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EXPERIMENTAL ANALYSIS OF STRENGTH AND DURABILITY OF GPC BY USING METAKAOLIN AND FLY ASH

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ABSTRACT-
This study studies the strength and durability of geopolymer concrete (GPC) employing metakaolin and fly ash. Metakaolin and fly ash are recognized for their high reactivity and ability to produce strong, durable binders when activated by an alkaline solution. Various quantities of metakaolin and fly ash were utilized to generate GPC samples, which were then subjected to rigorous mechanical and durability testing. The results demonstrated that the addition of metakaolin and fly ash considerably increases the early and long-term compressive strength of GPC. Additionally, durability evaluations, including water absorption, sorptivity, and resistance to chemical assault, indicated better performance in harsh conditions. Microstructural research demonstrated dense and homogenous matrices, leading to the increased durability properties. The study also showed the environmental benefits of employing industrial by-products like metakaolin and fly ash, lowering carbon footprints compared to regular Portland cement. Overall, the findings imply that metakaolin and fly ash-based GPC is a sustainable and durable option for building applications, delivering improved mechanical qualities and greater durability.

Keyword: GPC, Metakaolin, Sodium Sulphate, Sulphuric Acid and Sodium Chloride.

I. INTRODUCTION

Geopolymer concrete (GPC) has emerged as a promising alternative to conventional Portland cement concrete due to its potential for higher sustainability, improved mechanical properties, and enhanced durability. Among various types of GPC, those utilizing industrial by-products like fly ash and metakaolin have gained significant attention for their environmental benefits and performance characteristics.

Overview of Geopolymer Concrete

Geopolymer concrete is a type of inorganic polymer that is synthesized through the reaction of aluminosilicate materials with alkaline activators. Unlike traditional concrete, GPC does not rely on Portland cement as a binder. Instead, it uses industrial by-products such as fly ash, a waste material from coal combustion, and metakaolin, a dehydroxylated form of kaolinite clay. This makes GPC a more sustainable and eco-friendly option, as it helps in recycling industrial waste and reducing greenhouse gas emissions associated with cement production.

Strength and Durability Properties

The strength and durability of geopolymer concrete are influenced by various factors, including the type and composition of the precursor materials, the nature of the alkaline activators, and the curing conditions. Fly ash and metakaolin are commonly used precursors that contribute significantly to the properties of GPC.

1. **Fly Ash**: Fly ash is rich in silica and alumina, which are essential for the geopolymerization process. It provides high compressive strength and good workability to the concrete. The use of fly ash in GPC has been shown to improve the long-term strength development and resistance to chemical attacks, making it suitable for harsh environmental conditions[1].
2. **Metakaolin**: Metakaolin, on the other hand, is a highly reactive pozzolan that enhances the early strength and durability of GPC. Its high reactivity leads to a denser microstructure, which improves the concrete's resistance to permeability and durability against aggressive agents such as chlorides and sulfates[2].

Experimental Analysis

Experimental studies have shown that the combination of fly ash and metakaolin in geopolymer concrete can produce a material with superior strength and durability properties. For instance, an experimental study on metakaolin and ground granulated blast furnace slag (GGBS) based geopolymer concrete revealed significant improvements in both compressive strength and durability metrics when metakaolin was used alongside fly ash[3].

These studies typically involve preparing various mix designs with different proportions of fly ash and metakaolin, followed by curing under controlled conditions. The resulting GPC samples are then tested for compressive strength, flexural strength, and durability characteristics such as resistance to acid attack, chloride penetration, and sulfate attack. The findings indicate that geopolymer concrete incorporating fly ash and metakaolin not only meets but often exceeds the performance of conventional concrete in terms of strength and durability[4][5].

