BE CIVIL ENGINEERING

PROJECT REPORT

EXPERIMENTAL ANALYSIS OF FLY ASH BASED GEOPOLYMER CONCRETE AND ITS APPLICABILITY IN HIGHWAY CONSTRUCTION

Project submitted in partial fulfilment of the requirements for the degree
of
BE CIVIL ENGINEERING

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This is to certify that the Final Year Design project

EXPERIMENTAL ANALYSIS OF FLY ASH BASED GEOPOLYMER CONCRETE AND ITS APPLICABILITY IN HIGHWAY CONSTRUCTION

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BE CIVIL ENGINEERING DEGREE

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DEDICATION

Dedicated to our parents, siblings, our instructors at MCE who have guided us during the course of this research and our great institution MCE where we have spent the four most memorable years of our life.

DECLARATION

It is hereby declared that all the work carried out for this final year design project was performed by us and it has not been submitted by any institution, in whole or in part in any previous application for a degree. Any references to the work done by any other person, University or material used from other publications have been appropriately cited.

ACKNOWLEDGEMENTS

First of all we thank ALLAH ALMIGHTY who enabled us to complete our degree leading to the culmination point in the form this project. We would also like to give our profound gratitude to our project advisor Brig Dr Sarfraz Ahmed whose guidance and expert opinions have provided us with the correct direction in undertaking all the tasks connected to the fulfilment of the study. We would also like to thank all the lab instructors and engineers who all have provided us with valuable information and advice during the course of completing the lab component of the project. We would like to thank our peers who gave us their opinions and fruitful advice which helped us during the project work. Lastly, we would like to thank all the researchers out there whose publications we have consulted for the completion of this project.

ABSTRACT

The rising threat of global warming and the high cost of raw materials for the production of cement, which is widely regarded as the second most used material in the world after water, have prompted many construction industry leaders to ponder upon finding newer environmentally friendly (green) and cost-effective ways to produce concrete. One such method is the use of Geopolymer concrete, which is quickly becoming a popular material among academics, and as a result, there has been a great deal of worldwide and Pakistani research on this topic. But one aspect which has been found wanting is the comparison of two similar mixture designs i.e., one mixture of standard concrete (OPC) based and one mixture of fly ash geopolymer concrete (FGPC). From literature review it was found that fly ash geopolymer concrete (FGPC) showed optimum mechanical properties when sodium hydroxide (NAOH) had a range of 8 molar – 14 molar concentration in the mix, when sodium silicate and sodium hydroxide had a ratio of 2.5 and when it was cured at high temperature or with an added admixture for ambient curing. In this research three batches of ordinary Portland cement concrete **(OPCC)** as **(control mix)**, fly ash geopolymer concrete (**FGPC**) and **FGPC with 5 % cement** as an admixture were prepared respectively **with similar mix proportions** and then to check their **mechanical properties** some elementary tests like compression strength test and splitting test were performed to compare their behaviour in normal conditions prevalent in Pakistan. Three-point flexural test were also performed to investigate the behaviour of FGPC on rigid pavements. It was found out that **FGPC** concrete cured at higher temperatures of 60 C showed **an increase of 9 % compressive strength** at 7 days when compared with that of control mix at 28 days, whereas **FGPC with 5% cement** admixture showed **an increase of 4 %** in 28 days compressive strength form the control mix. Similarly, the 7 days flexural strength of FGPC was slightly higher that that control at 28 days but **FGPC with 5 % cement as an admixture at ambient curing showed a significant increase of up to 15 % in flexural strength with that of control mix after 28 days**. Thickness of a standard rigid pavement lane (1 km long and 3.65 m wide), calculated from the data collected showed that FGPC and OPCC rigid pavement had similar thickness **but FGPC with 5 % cement showed a decrease of 8 % in pavement thickness** compared with OPCC pavement. Finally, a cost analysis was carried out, it was found out that **FGPC pavement costs would reduce by 22 %** and FGPC with 5 % cement as admixture pavement cost would reduce by **18.8 %** respectively when compared with the costs of **OPCC** rigid pavements.

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LIST OF ABBREVIATIONS

Abbreviations	**Description**
FA	Fly Ash
OPC	Ordinary Portland Cement
GPC	Geopolymer Concrete
FGPC	Fly Ash based Geopolymer Concrete
OPCC	Ordinary Portland Cement Concrete
HVFA	High Volume Fly Ash Concrete
ASTM	American Society for Testing and Materials
GGBS	Ground Granulated Blast Furnace Slag
ACI	American Concrete Institute
AS	Australian Standards
IS	Indian Standards
LOI	Loss on Ignition
MCE	Military College of Engineering

CHAPTER 1

INTRODUCTION

1.1 General

Concrete is often regarded as the most frequently utilized material on the planet after water. In normal OPC concrete, cement is a primary source that can be employed as a bidding agent. There are many environmental hazards linked to ordinary Portland cement concrete (OPCC). OPC production necessitates burning of conventional hydrocarbons and the calcination of lime, resulting in significant emissions of carbon dioxide (CO2). One tonne of fuel is required to make one tonne of OPC, according to current estimates. Only steel and aluminium take more energy to be manufactured than OPC does. (Hardjito & Rangan, 2005). CO2 is damaging to our environment and causes various health problems such as asthma, bronchitis, and sinus infections, according to estimates that 1.6 billion tonnes of cement manufacturing each year contributes to around 7% of total CO2 generation per year.(Haseeb, 2017)

While on the contrary, burning of coal generates billions of tonnes of Fly ash (FA) in the world's more than 8000 coal power plants. This has led to many studies on the aspect of substituting OPC with FA as the main biding agent of concrete and thus reducing the stress on our environment. According to established uses FA is already being used as a partial substitute for OPC in OPCC in various percentages. When fly ash is used as a replacement of some OPC in concrete in the presence of water, it combines with calcium hydroxide and forms (C-S-H) gel. To put it another way, replacing up to 60% of OPC with FA is a significant leap ahead in fly ash geopolymer concrete (FGPC) research. (V. M. Malhotra & Mehta, 2002).

Joseph Davidovits was the first to propose “that binders can be made via a polymeric reaction between alkaline liquids, silicon, and alumina in source materials such as FA and rice husk ash in the 1980s, geopolymers is the name he gave to these binders” (Davidovits, 1999). According to Palomo, Grutzeck, and Blanco (1999) alkaline liquids can be used to activate pozzolans like FA to form a binder that can totally replace OPC in concrete. This would happen as alkaline activator reacts with calcium and silica of the pozzolan and C-S-H gel as a main binder is produced.

Similarly, the use of geopolymer concrete in rigid pavements which counts concrete as their main building component, is also being investigated by researchers these days. It is estimated that approximately 5 – 10 % of the roads around the world are categorized as rigid pavements. As it has been well established that OPCC emits large amount of greenhouse gasses which adversely effects the environment, as a result researchers are looking at the idea of adopting FGPC to tackle the problem because it uses less energy and emits less CO2 than OPC-based concrete.(Tahir, Abdullah, Hasan, & Zailani, 2019)

1.2 Fly Ash (Class F) Based Concrete

Rather than using standard cement, this project uses a low calcium (ASTM Class F) fly ash based geopolymer as the major binding agent. Like OPCC, a geopolymer based on fly ash is used to bind unreacting fine and coarse aggregates that are present in loose form, with or without admixtures. FGPC is manufactured in a similar manner as OPCC (Hardjito & Rangan, 2005).

As in OPCC 70 – 75 % volume is occupied by aggregates in FGPC. (ASTM Class F) fly ash consists of silicon and aluminium which reacts with an alkaline solution consisting of sodium hydroxide and sodium silicate, which than forms a geopolymer paste which is than used to bind the aggregates together.

1.3 Problem Statement

- Cement is a major component of concrete, cement production is energy intensive, and it is observed that for a production of **1 pound of cement** about **0.9 pound of CO_2** is released in the atmosphere.
- Cement is subject to a lot of **cost fluctuation** in the market due to various factors like fuel costs, electricity costs and availability of raw material
- There is a need felt by industry leaders to find alternate sources for production of concrete to offset the high costs effects for relying on a single material (cement).

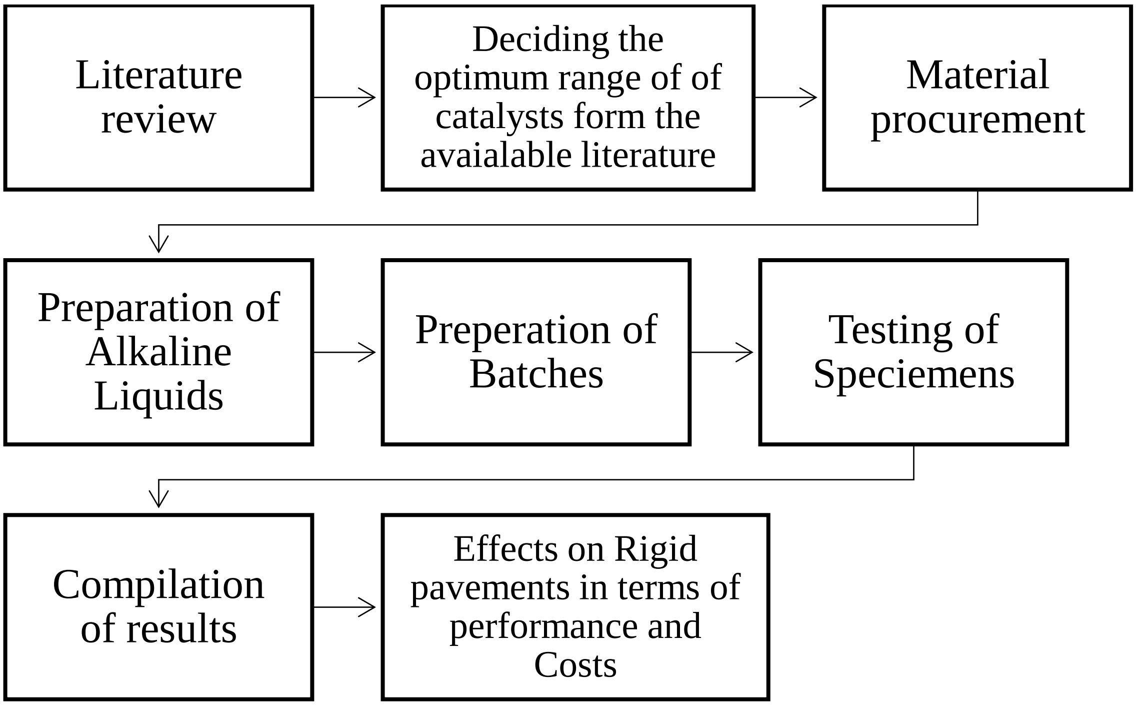
1.4 Objectives of Project

As already stated, a lot of research has already 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 casted 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 examine the efficacy of FGPC** concrete for general use instead of OPCC
- **To evaluate the mechanical properties** of concrete like compressive strength, split tensile strength and flexural strength of FGPC
- To carry out a **cost benefit analysis** of FGPC in utilization in rigid pavement construction.

1.5 Scope of Work



Fly ash was procured from Sahiwal coal power plant as a binder material for making FGPC. Alkaline liquids were procured from a chemical manufacturer in Mardan. The same method of production and equipment was used for making FGPC as is used for OPCC. It was envisaged that the characteristics of concrete were affected by their compressive, indirect tensile, and flexural strengths.

1.6 Sustainable Development Goals

The following sustainable development goals which were adopted by the UNGA in 2015 are:

- SDG-9 : Industry, Innovation and Economic Growth
- SDG-11: Sustainable Cities and Communities
- SDG-13: Climate Action

1.7 Project Report 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. It also investigates using different binders instead of concrete to make concrete and the use of low-calcium fly ash concrete (ASTM Class F).

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 effect of use of fly ash in concrete and curing conditions on the mechanical properties of concrete are discussed. The effects of use of FGPC in rigid pavement is also explained in terms of thicknesses achieved for 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

Carbon trading involves purchasing and selling carbon permits and certificates. Carbon trading is an essential control tool for different industries including the cement industry, to overlook the amount of greenhouse gas emissions which leads to the increase in global temperature resulting in climate change. These trading mechanisms are used to encourage industries to reduce their emission in order to meet sustainable targets for the better of the planet. “It is estimated that one ton of carbon emission can have trading value about US $ 10” (V. Malhotra, 1999).

