rigid pavements are cost-effective due to the fact that fly ash, which is the primary binding agent in FGPC, is a byproduct of coal burning in power plants and is available at much lower prices than cement in the market. Additionally, the price of fly ash is relatively stable compared to OPC, which is subjected to frequent fluctuations in the market due to various factors like increasing energy costs, transportation costs, taxes, and labor costs. As OPC is an indispensable component of concrete, such fluctuations can significantly impact its price, making FGPC a more reliable and cost-effective option.

Table 4.13 Comparison of Costs 1 lane kilometer Rigid Pavement Slab

Constituents	OPC Road Construction (h=6.5 in)	FGPC + 5% CEMENT Road Construction (h=6.5 in)	100% FGPC Road Construction (h=7 in)
Cement	6.99	.21 Mn	-
Fly Ash	-	3.75 Mn	3.46
Coarse aggregate	2.23 Mn	2.23 Mn	2.4 Mn
Fine aggregate	1.64 Mn	1.64 Mn	1.76 Mn
Super plasticizer	1.22	1.2 Mn	1.3 Mn
Na_2SiO_3	-	1.27 Mn	1.37 Mn
NaOH	-	.066 Mn	.07 Mn
Total	**Rs 12.09 Mn**	**Rs 10.06 Mn**	**Rs 10.85 Mn**

4.7 Summary

The findings of this chapter involved the analysis of test results, determination of rigid pavement thicknesses and stresses for each concrete batch using empirical relations and a subsequent cost benefit analysis. The analysis revealed that FGPC batches were notably more cost-effective than OPCC when utilized for the construction of rigid pavements

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This chapter presents deductions and recommendations based on the literature review and experimental work conducted on Fly ash Reinforced Geopolymer Concrete (FGPC) in the field of construction. The deductions are derived from the findings of the study, and recommendations are provided for further development and research in this area.

5.2 Conclusions

Based on the experimental results of FGPC, the following conclusions were made:

- Oven-cured FGPC exhibited up to 8% higher compressive strength at 7 days compared to OPCC cured for 28 days. This indicates that FGPC is better suited for time-constrained construction environments.
- FGPC cured at room temperature demonstrated up to 4% higher compressive strength than OPCC.
- The tensile strength of FGPC with 5% cement was higher than both FGPC and OPCC.
- Oven-cured FGPC and ambient-cured FGPC exhibited up to 5% and 15% higher bending strength than OPCC, respectively.
- The calculation of hard pavement thickness for the three concrete batches revealed that both oven-cured OPCC and FGPC had a thickness of 6.5 inches, while ambient-cured FGPC pavement had a thickness of 6 inches due to its superior bending strength.
- Cost analysis of a standard 1 km road with specific pavement depths indicated that ambient-cured FGPC pavement was **17%** cheaper than OPCC pavement, and oven-cured FGPC pavement was **12%** cheaper.

5.3 Recommendations

Based on the results of this study, the following recommendations for future work are drawn.

- Investigate the short- and long-term effects of water curing on FGPC.
- Explore the bond strength between FGPC and steel reinforcement.
- Investigate cost reduction strategies for alkaline liquids.
- Research the application of geopolymer technology in other construction fields.
- Explore a range of KOH molarities (concentrations) in the alkali activator solution, such

as 6M, 8M, 10M, and higher.

- Investigate different mix ratios of KOH and sodium silicate, vary the proportions of KOH and sodium silicate, such as 1:1, 2:1, or 1:2, while keeping the total concentration of the alkali activator constant.
- Explore the utilization of other by-products such as ground granulated blast furnace slag (GGBFS) as replacements for fly ash in geopolymer concrete
- Research and microstructure study using X-ray diffraction (XRD) analysis on concrete specimens

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