The growth rate of infrastructure, closely linked to cement production, is a key driver of a country's economic development. The rapid increase in concrete usage for infrastructure projects has accelerated cement production. This has raised significant environmental concerns, primarily climate change due to greenhouse gas emissions from the cement manufacturing process. The Carbon Dioxide Information Analysis Center reports that CO2 constitutes about 68.2% of atmospheric emissions, with approximately one ton of CO2 released per ton of cement produced. Concrete is a staple in construction, placing constant pressure on the cement industry to reduce CO2 emissions while still dealing with greenhouse gases throughout the conversion of raw materials into cement. Researchers are exploring various cement substitutes, including metakaolin (MK), fly ash (FA), slag, and nano-silica, to mitigate greenhouse gas emissions. Using FA as a cement replacement reduces the water needed for concrete mix by about 10% when FA constitutes 20% of the cement base, without significantly impacting drying or cracking. MK, a highly reactive aluminosilicate, is used to enhance the strength and properties of cement concrete. These materials, with their compact structure and glassy nature, help reduce labor and water usage, leading to more economical and environmentally friendly construction solutions.

II. METHODOLOGY

A. Geopolymer concrete (GPC)

Geopolymer concrete (GPC) is an innovative and eco-friendly building material developed as a sustainable alternative to traditional Portland cement concrete. Introduced by Davidovits in 1978, GPC is created by activating aluminosilicate materials like fly ash or metakaolin with an alkaline solution, typically sodium or potassium-based. This results in a denser microstructure and longer C-A-S-H chains compared to the C-S-H chains in ordinary Portland cement, enhancing durability and strength. GPC offers significant environmental benefits by reducing CO2 emissions associated with cement production, making it a promising option for sustainable construction practices [1] [2].

Advantages of GPC

The benefits of GPC are as follows.

- Completely eliminates the need for Portland cement and thereby reduces the CO2 emissions
- Uses by-products of industrial such as FA, GGBS, etc as the primary base material to address the solid waste disposal problem.
- Minimizes pollution and retain sustainability
- Rapid early strength gain and cures quickly
- Less creep and little drying shrinkage
- Reduces permeability and enhances durability
- Blast, earthquake and fire resistant

Components of Concrete Made of Geopolymer

The components of GPC include aggregates, necessary admixtures, activators, and a binder material. The elements of GPC are listed in Figure 1 along with a few frequently used examples.

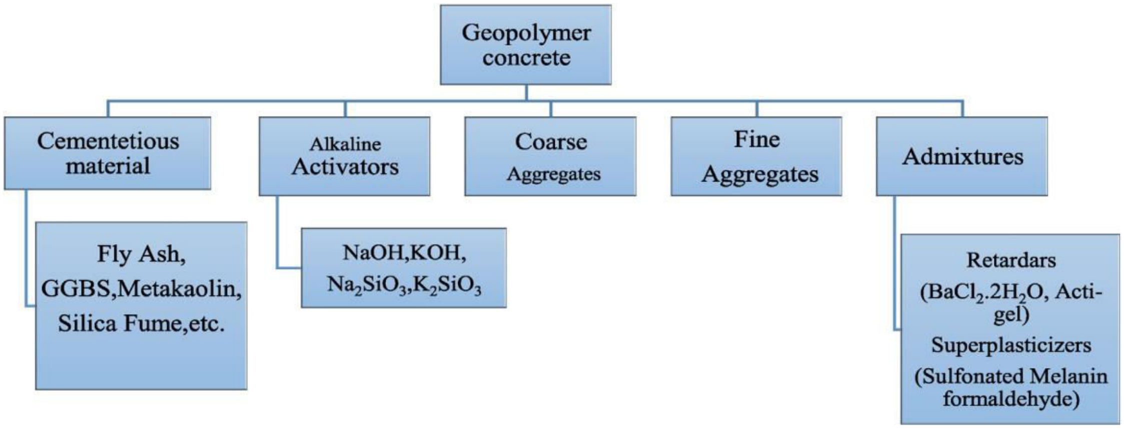

Figure.0 Components of a GPC ((Bisarya 2015, Aldin, 2019).