Cement production is rising about 3 % annually (Mccaffrey, 2002). “About one tonne of carbon dioxide (CO2) is released into the atmosphere during the manufacturing of one tonne of cement.” OPC production accounts for roughly 7% of global greenhouse gas emissions, or 1.35 billion tonnes (V. Malhotra, 2002). In addition to steel and aluminium, OPC is one of the most energy-intensive building material.

These problems have been acknowledged by the concrete industry. For example, 'Vision 2030: "A Vision for the U.S. Concrete Industry". According to the document “concrete technologists are faced with the challenge of leading future development in a way that protects environmental quality while projecting concrete as a construction material of choice. Public concern will be responsibly addressed regarding climate change resulting from the increased concentration of global warming gases”. This vision effectively suggests solutions for retaining concrete as a preferred construction material for infrastructure projects while also making it an environmentally benign material in the future (Mehta, 2001).

2.2 Fly Ash

According to the American Concrete Institute (ACI) Committee 116R, fly ash is defined as “the finely divided residue that results from the combustion of ground or powdered coal and that is transported by flue gasses from the combustion zone to the particle removal system” (ACICommittee, 2004). Before the combustion gases are released into the environment, fly ash is removed from them using a dust collecting device installed in the power plant's chimney. This can be done manually or electrostatically. In comparison to OPC and lime, fly ash fragments are typically spherical, with a diameter of between 1 micron and 150 microns.

The chemical makeup of FA is classified by the characteristics of coal that is being burned. Magnesium, potassium, sodium, titanium, and sulphate are all present in trace amounts in fly ash, which is mostly composed of silicon, aluminium, iron, and calcium oxides (CaO). Coal has a higher iron content, such as bituminous coal, burns more efficiently than coal with a low calcium content. Physical and chemical properties are also affected by the type of combustion, the type of coal used, and the particle form (V. Malhotra & Ramezanianpour, 1994).

Burning sub-bituminous coals, which generally contain more than 20% CaO in their ash, produces Class C fly ash, also known as high-calcium fly ash. Bituminous and anthracite coals are used to produce ASTM Class F fly ash, which has minimal calcium content. Coloration is determined by the fly ash's chemical composition and material content. (V. Malhotra & Ramezanianpour, 1994). The further details of both class F and C are given in Table 2.1.

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

Description	Class F	Class C
SiO_2 + Al_2O_3 +Fe_2O_3	50	50
CaO (%)	18 (max)	>18
SO_3 (max %)	5	5
Loss on Ignition (max %)	6.0	6.0
Moisture Content (max %)	3.0	3.0

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

1. Inexpensive material
2. Better Mechanical properties
3. Suitable for high temperature curing conditions
4. Better durability and strength properties
5. Available as a byproduct of coal combustion

2.3 Use of Fly Ash in Concrete

One way to decrease the harmful effects of concrete on the environment is to reduce the OPC content of the concrete and it is done in several ways. One option is to use fly ash in exchange of some of the cement in the concrete mix. FA acts as a synthetic pozzolan, when used as a cement substitute. Calcium silicate hydrate (C-S-H) gel is formed when silicon dioxide from the cement hydration phase combines with calcium hydroxide (Hardjito & Rangan, 2005). Because of its globular and microscopic particle diameter, workability of fresh concrete can be improved by filling of spaces between aggregates by FA.

Development of high volume fly ash concrete (HVFA) concrete was an important milestone in this aspect where the OPC content was successfully, partially replaced by the FA up to 60%. However, despite this, the concrete was good in mechanical characteristics and had an improved endurance capability. In several circumstances, HVFA concrete outperformed OPC concrete in terms of durability and resource efficiency (V. M. Malhotra & Mehta, 2002). Many places, particularly in India, have begun using this innovative form of concrete for pavement development projects where FA has replaced OPC to a greater or lesser extent(Deasai, 2004).

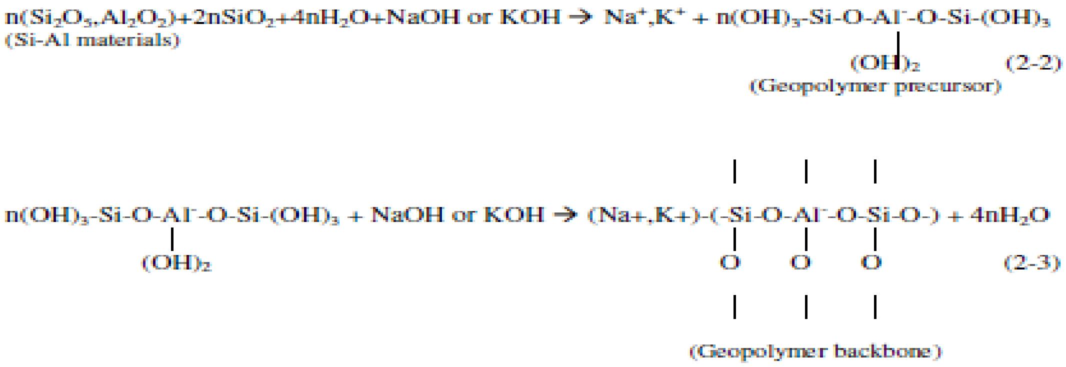
2.4 Geopolymers

According to Davidovitz, “an alkaline liquid could be utilised to bond with silicon (Si) and aluminium (Al) in any source material from a geological location or an industrial process such as FA (rice husk) or crushed granulated blast furnace slag to make binder materials” (Hardjito & Rangan, 2005). Geopolymer is a name Davidovits coined to describe these binders because of the polymerization process which occurred during this operation (Davidovits, 1999).

Inorganic polymers include geopolymers. Although the geopolymer material has a comparable chemical makeup to conventional zeolitic minerals, “it has an amorphous microstructure instead of crystalline microstructure”(Xu & Vans Deventer, 2000). “The polymerization process involves a quick chemical reaction under alkaline settings on Si-Al minerals, which leads to the production of three dimensional polymeric chains and rings of Si-O-Al-O links” (Davidovits, 1999):

$$Mn\ [-(SiO2)\ z–AlO2]\ n\ .\ wH2O$$

"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):



$$\underset{\text{(Si-Al materials)}}{n(Si_2O_5,Al_2O_2)}+2nSiO_2+4nH_2O+NaOH \text{ or } KOH \rightarrow Na^+,K^+ + \underset{\text{(Geopolymer precursor)}}{n(OH)_3\text{-}Si\text{-}O\text{-}\underset{|\atop (OH)_2}{Al^-}\text{-}O\text{-}Si\text{-}(OH)_3} \qquad (2\text{-}2)$$

$$n(OH)_3\text{-}Si\text{-}O\text{-}\underset{|\atop (OH)_2}{Al^-}\text{-}O\text{-}Si\text{-}(OH)_3 + NaOH \text{ or } KOH \rightarrow \underset{\text{(Geopolymer backbone)}}{(Na+,K+)\text{-}(\text{-}\overset{|}{\underset{|\atop O\atop |}{Si}}\text{-}O\text{-}\overset{|}{\underset{|\atop O\atop |}{Al^-}}\text{-}O\text{-}\overset{|}{\underset{|\atop O\atop |}{Si}}\text{-}O\text{-})} + 4nH_2O \qquad (2\text{-}3)$$

Figure 2.1 Schematic Equation of Geopolymer Material

As seen in eq 2-3 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

Any amorphous substance containing Silicon (Si) and Aluminum (Al) is a possible source for geopolymer production. In the past, numerous minerals and industrial byproducts have been explored. “Metakaolin or calcined kaolin” (Teixeira-Pinto, Fernandes, & Jalali, 2002), “low calcium ASTM class F fly ash” (Palomo et al., 1999), “combination of calcined minerals and non calcined materials” (Xu & Vans Deventer, 2002) and “combination of granulated blast furnace slag and metakaolin” (Cheng & Chiu, 2003)have been studied as source materials.

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, for making concrete at a large scale it is too costly.

To ensure that the polymerization of concrete is not hindered by the presence of large amount 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 geopolymerisation (Barbosa, MacKenzie, & Thaumaturgo, 2000).

Palomo et al. (1999) determined that the type of alkaline liquid utilised in the polymerization reaction has a significant impact on the polymerization process. When sodium or potassium silicate is included in an alkaline solution, the reactions occur more quickly than when other alkaline hydroxides are used. Xu and Vans Deventer (2000) confirmed that combining sodium silicate solution with sodium hydroxide solution enhances the reaction among the parent material and the solution. Furthermore, it was discovered that the NaOH solution dissolved more material than the KOH solution, on average.

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), investigated mechanical properties of high volume fly ash HVFA concrete made with Types I and III cements. Using twelve batches of concrete, they made eight different concrete combinations, each of 0.06 m^3 in volume, with w/c ratio of 0.32. They replaced 60 % of the cement in the mix with fly ash and kept rest of the constituents same.

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	Density at 1 Day kg/m3	Compressive Strengths of 102 by 203 mm Cylinders, MPa			28-day Flexural Strength of 76 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	

Concrete produced using Type I cement had a maximum one-day compressive strength of 9.6 MPa and a 28-day strength of 33.3 MPa respectively . Low C3S and C2S concentrations in Type I cement explains these inadequate strengths at one day. The compressive strengths of Type III cement after one day are much higher than those of Type I cement concrete, with a maximum compressive strength 15.3 MPa which is about **37 % more** than that of Type 1 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.

Concrete created with Type I cement had a maximum 28-day splitting tensile strength of 3.3 MPa, while concrete made with Type III cement had a maximum tensile strength of 3.6 MPa. According to published statistics, the splitting tensile strength values are **10%** of the 28-day crushing strength results. These tensile strengths are comparable with normal OPCC of 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 concrete particles at 28 days, when there is little pozzolanic interaction between low-calcium fly ash and Portland cement.

This study by Giaccio and Malhotra (1988) about class F fly ash concrete reveals that it has outstanding mechanical qualities and has a significant promise for structural concrete sections, particularly huge portions. Using ASTM Type III cement and superplasticizers to make structural concrete with a large amount of fly ash appear to be crucial for achieving enough workability in the early phases of the construction process. Form this study it was

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.

They prepared the alkaline liquid component for the FGPC by using NAOH in **10 molar** concentration. The ratio of sodium silicate to sodium hydroxide was kept at **2.5**. The curing method selected was dry curing in oven at 60 C for 24 hours, after that the specimens were left to cure in ambient conditions till the day of testing. Slump, compressive strength, split tensile strength, modulus of elasticity and flexural strength tests were performed to ascertain the mechanical properties of FGPC and compare them with OPCC.

After 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 condition 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 strength of FGPC showed a **12 %** increase from that of OPCC. Similarly, the modulus of elasticity of FGPC was higher than that of OPCC by **29 %.** 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.

2.7.3 Influence of Alkaline Activators on The Mechanical Properties of Fly Ash Based Geopolymer Concrete Cured At Ambient Temperature

Ghafoor, Khan, Qazi, Sheikh, and Hadi (2020), studied the effects of alkaline activators (AA) on mechanical properties of concrete at ambient temperature, by altering the molarity of NAOH between the range of **8 molar to 16 molar**, varying the ratio of sodium silicate to sodium hydroxide between **1.5 – 2.5** and varying the alkaline activator (AA) to fly ash (FA) ratio between **0.4 to 0.6**.

2.7.3.1 Workability

It was noted that with the increase in AA/FA ratio from **0.4 to 0.6** the slump of FGPC increased drastically. An increase of about **85 %** was observed in slump of FGPC when AA/FA ratio was increased from 0.4 to 0.5, similarly when the AA/FA ratio was raised from 0.5 to 0.6 an increase of **134 %** was observed (Ghafoor et al., 2020). The variation of ratio of sodium silicate to sodium hydroxide had no significant effect on the slump of FGPC.

Change of molarity of NAOH from 8 M to 10 M had no effect on slump. But slump of FGPC reduced by " **11%, 14.5% and 25%** when molarity of NAOH was changed from 10 M – 12 M, 12 M – 14 M and 14 M – 16 M respectively" (Ghafoor et al., 2020). This decrease in slump due to increasing NAOH molarity can be explained by the fact that NAOH solution has more viscosity than water and with increasing molarity the solutions become more viscous.

2.7.3.2 Compressive Strength

The compressive strength of FGPC was found to increase when the molarity of NAOH was increased from 8 M – 14 M, an increase of about **95 %** was observed in the compressive strength of FGPC. However, the compressive strength of FGPC decreased by 10 % when molarity of NAOH was increased from 14 M – 16 M. It was found that FGPC attained maximum compressive strength when NAOH had a **14 M** concentration in solution. Generally, the molarity of NAOH controls the dissolution of silicon and aluminum in solution during geopolymerization process, high molarity of NAOH will ensure more dissolution of silicon and aluminum during geopolymerization and consequently higher compressive strength.

For a given molarity of NAOH solution it was found that by increasing the ratio of sodium silicate and sodium hydroxide from 1.5 to 2.5 an average decrease of **8 %** in compressive strength of FGPC was found.

2.7.3.3 Flexural Strength

Like compressive strength the flexural strength of FGPC also increased when molarity of NAOH was increased in the solution form 8 M – 16 M. "The average flexural strength of FGPC increased about **20%, 22%, 19% and 9.5%** with increase in molarity of NAOH from 8 M – 10 M, 10 M – 12 M, 12 M – 14 M and 14 M to 16 M respectively. The optimum flexural strength of FGPC was achieved at a molarity of 16M" (Ghafoor et al., 2020).

Like compressive strength, the flexural strength of FGPC also decreased, for increasing sodium silicate to sodium hydroxide ratios for given molarities of NAOH. This was due to the reduction of (OH^-) in the solution which consequently reduced the formation of 3-d network of "aluminosilicates hydrates".

2.7.4 Development and Properties of Low Calcium Fly Ash Based Geopolymer Concrete

Hardjito and Rangan (2005) conducted research about the procedure of development and Properties of Low calcium (Class F) fly ash concrete. They made 26 mixtures of varying proportion of FA, concentrations of NAOH in terms of their molarities ranging from 8 M to 16 M, ratio of sodium silicate to sodium hydroxide varying between 0.4 and 2.5 and different curing temperatures in the oven. Tests were conducted to study the mechanical properties of FGPC concrete.

2.7.4 Effects of Salient Parameters

2.7.4.1 Concentration of Sodium Hydroxide (NaOH) Solution

Mixture 1 to 4 as shown in figure 2.2 were casted to study the effects of concertation of NaOH on compressive strength of concrete and it was observed that by increasing the molarity of NaOH solution in the concrete batches, higher compressive strengths were achieved up to **65 %** for FGPC mix having 0.4 ratio of sodium silicate to sodium hydroxide, similarly higher compressive strengths were achieved of up to **15 %** for FGPC mix having 2.5 ratio of sodium silicate to sodium hydroxide results shown below in Table 2.4.

Table 2.4 Effect of Molarity of NAOH and ratio Alkaline Solutions on Compressive Strength of FGPC

Mixture	Concentration of NaOH liquid (in Molars)	Ratio of sodium silicate to NaOH solution (By Mass)	Compressive strength at 7th day (MPa) (Cured for 24 hours at 60 C)
1	8 M	0.4	17
2	8 M	2.5	57
3	14 M	0.4	48
4	14 M	2.5	67

2.7.4.2 “Ratio of Sodium Silicate Solution-to-Sodium Hydroxide Solution”

If the ratio of sodium silicate solution to NaOH solution by mass is kept more for the same molarity of NaOH than the requisite mixture will yield greater compressive strength than that mixture having more ratio of NaOH solution by mass. This is clearly shown in Table 2.4. Keeping the ratio of sodium silicate solution to NaOH solution at 2.5 rather than 0.4 **reduces the cost** of alkaline liquid significantly.

2.7.4.3 Curing Temperature

Compressive strength was found to increase with increasing curing temperature in both Mixture 2 and 4 after dry curing the test cylinders in a furnace for 24 hours and keeping all other test variables constant. However, increasing the curing temperature beyond 60 C did not significantly increase the compressive strength. It was observed that the FGPC attained optimum strength at 90 C temperature however most researchers have decided to cure FGPC at 60 C as up to this temperature a rapid gain in compressive strength is observed. The results are shown in graph form in figure 2.2.

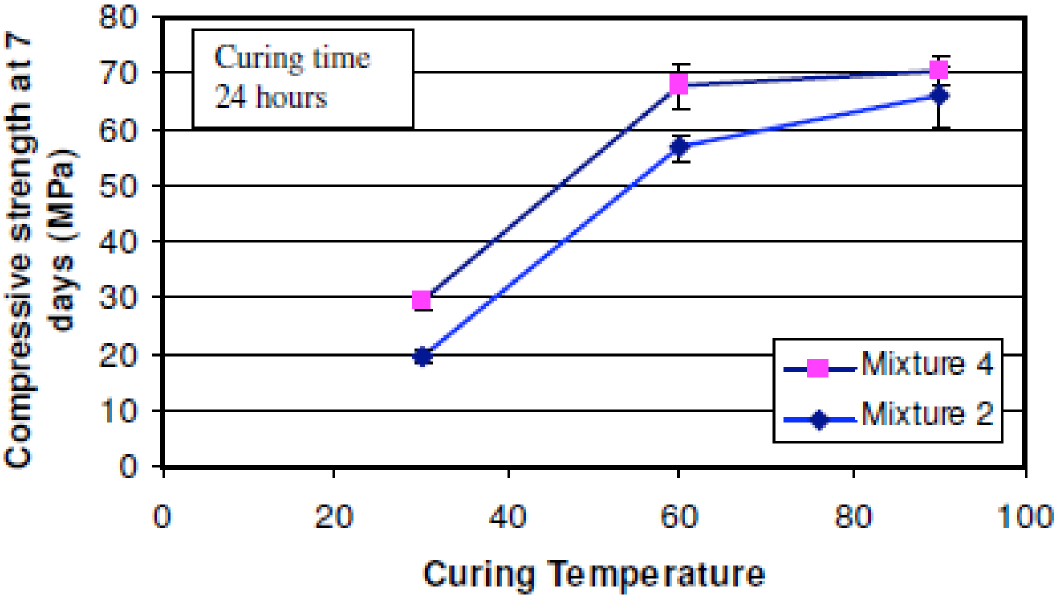


Figure 2.2 Effect of Curing Temperature on Compressive Strength (Hardjito & Rangan, 2005)

2.7.4.4 Effects of Curing Time on compressive strength of concrete

The polymerization process in concrete was shown to be improved with extended curing times, which resulted in better compressive strengths. Up to 24 hours of curing, the concrete's strength increased at a quick rate. After 24 hours it was observed that the rate of strength gain in FGPC reduced significantly. This gain of compressive strength with time is due to the improved polymerisation process of FGPC on higher temperatures at longer curing periods. It has been shown in graphical form in figure 2.9 below.

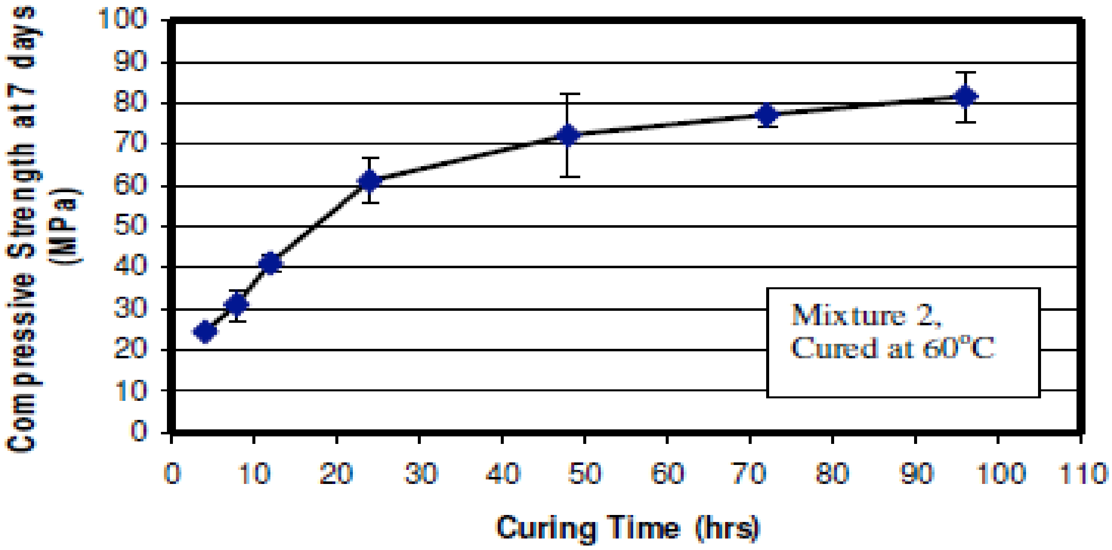


Figure 2.3 Effect of Curing Time on Compressive Strength (Hardjito & Rangan, 2005)

2.7.4.5 Effect of Superplasticiser (Naphthalene Sulphonate based) on workability and compressive strength

It was observed that if up to **2%** use of superplasticizer improved workability appreciably and also didn’t adversely affect the compressive strength, however if more that 2% superplasticizer was used than workability increased substantially but consequently the compressive strength also decreased.

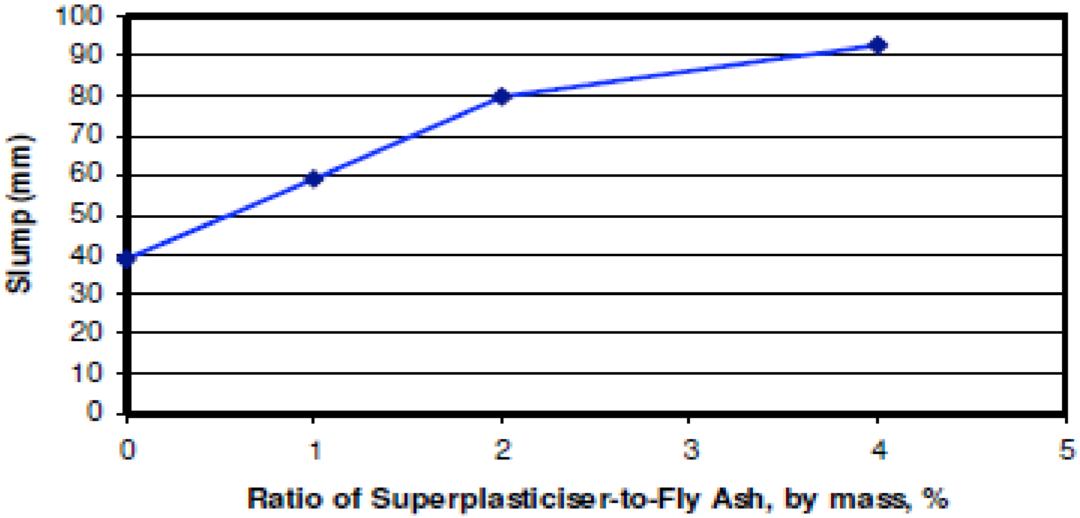


Figure 2.4 Effect of Super plasticiser on Slump (Hardjito & Rangan, 2005)

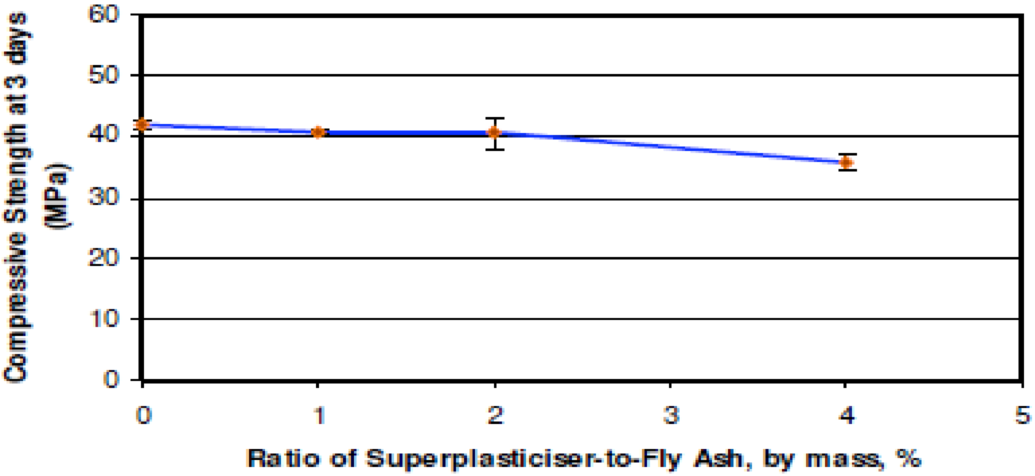


Figure 2.5 Effect of Super plasticiser on Compressive Strength (Hardjito & Rangan, 2005)

2.7.5 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. Nath and Sarker (2015) investigated the effects of different admixtures when added to FGPC mechanical properties if ambient curing is carried out. Alot 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.