Table 1: Properties of GPC mixes (Singh 2015, Hardjito, 2004, Sofi 2007)

S No.	Molarity (M)	Activator/ binder ratio	Curing temp.	CS (in MPa)	STS (in MPa)	FS (in MPa)	Modulus of elasticity (in GPa)
1	10–16	0.35–0.40	60–80 °C for 24hrs	30–80	3.74–6	5–12	23–31
2	8 & 12.5	0.40 & 0.55	85 °C for 20hrs	29–43.5	–	6.86	10.7–18.4
3	–	0.45–0.59	23 °C till testing	47–56.5	2.8–4.1	4.9–6.2	23–39
4	14	0.40–0.94	60 °C for 72hrs	10–80	–	2.24–6.41	1.9–42
5	8	0.40–0.65	60 °C for 24 hrs	65.1–77.9	2.8–5.1	–	11.2–41.2
6	8 & 12.5	0.55	85 °C for 20hrs	45	–	6.85	13.4

The table 1 depicted mechanical properties about GPC mixture. It include the property like molarity, activator, curing temperature , CS,STS, FS and Modulus of elasticity with their ranges.

B. Fly ash

Precursors are compounds involved in a chemical reaction to form another compound. Aluminosilicate-rich source materials serve as precursors in the polymerization process to create geopolymers. Fly ash (FA), a fine residue from coal combustion in thermal power plants, is a commonly used precursor. Fabric filters or electrostatic precipitators separate FA from flue gases. The quality of FA is influenced by factors such as coal type, furnace type, precipitator type, and location. As thermal power remains a primary energy source, FA generation is inevitable. Proper disposal of FA poses a significant challenge unless it is effectively utilized. FA possesses pozzolanic properties and can replace 20-40% of cement in cement products.

Advantages of Fly ash

FA has several benefits and is inexpensive when used in place of cement in concrete.

- The small size of the FA particles is essential for creating a smooth cement paste, which improves the bonding between the cement and aggregate and produces more resilient, impermeable concrete.
- The spherical particles make the concrete easier to work with.
- FA will eventually harden and become more powerful when it is in contact with water.

- Less shrinkage and thermal cracks occur from FA concrete's slower curing rate and lower heat of hydration.
- FA is long-lasting because it actually gets stronger with time.

C. Metakaolin

Metakaolin is a dehydroxylated form of the clay mineral kaolinite, produced through the calcination of kaolin clay. It is widely used in the construction industry due to its pozzolanic properties, which enhance the strength and durability of cement, mortar, and concrete. Metakaolin improves the microstructure of concrete by reducing porosity and increasing resistance to chemical attack. Its high reactivity with calcium hydroxide in cement leads to improved mechanical and durability characteristics. Metakaolin is also employed in ceramics and other industrial applications, making it a versatile material in modern construction and manufacturing [1][2].

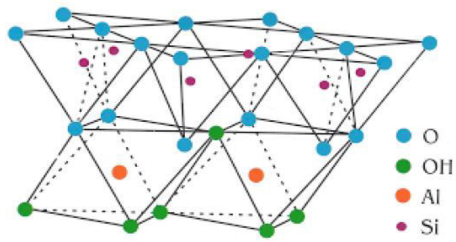

Figure.2 Structure of Kaolin

Table 2 Characteristics of cement and MK (Dinakaret al.,2014)

S.N	Chemical composition	Chemical Name	Cement (%)	Met kaolin (%)
1	Silica	(SiO_2)	34	54.3
2	Alumina	(Al_2O_3)	5.5	38.3
3	Ferric oxide	(Fe_2O_3)	4.4	4.28
4	Calcium oxide	(CaO)	63	0.39
5	Magnesium oxide	(MgO)	1.26	0.08
6	Sodium oxide	(Na_2O)	0.1	0.12
7	Potassium oxide	(K_2O)	0.48	0.50
8	Sulphuricanhydride	(SO_3)	1.92	0.22
9	Lossonignition	(LOI)	1.3	0.68
10	Blaine(m^2/kg)		360	15,000[a]
11	Specificgravity		3.15	2.5

Table 3: Physical properties of MK (Deveshan et al., 2020)

S. N	Physical Property	Description
1	Specific gravity	2.40–2.60
2	Specific surface area	8–15 m^2/g
3	Brunauer–Emmett–Teller (BET) surface area	15 m^2/g
4	Brightness	80–82 Hunter L
5	Physical form	Powder
6	Color	Off white, gray to Buff

Metakaolin offers several advantages when used in concrete:

1. **Improved Strength and Durability**: Metakaolin enhances the compressive, flexural, and tensile strengths of concrete, leading to more robust structures [1][3].
2. **Reduced Permeability**: It decreases the permeability of concrete, making it more resistant to chloride and other chemical ingress, which helps prevent corrosion of reinforcement bars [2].