A number of research were conducted to improve the geopolymerization process at room temperature by adding various admixtures, such as OPC, nano silica, rice husk ash, GGBS and Alcoofine, into the mixture. Some results for different OPC percentage in FGPC for ambient curing are given below in figure.

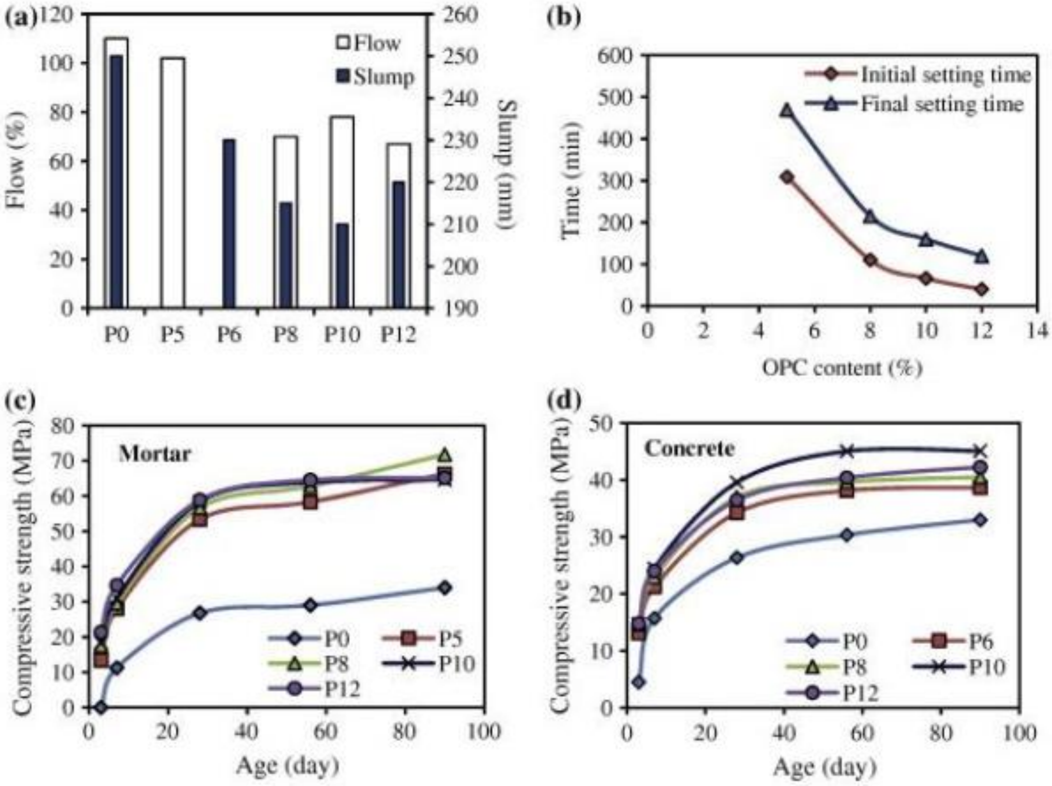


Fig 2.6 Effect of different percentages of OPC on the (a) workability of concrete, (b) setting times of pastes, (c) compressive strength of mortars and (d) compressive strength of concretes (Nath & Sarker, 2015)

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.

2.8 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 NAOH 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 between 5% - 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.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

This Chapter presents the details of the process that is required to take place for the manufacturing of (ASTM Class F) FGPC. Up till now no widely used calculation method has been defined to calculate the mix proportion by established standards organization like ACI, AS and IS etc. Generally, the researchers have been using trial and error processes to develop the mix proportion of the FGPC for required parameters. In this study the mix proportion was taken from (Hardjito & Rangan, 2005) which was similar to that of our control (OPCC).

To keep the testing and manufacturing process less complex existing practices used in the manufacturing and testing of OPCC were adopted for FGPC. The aim of this action was to ascertain the adequacy of FGPC if it is manufactured by the existing practices in the field. By doing this it would be easier to introduce this new material in the field of construction in Pakistan in the future.

Various materials can be used to produce geopolymer concrete, but we have selected (ASTM Class F) fly ash for this purpose due to its availability in Pakistan. The Cement was procured from the local market. Fly ash was tested using aggregates from only one source, the PRC lab, to ensure that the effects of aggregate qualities on fly ash parameters were minimized.

3.2 Materials used in this study

3.2.1 Fly Ash

In this project Fly Ash (FA) was obtained from Sahiwal Coal Power Plant in Punjab, Pakistan. It was used as 100 % replacement for cement to produce FGPC. The elements that make up the chemical makeup of fly ash have been extracted from (Abdullah, 2021), as the fly ash used in that research has also been obtained from the same source. Fly ash procured was similar in texture to cement and was of light grey color. From its analysis it was found to contain Ca0 content of about 14.12 % which meant that this was indeed Class F fly ash which was required for our study. Other major minerals found in fly ash were SiO_2 (59.96%) and Al_2O_3 (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)			$14.12 \leq 18$	$2.85 \leq 5$	$0.41 \leq 6$	$0.445 \leq 3$

From the results it is evident that SiO_2, Al_2O_3 and Fe_2O_3 was 80.27%, the amount of CaO was 14.12 %, the amount SO_3 was 2.85% and loss on ignition value was 0.445. Low amount of CaO (14.12 %) less than 18% indicates that this was class F fly ash.

Figure 3.1 Fly Ash

3.2.2 Fine Aggregates

In this study, we made use of the fine aggregates that were made available in the concrete laboratory. The loose bulk density of these aggregates was approximately 1600 kg/m3. Sieve analysis of the fine aggregate are shown below.

Figure 3.2 Fine Aggregates

Table 3.2 Sieve Analysis of Fine Aggregate

Sieve No.		Weight retained	% Retained	Cumulative % Retained	% Passing
No.	mm	(g)	(%)	(%)	(%)
#4	4.75	2	0.38	0.38	99.62
#8	2.36	3	0.60	0.98	99.02
#16	1.18	59	11	11.98	88.02
#30	0.6	132	24.9	36.88	63.15
#50	0.3	253	47.75	84.63	15.37
#100	0.15	56	10.60	95.23	4.77
#200	0.75	9	1.75	96.98	3.02
Pan	0	16	3	99.98	0

3.2.3 Coarse Aggregate

Coarse aggregate from the concrete lab was employed in the same way as fine aggregate, with a bulk density of 1794 kg/m3 and an aggregate size range of 20 mm to 7 mm. There was a 22.73 percent aggregate impact value and a 22.55 percent aggregate crushing value in the aggregate sample. Table 3.3 provides the sieve analysis for coarse aggregate.

Table 3.3 Coarse Aggregate Sieve Analysis

Sieve No.	Weight retained	% Retained	Cumulative % Retained	% Passing
No.	(kg)	(%)	(%)	(%)
3/8	1	0.7	0.7	99.28
1/2	2.5	1.74	2.44	97.54
3/4	5	3.48	5.92	94.06

1	10	6.97	12.89	87.09
$1^{1/2}$	15	10.45	23.34	76.64
2	20	13.94	37.28	62.7
$2^{1/2}$	25	17.42	54.7	45.28
3	30	20.91	75.61	24.37
$3^{1/2}$	35	24.39	99.81	0.17
Pan	0.24	0.17	99.98	0

Figure 3.3 Coarse Aggregates

3.2.4 Alkaline Liquid

A solution of sodium silicate (Na2SiO3) and sodium hydroxide (NaOH) was the prime source of alkaline liquids which were used to make FGPC. Sodium-based activators were selected because they were readily available in the local market and were less expensive.

NaOH solution was obtained by dissolution of NAOH pellets in water. When NaOH particles are dissolved in water, their mass is determined by their Molarity (M). The molecular weight of NaOH is 40 g/L, hence a 14 M concentration of NaOH solution contains 560 g/L of the compound. The majority of the NaOH solution is composed of water, not NaOH solids, which must be kept in mind when calculating the mass of the solution.

Sodium Silicate solution was obtained locally from a chemical supplier in Mardan in solution form with 14.7% Na_2O and 29.4% SiO_3 concentration with the rest of the concentration of water.

3.2.5 Super Plasticizer

The usage of "Ultra Super Plast 470," an organic polymer-based super plasticizer, was found to increase the workability of fresh FGPC concrete.

3.3 Mixture Proportions

First a control mixture of OPCC was prepared, with which all other mixtures would have to be compared. FGPC mixture proportion as mentioned earlier was taken from an existing research by (Hardjito & Rangan, 2005). That mixture proportion was selected which was similar with control mixture proportion. A third mixture was also prepared which contained 5 % cement as an admixture in FGPC mixture. The Mixture proportion of this mixture was exactly as that of FGPC with just an addition of 5 % of cement by weight of FGPC which came out to be 20.4 kg/m^3. Mixture proportions are shown 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	-	20.4
Fly ash	-	408	408
Coarse Aggregate	1512	1512	1512
Fine Aggregate	672	672	672
Sodium Silicate (SiO_2/ Na_2O=2)	-	103	103
Sodium Hydroxide Solution	-	41	41
Water	241.8	22.5	22.5
Super Plasticizer	8.06	6	6

3.4 Manufacturing Process

The manufacturing process of OPCC is well known and standard practices were used to produce control batch for the comparison purposes. The manufacturing process of FGPC is quite similar to that of OPCC with some exceptions. The manufacturing steps involved in production of FGPC are:

- Preparation of liquids
- Mixing of materials and casting
- Curing of test specimens

3.4.1 Liquid Preparation

According to Davidovits (2002) a day before mixing and pouring fly ash concrete, make the alkaline liquid first. Dissolving sodium hydroxide pellets in water is an exothermic process, meaning that a great deal of heat is generated as a result of the reaction taking place. Because of this, the sodium silicate solution and sodium hydroxide solution were mixed one day before the solid elements of the mix were prepared.

The mass of sodium hydroxide pellets which was used to prepare the solution depended on the molarity selected as explained in section 3.2.4. So, 560 grams of NaOH was dissolved per liter of water to prepare the sodium hydroxide solution.

After the preparation of sodium hydroxide solution, it was mixed with sodium silicate, required amount of water and super plasticizer. This method of mixing was taken from the existing research (Wallah & Rangan, 2006) . This process of mixing released immense heat, therefore as per existing literature the solution was left to cool down over night in the lab.

Figure 3.4 Chemicals for Preparation of Alkaline Liquid

Figure 3.5 Preparation of Alkaline Liquids

3.4.2 Mixing of Materials and Casting

The solid components of the mixture were mixed for 2-3 minutes in a concrete drum mixer after which the liquid portion of the mix was added to the mixer and the constituents were further mixed for 5 minutes.

After the mixing concrete was poured into the 150 mm x 300 mm cylinders in three layers, with each layer manually tamped with a rod for 25 blows. Each layer was also stabilized by putting the cylinder on vibrating table for 10 seconds. Similarly, the 100 mm x 100 mm x 400 mm prisms were also casted in two layers, with each layer tamped for 25 blows and stabilized by placement on vibrating table for 10 secs.

Figure 3.6 Mixing of Concrete

Figure 3.7 Casting of Concrete

3.4.3 Curing

It is important to note that FGPC does not require water for its curing as stated in section 2.7.4. It requires dry or heat curing to accelerate the geopolymerisation process inside FGPC for it to gain requisite strength (Jindal, 2018).

Two types of curing were adopted to study their effects on the properties of FGPC. The first type was dry curing in oven. After the specimens were casted, they were left in their molds for a day at ambient temperature. After a day the specimens were taken out from their molds and placed in an oven in structural dynamics lab of MCE. The temperature in the oven was set to 60°C for 24 hours and after that the specimen was left for ambient curing again for 7 days.

The second type of curing was ambient curing, in which 5% cement as a percentage of total FA content was added to the mixture as an admixture to speed up the geopolymerization process of the concrete during ambient curing at room temperature. For this type of curing the specimen was left in its mold for 24 hours after that it was removed and put at a place in the lab where sufficient sunlight was available during the day for curing till the time of application of tests on that specimen.

Care had to be taken to ensure the correct data entry into the industrial oven interface which was present in the structural dynamic lab of MCE. If any negligence is carried out while inputting data into the machine, the curing process of FGPC would be compromised and requisite strength gain in FGPC will not occur.

Figure 3.8 Dry Curing of FGPC in Oven

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 test of specimens were performed on 3000 KN automatic servo plus machine available in structural dynamics lab, MCE. The tests were performed according to ASTM C39. The size of cylinders were 150 mm x 300 mm. The cylinders in case of OPCC batch were removed from curing tank on 7th and 28 days and were immediately taken for testing, as according to ASTM standard the test should be performed on moist specimens. In case of FGPC specimens which was dry cured the specimens were taken for testing on the

7th day only. The FGPC specimen which was undergoing ambient curing conditions were tested for 7 and 28 days strengths. The tests were performed at standard room temperature. Sulphur capping was carried out for FGPC specimens due to their rough surface at top and bottom, after application of sulphur to the face of cylinders the specimens were left to cure for 5 hours before testing them. The specimens were placed in the machine and the relevant testing mode was selected from the menu in the machine. The test was stress controlled with the load being applied at "0.25 MPa/s as per ASTM C39". The machine automatically stopped the application of load when the ultimate strength of the specimen was achieved. The results of the compressive strength test were than noted from the machine interface.

3.5.2 Splitting Tensile Test

The Splitting tensile tests of specimens were performed on the same (3000 KN automatic servo plus) machine which was used for compressive strength tests . The tests were performed according to ASTM 496. The size of cylinders were 150 mm x 300 mm. The cylinders in case of OPCC batch were removed from curing tank on 7th and 28 days and were immediately taken for testing, as according to ASTM standard the test should be performed on moist specimens. In case of FGPC specimens which was dry cured the specimens were taken for testing on the 7th day only. The FGPC specimen which was undergoing ambient curing conditions were tested for 7 and 28 days strengths. The tests were performed at standard room temperature. The specimens were placed in the steel jig for correct alignment of the bearing surface of the specimen. The jig was then placed in the machine and relevant test mode was selected for the testing mode. The test was a stress-controlled test in which load was applied at a rate of " 0.7 – 1.4 MPa/min as per ASTM 496". The machine automatically stopped applying the load when ultimate tensile strength of the cylinder was achieved. The results were than notes from the machine's interface.

3.5.3 Three Point Loading Test

The three-point loading tests of specimen were performed on prisms. The tests were performed according to ASTM C293. The size of prisms were 100 mm x 100 mm x 400 mm. The cylinders in case of OPCC batch were removed from curing tank on 7th and 28 days and were immediately taken for testing, as according to ASTM standard the test should be performed on moist specimens. In case of FGPC specimens which was dry cured the specimens were taken for testing on the 7th day only. The FGPC specimen which was undergoing ambient curing conditions were tested for 7 and 28 days strengths. The tests were performed at standard room temperature. The supporting blocks which would act as supports for the prism were attached to the machine and the prism was then placed on the supporting blocks. A space of 25 mm was left between the point support and end face of the prism as per the ASTM standard. The load applying block was then applied on the upper face of prism at center point. The load was applied on the specimen without any abrupt changes and the rate of loading was kept at 1 MPa/s which was well within the range mentioned in ASTM standards.

3.6 Summary

In this chapter the materials required for producing FGPC concrete were discussed in detail along with the methods of preparation of FGPC. It was found that FGPC can be produced by following the same manufacturing process which is used for OPCC. Mixture proportion of the control and modified batch were also discussed. In the end a testing matrix was discussed, the tests involved in this research will tell us about the mechanical properties of concrete and we can also infer some extra observations regarding the use of FGPC in rigid pavement form the flexural strength data.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

In this chapter the experimental results are evaluated and analyzed. The tests which were performed during the course of this research pertains to the mechanical properties of the concrete. The test data of following tests is discussed here:

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

After the presentation of data, study of the effects of all the batches of concrete involved in this research will be carried out. Thickness for a standard length of rigid pavement were calculated from the data collected during the testing. After the thicknesses were calculated a cost benefit analysis was undertaken for all the type of batches involved in finding the respective thicknesses.

4.2 Compressive Strength Test

Table 4.1 Compressive Strength Test Data

	Compressive Strength (psi)		
Sample	**7 Days**	**28 Days**	**Remarks**
OPC (Control)	2900	4458	Water Cured
FGPC	4850	-	Oven Cured at 60° for 24 hours
FGPC + 5% Cement	2997.9	4641.2	Ambient Cured

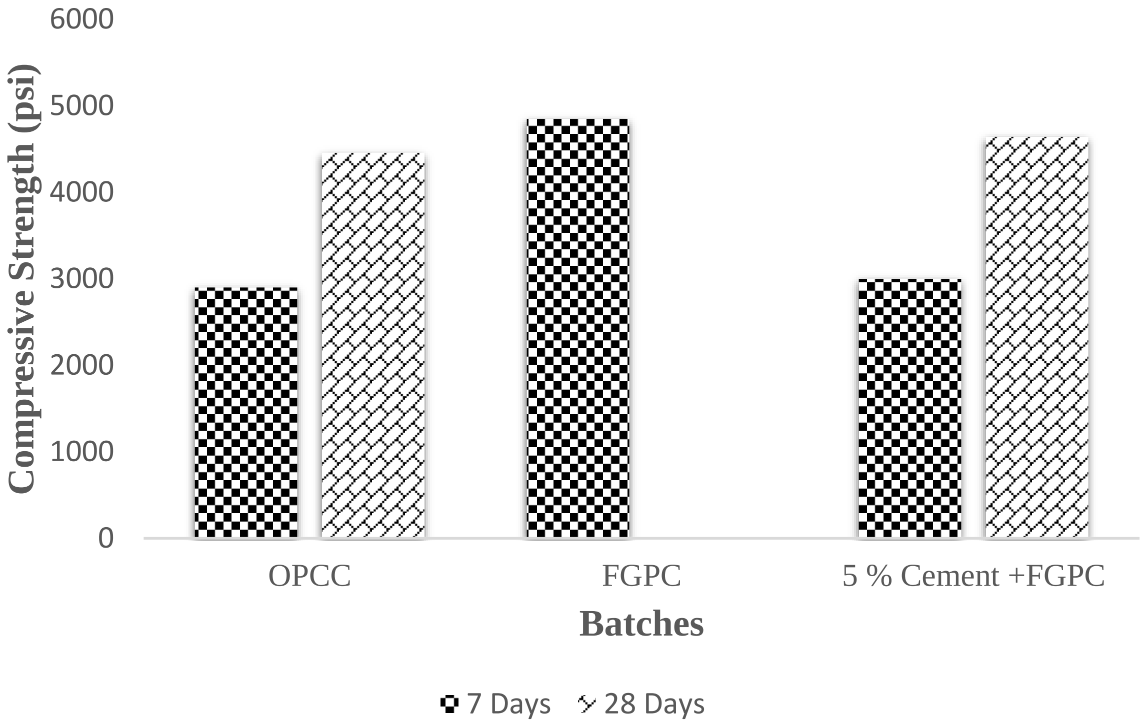


Figure 4.1 Comparison of Compressive Strength at 7 & 28 days of all Batches

It is evident from figure 4.1 that the highest 28 days compressive strength was gained by FGPC (4850 psi) from all the batches, it was about **8%** more than that of control and **4%** more than that of 5% cement + FGPC. The compressive strength of 5% cement + FGPC concrete has the second highest 28 days compressive strength (4641.2 psi), it was about **4%** more than that of control. It is evident from the results that both the batches containing fly ash as binding agent were able to get higher compressive strength values than that of OPCC.

4.3 Splitting Tensile Test

Table 4.2 Splitting Tensile Strength Data

	Split Tensile Strength (psi)		
Sample	**7 Days**	**28 Days**	**Remarks**
OPC (Control)	1674	1955.4	Water Cured
FGPC	1837.6	-	Oven Cured at 60º for 24 hours
FGPC + 5% Cement	1069.7	1360	Ambient Cured

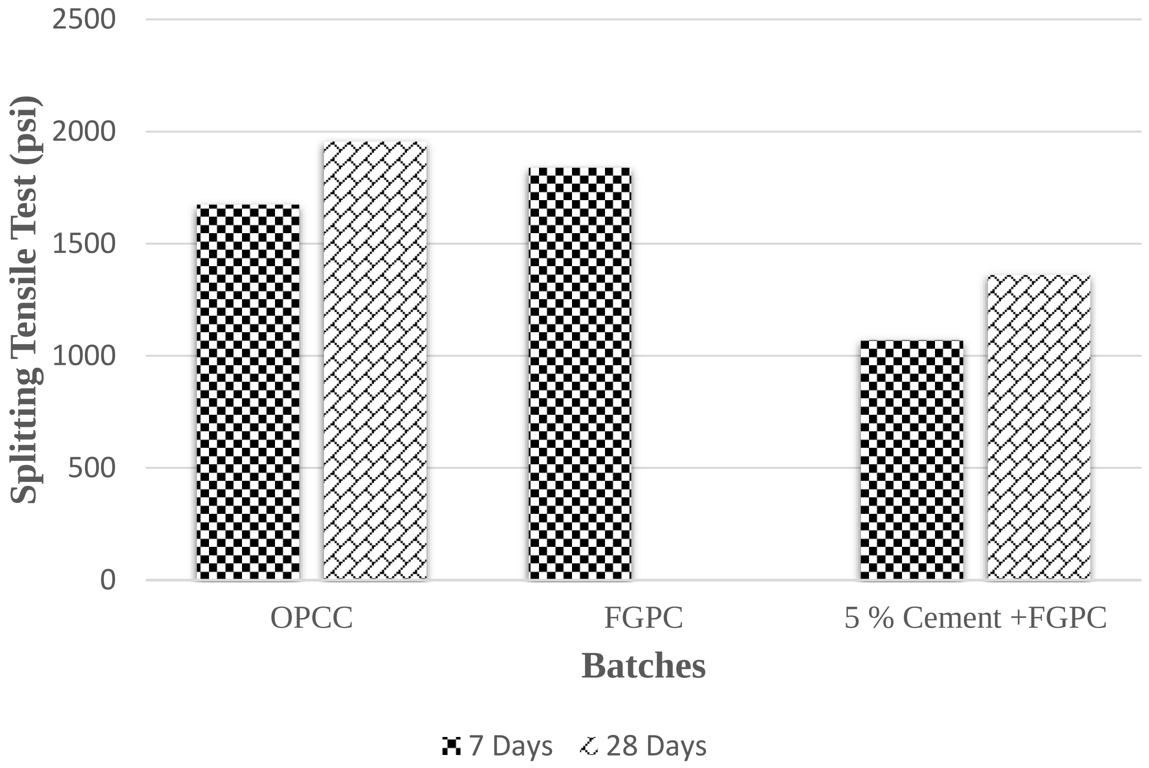


Figure 4.2 Comparison of Splitting Tensile Strength at 7 & 28 days of all Batches

From the data it is evident that OPCC had the highest tensile strength from all the batches followed by FGPC and 5% Cement + FGPC. From the comparison chart in Figure 4.2 it is clear that the tensile strength of geopolymer concretes are less than that of OPCC.

4.4 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)	680.23	1055.8	Water Cured
FGPC	1065	-	Oven Cured at 60º for 24 hours
FGPC + 5% Cement	768.7	1232.8	Ambient Cured

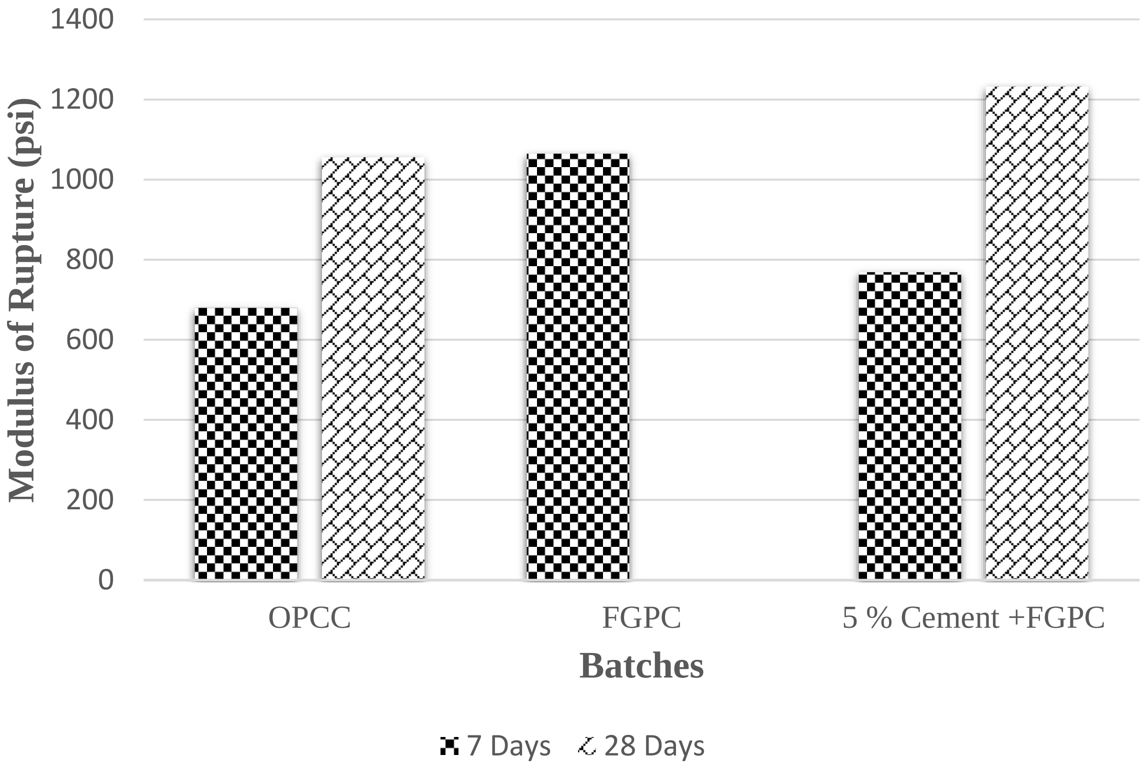


Figure 4.3 Three-Point Loading Test (Modulus of Rupture) at 7 & 28 days of all Batches

It is clear from the test data and graph that the flexural strength of both OPCC and FGPC batches are similar. The highest flexural strength was achieved for 5% Cement + FGPC batch, which was **14%** and **15 %** more than that of FGPC and OPCC respectively, it may be because of the presence of cement as admixture in the mix.

4.5 Structural Design Thickness of Rigid Pavement

The calculation of thickness for pavement was carried out based on AASHTO road test parameters. Current pavement design techniques are based on the AASHTO road test (finished in the 1950s) and subsequent AASHTO Guide for the Design of Pavement Structures (AASHTO Design Guide). The AASHTO Design Guide is still utilized in the industry for pavement thickness design, despite the fact that it is several years old. To design a pavement by the AASHTO method, several design parameters must be determined or assumed.

4.5.1 Design Parameter Values

For carrying out comparison between our 3 compositions of samples to obtain pavement thickness, 1993 AASHTO Design Guide provides certain values which are fixed for the AASHTO design parameters:

- Design Traffic, W_{18} - 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 pci (assumed)
- Soil Resilient Modulus, M_R - 5000 psi

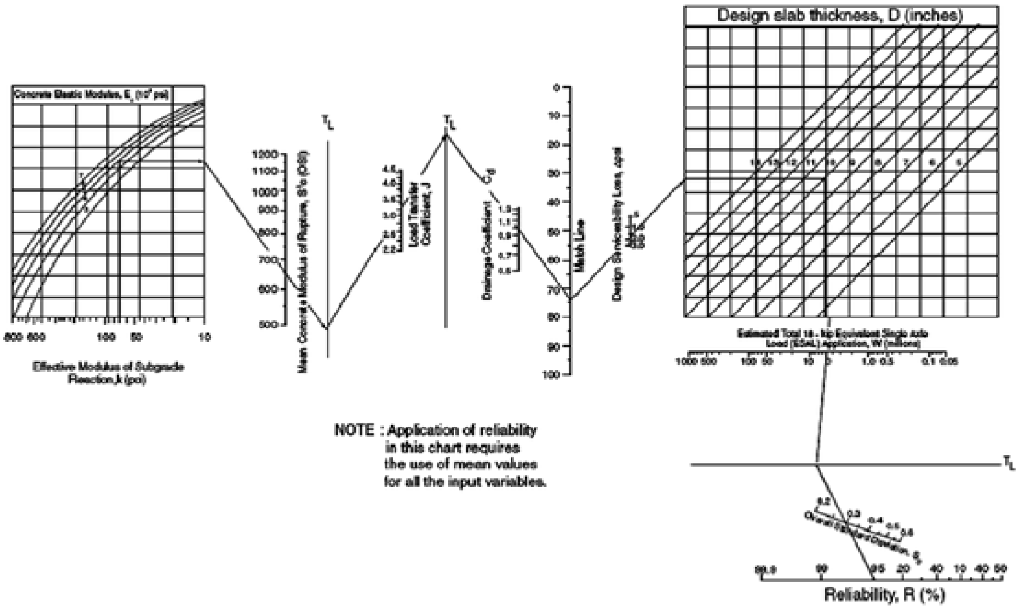
4.5.2 Design Parameters

3 samples under consideration were tested and their Modulus of Elasticity E and Modulus of Rupture (S'c) were obtained. The other AASHTO parameters were assumed for a standard traffic under AASHTO test conditions, and the variables were kept constant, only the modulus of elasticity and modulus of rupture were varied. Afterwards using the undermentioned Empirical formula and the Nomograph, following thicknesses were calculated.

4.5.2.1 Design Equation of Rigid Pavement

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

4.5.2.2 Rigid Pavement Nomograph



4.5.3 Results

Table 4.4 Thicknesses of Pavements for Various Batches

Sample	Modulus of Elasticity (Psi)	Modulus of rapture Sc (Psi)	Slab Thickness D (in)
Cement	3.8×10^6	1055.8	6.5
FGPC*	3.96×10^6	1065	6.5
FGPC + 5% Cement	3.88×10^6	1232.8	6

* 7 Days

The thickness of OPCC and FGPC rigid pavement was same due to the similarity in their values of modulus of rupture. 5% Cement + FGPC gave less thickness of pavement about **8%** less, as its modulus of rupture was greater than both batches of concrete.

4.5.4 Comparison of Stress and Deflection

Utilizing the calculated thicknesses of Slabs, we can conclude the stress and deflection they would bear. Keeping some control/ assumed values for tire loads and their spacings we can deduce the following results for interior stresses due to the loading by dual tires arrangement.

Table 4.5 Stress and Deflection values for different batches

Sample	Stress σ (psi)	Deflection Δ (in)
OPCC	273.6	0.01538
FGPC	275.59	0.01493
FGPC + 5% Cement	312.1	0.01695

4.5.5 Comparison of Results with PAVEXpress

A comparison of calculated slab thicknesses along with the stresses it is bearing was drawn via web-based design tool. PAVEXpress Suite is used to verify the already obtained results.

PAVEXpress is a free web-based pavement design tool available for use by local agencies, engineers, and architects who need a reliable way to quickly determine the necessary pavement thickness for a given section of roadway or project. It was designed to be an extension of AASHTO 93/98 and has been adopted by public agencies such as the Washington State Department of Transportation as an accepted tool to help assess, scope, and design pavements.

This software was used to identify the values of thicknesses of rigid pavements, their stresses for different load scenarios and critical deflections. For each batch a separate profile was made in which the relevant parameters regarding the design of thickness for rigid pavements were given as inputs to the software after which the thicknesses for different batches were calculated by the software. Similarly different load scenarios were also given as inputs after which the software calculate the critical stresses and deflections occurring for all the batches of concrete which were to be used in making rigid pavements.

A pictorial view of the results obtained from PAVEXpress along with their comparison is shown

Details

Scenario: New Rigid Pavement Design OPCC

Created By: umar zia, umer_zia14@gmail.com

Last Modified: May 30, 2022 8:09:22 pm

Design Parameters

Design Period: 30 years

Reliability Level (R): 95%

Combined Standard Error (S_0): 0.3

Initial Servicability Index (p_i): 4.5

Terminal Servicability Index (p_t): 2.5

Delta Servicability Index (ΔPSI): 2

Total Design ESALs (W_{18}): 5000000

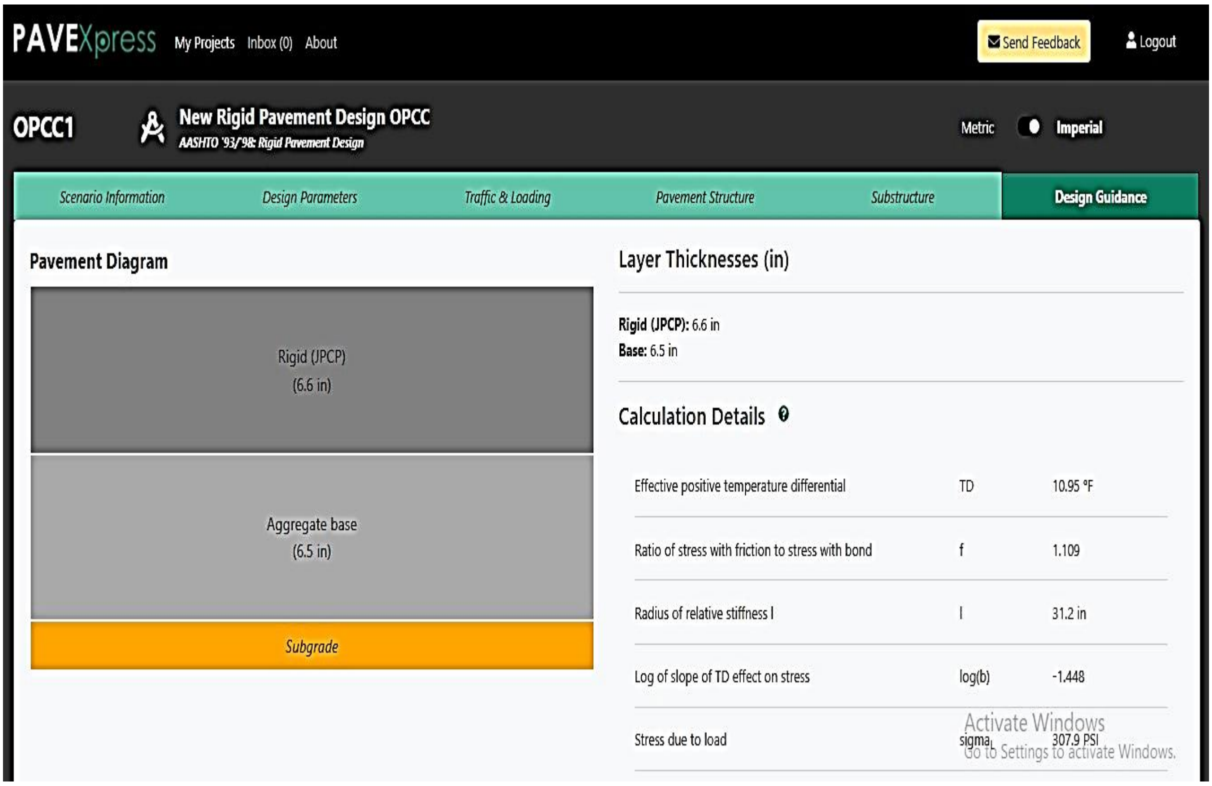
Layers

Rigid (JPCP) - Concrete
Thickness: 6.60000000000003 in

Aggregate base - Base
Thickness: 6.5 in

Subgrade - Subgrade
Thickness: 0 in

Figure 4.4 OPCC Design Parameters



New Rigid Pavement Design OPCC
AASHTO '93/'98: Rigid Pavement Design

Layer Thicknesses (in)

Rigid (JPCP): 6.6 in
Base: 6.5 in

Calculation Details

Effective positive temperature differential	TD	10.95 °F
Ratio of stress with friction to stress with bond	f	1.109
Radius of relative stiffness l	l	31.2 in
Log of slope of TD effect on stress	log(b)	-1.448
Stress due to load	sigma$_l$	307.9 PSI

Figure 4.5 OPCC Design Results

Details

Scenario: FGPC

Created By: umar zia, umer_zia14@gmail.com

Last Modified: May 30, 2022 8:12:01 pm

Design Parameters

Design Period: 30 years

Reliability Level (R): 95%

Combined Standard Error (S_0): 0.3

Initial Servicability Index (p_i): 4.5

Terminal Servicability Index (p_t): 2.5

Delta Servicability Index (ΔPSI): 2

Total Design ESALs (W_{18}): 5000000

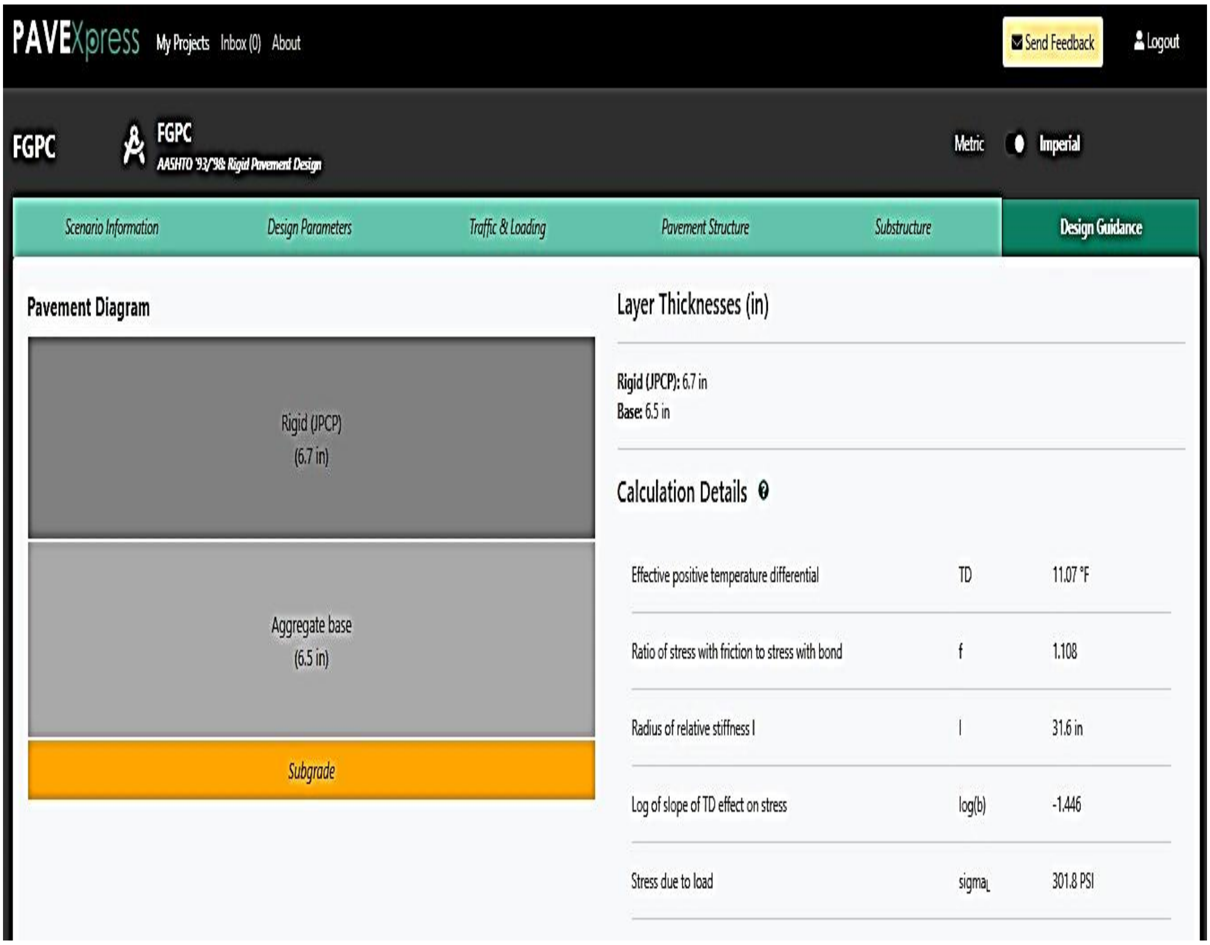
Layers

Rigid (JPCP) - Concrete
Thickness: 6.7000000000000295 in

Aggregate base - Base
Thickness: 6.5 in

Subgrade - Subgrade
Thickness: 0 in

Figure 4.6 FGPC Design Parameters



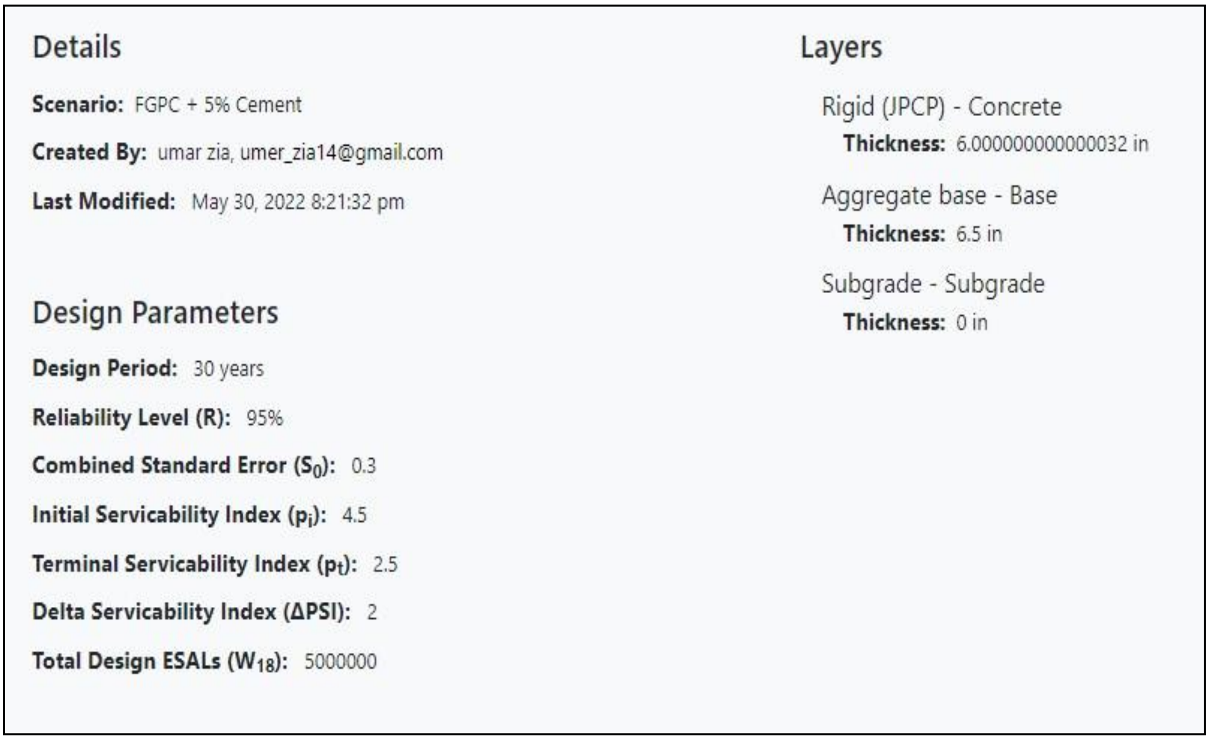
Layer Thicknesses (in)

Rigid (JPCP): 6.7 in
Base: 6.5 in

Calculation Details

Effective positive temperature differential	TD	11.07 °F
Ratio of stress with friction to stress with bond	f	1.108
Radius of relative stiffness l	l	31.6 in
Log of slope of TD effect on stress	log(b)	-1.446
Stress due to load	$sigma_L$	301.8 PSI

Figure 4.7 FGPC Design Results


Details

Scenario: FGPC + 5% Cement
Created By: umar zia, umer_zia14@gmail.com
Last Modified: May 30, 2022 8:21:32 pm

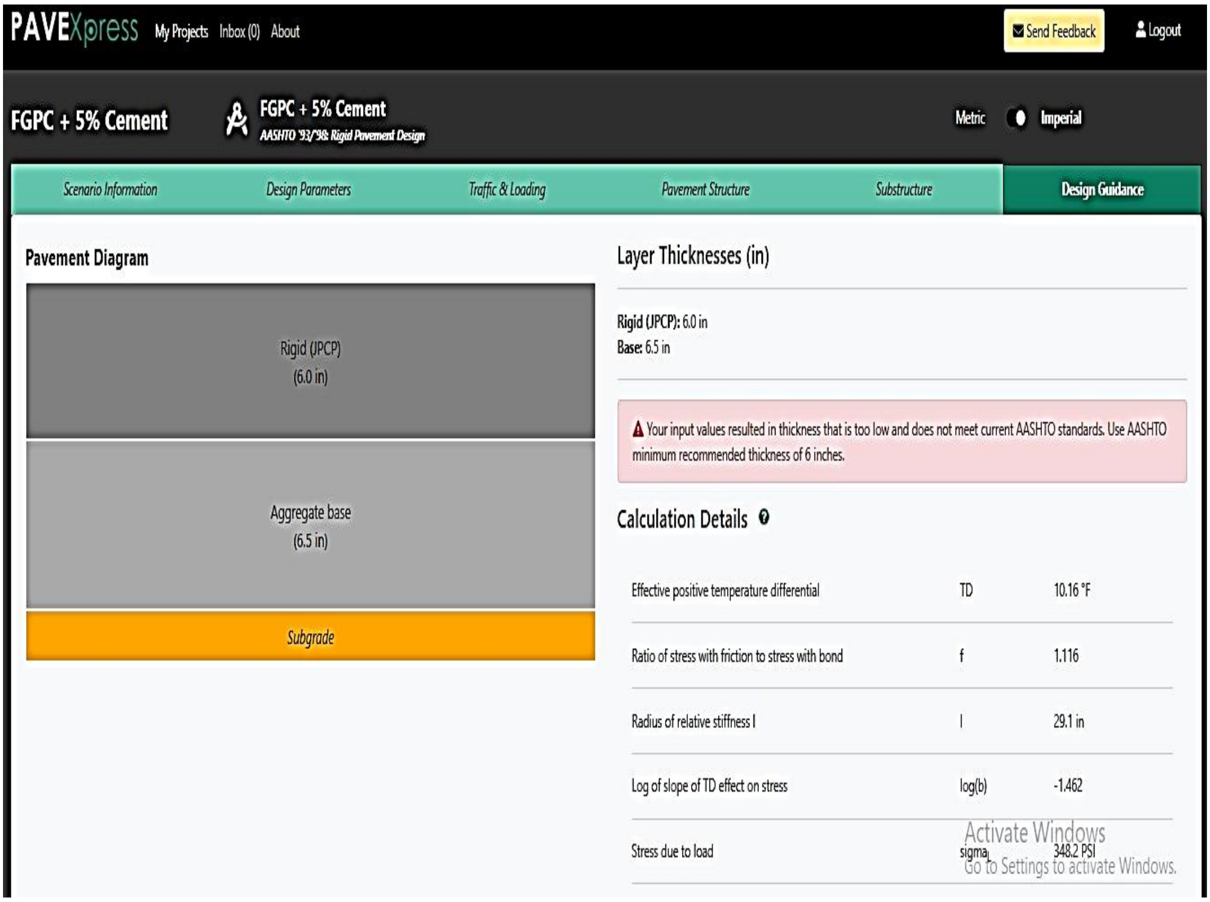
Design Parameters

Design Period: 30 years
Reliability Level (R): 95%
Combined Standard Error (S_0): 0.3
Initial Servicability Index (p_i): 4.5
Terminal Servicability Index (p_t): 2.5
Delta Servicability Index (ΔPSI): 2
Total Design ESALs (W_{18}): 5000000

Layers

Rigid (JPCP) - Concrete
Thickness: 6.000000000000032 in
Aggregate base - Base
Thickness: 6.5 in
Subgrade - Subgrade
Thickness: 0 in

Figure 4.8 FGPC + 5% Cement Parameters



Layer Thicknesses (in)

Rigid (JPCP): 6.0 in
Base: 6.5 in

Your input values resulted in thickness that is too low and does not meet current AASHTO standards. Use AASHTO minimum recommended thickness of 6 inches.

Calculation Details

Effective positive temperature differential	TD	10.16 °F
Ratio of stress with friction to stress with bond	f	1.116
Radius of relative stiffness l	l	29.1 in
Log of slope of TD effect on stress	log(b)	-1.462
Stress due to load	sigma_L	348.2 PSI

Activate Windows
Go to Settings to activate Windows.

Figure 4.9 FGPC + 5% Cement Design Results

A comparison between the thicknesses and stresses calculated manually and by PAVEXpress software is given below. An average deviation of **10%** was found between manually calculated values of stresses, through available formulas and from the software. An average deviation of **2%** was found between manually calculated values of thickness of pavement, through available formulas and from the software.

Table 4.6 Comparison Between Values Calculated Manually and by PAVEXpress

Sample	Calculated Results		PAVEXpress	
	Slab Thickness (in)	Stress σ (psi)	Slab Thickness (in)	Stress σ (psi)
OPCC	6.5	273.6	6.6	307.9
FGPC	6.5	275.59	6.7	301.8
FGPC + 5% Cement	6	312.1	6	348.2

4.6 Cost Benefit Analysis

After finding the thickness of rigid pavements involving all the batches a detailed cost analysis was undertaken for all the three batches. For the purpose of cost analysis, a standard road dimension of 1000 m long and 3.65 m wide road was selected, and the thickness varied according to the batch that was used in construction of that road patch.

The prices of all the materials were taken from the local markets except those of the alkaline liquids. This is because in Pakistan the alkaline liquids required for production of FGPC are not available on a large commercial scale. For e.g., the amounts in which sodium silicate and sodium hydroxide was available in the market was very miniscule and because of that their prices were very high. But if same chemicals are ordered in bulk values of say a ton than their costs are substantially decreased. According to Hardjito and Rangan (2005) "based on the bulk cost of sodium silicate and sodium hydroxide the quantity of chemicals required to react with one ton of fly ash costed approximately AU $50 in 2005", which is approximately worth AU $76 today which is equal to Rs 10135. This implies that the low calcium FGPC concrete will be cheaper than OPCC.

4.6.1 OPCC rigid pavement cost analysis

OPCC is the control sample as per standard SOPs and sample composition cost is given below in table. Rates shown in table are standard market rates at the time of sample procurement, these may vary slightly as per inflation rate. One table shows the cost of per cubic meter sample and the other table shows the cost of a 577.5 m^3 (1000m x3.5m x 0.165m) (6.5 in) patch of rigid pavement.

Table 4.7 OPCC Cost per cubic meter

Constituents	Quality (Kg/m^3)	Cost Per Unit (Rs)	Total Cost (Rs/m^3)
Cement	403 kg	25 / kg	10075
Coarse aggregate	1512 kg (29.66 ft^3)	105 / ft^3	3114
Fine aggregate	672 (14.83 ft^3)	80 / ft^3	1186
Super Plasticizer	6 Kg	100	600
Total			**Rs 14975**

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

Constituents	Material Quality for road ($577.5\ m^3$)	Total material required (1000 x 3.5 x 0.165 m)
Cement	242.7 Ton	6.06 Mn
Coarse aggregate	0.503 Ton	1.87 Mn
Fine aggregate	0.252 Ton	0.71 Mn
Super Plasticizer	3.6 Ton	0.36 Mn
Total		**9 Mn**

4.6.2 FGPC Rigid Pavement Cost Analysis

This FGPC batch is 100% fly ash made sample as per standard SOPs and sample composition cost is given below in table. Rates shown in table are standard market rates at the time of sample precuring, these may vary slightly as per inflation rate. Table shows the cost of per cubic meter sample and in last column it shows the cost of a 577.5 m^3 (1000m x3.5m x 0.165m) (6.5 in) patch of rigid pavement.

Table 4.9 FGPC Cost per cubic meter

Constituents	Quality (m^3)	Cost Per Unit (Rs)	Total Cost (Rs)
Fly Ash	408 Kg	6 / Kg	2448
Coarse aggregate	29.66 ft^3	105 / ft^3	3114
Fine aggregate	14.83 ft^3	80 / ft^3	1186
Super Plasticizer	6 Kg	100	600
Na_2SiO_3	103 Kg	21 / Kg	2152
NaOH	41 kg	53 / Kg	2181
Total			**Rs 11681**

Table 4.10 FGPC Total Cost 1 lane kilometer Rigid Pavement Slab

Constituents	Material quantity for road (577.5 m^3)	Road Construction (1000m x 3.5m x 0.165m)
Cement	-	-
Fly Ash	245.7 Ton	1.47 Mn
Coarse aggregate	0.503 Ton	1.87 Mn
Fine aggregate	0.252 Ton	0.71 Mn
Super plasticizer	3.6 Ton	0.36 Mn
Na_2SiO_3	62 Ton	1.3 Mn
NaOH	24.07 Ton	1.31 Mn
Total		**7.02 Mn**

4.6.3 FGPC rigid + 5% Cement pavement cost analysis

This FGPC batch is 100% fly ash and 5% cement made sample as per standard SOPs and sample composition cost is given below in table. Rates shown in table are standard market rates at the time of sample procurement, these may vary slightly as per inflation rate. Table shows the cost of per cubic meter sample and in last column it shows the cost of a 539 m^3 (1000m x3.5m x 0.154m) (6in) patch of rigid pavement.

Table 4.11 FGPC + 5% Cement Cost per cubic meter

Constituents	Quality (m^3)	Cost Per Unit (Rs)	Total Cost (Rs)
Cement	20 Kg	25 / Kg	500
Fly Ash	408 Kg	6 / Kg	2448
Coarse aggregate	29.66 ft^3	105 / ft^3	3114
Fine aggregate	14.83 ft^3	80 / ft^3	1186
Super Plasticizer	6 Kg	100	600
Na_2SiO_3	103 Kg	21 / Kg	2152
NaOH	41 kg	53 / Kg	2181
Total			**12131**

Table 4.12 FGPC + 5% Cement Total Cost 1 lane kilometer Rigid Pavement Slab

Constituents	Material quantity for road (602.25 m^3)	Road Construction (1000m x 3.5m x 0.154m)
Cement	11.1 Ton	0.30 Mn
Fly Ash	245.7 Ton	1.47 Mn
Coarse aggregate	0.503 Ton	1.87 Mn
Fine aggregate	0.252 Ton	0.71 Mn
Super plasticizer	3.6 Ton	0.36 Mn
Na_2SiO_3	62 Ton	1.3 Mn
NaOH	24.07 Ton	1.31 Mn
Total		**7.32 Mn**

4.6.4 Comparison Between Costs of Different Batches

A comparison is held between the sample cost shown in table below. Results indicates that the sample made up of 100% fly ash is comparatively at lowest cost from all the batches, even though the FGPC pavement is having same thickness as that of OPCC pavement, but it is still cheaper than OPCC pavement, it is **22%** cheaper than OPCC pavement. Similarly, from data it is evident that 5% Cement + FGPC pavement is **18.8%** cheaper than OPCC pavement. Also, if we compare both fly ash concrete pavements than it becomes clear that FGPC pavement is **4%** cheaper than 5% Cement + FGPC pavement. Chemicals used in this process can only be at given cost when procured in bulk quantity i.e., in Tons**.** The significant reduction in cost between FGPC and OPCC mixtures shows that on large scale transportation rigid pavements projects a huge amount of capital can be saved.

One of the reasons that FGPC rigid pavements are less expensive is because the main binding agent of FGPC which is fly ash is a byproduct of the burning of coal in power plants and is available at much cheaper rates than cement in the market. Furthermore, fly ash is not subject to a lot of fluctuation in market as is the case with OPC due to many factors like: rising energy costs, transportation costs, governmental taxes and labor costs. These factors are constantly having a negative effect on the price of OPC which is an essential component of concrete.

Table 4.13 Comparison of Costs 1 lane kilometer Rigid Pavement Slab

Constituents	OPC Road Const (1000m x 3.5m x 0.165m)	FLY ASH WITH 5% CEMENT Road Construction (1000m x 3.5m x 0.154m)	100% FLY ASH Road Construction (1000m x 3.5m x 0.165m)
Cement	6.06 Mn	0.30 Mn	-
Fly Ash	-	1.47 Mn	1.47 Mn
Coarse aggregate	1.87 Mn	1.87 Mn	1.87 Mn
Fine aggregate	0.71 Mn	0.71 Mn	0.71 Mn
Super plasticizer	0.36 Mn	0.36 Mn	0.36 Mn
Na_2SiO_3	-	1.3 Mn	1.3 Mn
NaOH	-	1.31 Mn	1.31 Mn
Total	**9 Mn**	**7.31 Mn**	**7.02 Mn**

4.7 Summary

In this chapter the results of the tests were analyzed and afterwards thicknesses and stresses of rigid pavements were found for each batch of concrete through empirical relations and PAVEXpress software. In the end a cost benefit analysis was performed, and it was observed that FGPC batches were significantly cheaper than OPCC, when used for the rigid pavements construction.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

In this chapter conclusion and recommendations have been given. These conclusions and recommendations have been derived from literature review and all the experimental work that has taken place and afterwards some recommendations have been given in the end for further development of FGPC in field of construction. Some outcomes are stated in below sections.

5.2 Manufacturing Process

5.2.1 Preparing the Materials

The standard practices which are used in for selecting aggregates for OPCC was also used for selecting aggregates for FGPC. Aggregates were in saturated surface dry condition.

A mixture of sodium silicate solution and sodium hydroxide solution was used to create the alkaline liquid. Both of these solutions were prepared a day before the solid components of FGPC were combined together.

5.2.2 Mixing, Placing and Compaction

The solid constituents of the mix were mixed a drum roller for three minutes after which the liquid portion of the mix was added to them. They were further mixed for five more minutes after which they were poured into the molds in three layers and each layer was tamped 25 times. For further compaction each mold was put on the vibrating table for 15 seconds. It was also observed that FGPC could be easily handled for 120 minutes without any sign of setting. In all these processes the same equipment was used, which is used for the manufacturing process of OPCC.

5.2.3 Curing

Two types of curing were carried out. The FGPC batches were dry cured for 24 hours at 60́ C in an industrial furnace. After that they were taken out of the furnace and placed in the lab for ambient curing for 7 days, after which all the tests on that batch took place.

For 5% Cement + FGPC concrete ambient curing was adopted to study the effects of ambient curing on FGPC concrete. For this the specimens were left for curing in the lab at ambient conditions for 7 and 28 days after which the relevant tests were performed.

5.3 Conclusions

Based on literature review and experimental work performed on FGPC following conclusions were drawn:

- **Oven cured** FGPC has greater 7-days compressive strength from OPCC (28-days) by up to **8%,** this means that FGPC will have better application in areas where rapid construction under constrained time environment is required
- **Ambient cured** FGPC has greater compressive strength from OPCC by up to **4%**
- **OPCC** highest tensile strength from both batches; FGPC (6%) & FGPC+5% Cement (30%)
- Oven cured FGPC and Ambient cured FGPC have higher flexural strength than OPCC by up to **1%** and **15%,** respectively
- Thickness of rigid pavement calculated for three batches of concrete, showed that OPCC and oven cured FGPC has same thickness of 6.5in but ambient cured FGPC pavement had 6in thickness, because it has **highest flexural strength** between all the batches
- From cost analysis of a standard 1 km long and 3.65 m wide lane for given thicknesses of all the batches. It was found that ambient cured FGPC pavement was **19% cheaper** than OPCC pavement and oven cured FGPC pavement was **22% cheaper** than OPCC pavement.

5.4 Recommendations

After the conduct of research following recommendation were proposed:

- Further research needs to be caried to find the short- and long-term effects of water curing on FGPC.
- The strength of the bond between FGPC and steel reinforcement, as well as their behaviors, require more investigation.
- To promote the usage of FGPC, it is necessary to cut the price of alkaline liquids like sodium hydroxide and sodium silicate and for that it is necessary to encourage their production at industrial scale by the local chemical industry.

- Further research is necessary to find out the application of geopolymer technology in other fields of construction.

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