3. **Enhanced Workability**: Metakaolin improves the workability of concrete mixtures, making them easier to handle and place [3].
4. **Pozzolanic Activity**: Its high pozzolanic activity leads to better chemical resistance and long-term durability of the concrete [6].
5. **Reduced Carbon Footprint**: By partially replacing cement in concrete mixtures, metakaolin helps reduce the overall carbon footprint associated with cement production [4]

III. RESULT AND DISCUSSION

Durability refers to concrete's ability to withstand weathering, chemical erosion, and abrasion while retaining its engineering properties. Enhanced durability extends a structure's service life. Permeability, sorptivity, and diffusivity key material transport properties—significantly influence a concrete structure's longevity. Permeability is critical in aggressive environments, affecting processes like carbonation, chloride penetration, and sulfate attack.

Sulfate attack is particularly damaging to concrete structures, highlighting the need for protection in high sulfate ion environments. Acid resistance is vital for structural materials, especially against sulfuric acid, which simulates sewer pipe conditions. Sulfuric acid, produced bacterially from hydrogen sulfide, poses unique challenges. Studies have subjected high-calcium FA-based GPC specimens to up to 80 days of immersion in magnesium sulfate and sulfuric acid solutions to assess their resistance.

To assess the durability characteristics of high FA based GPC, the following tests are conducted.

- Acid attack
- Sulphate attack
- Sorptivity
- Water absorption

Concrete Durability

Table 4: Test results for Acid attack

SL.NO	%MK+%FA (Mix ID)	Initialcube weight after 28days curing in grams	Final weight of after 90days curing in grams	% loss of weight due to acid attack	CS of cube after 28days curing	CS of cubes after 90days curing	% loss of CS due to acid attack
1	0%MK+100%FA (M1)	2234	2205	1.28	29.6	26.8	9.44
2	20%MK+80%FA (M2)	2362	2323	1.68	30.34	27.22	10.28
3	40%MK+60%FA (M3)	2420	2367	2.18	31.26	27.8	11.1
4	60%MK+40%FA (M4)	2448	2381	2.74	31.02	27.15	12.46
5	80%MK+20%FA (M5)	2362	2298	2.7	30.62	26.755	12.62
6	1000%MK+0%FA (M6)	2340	2290	2.2	30.12	26.08	13.4

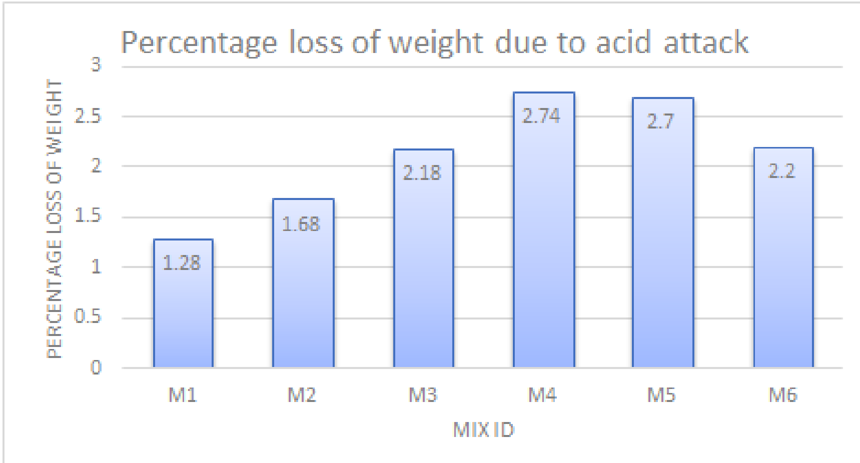

Figure.3 Percentage of weight loss caused due to an acid attack

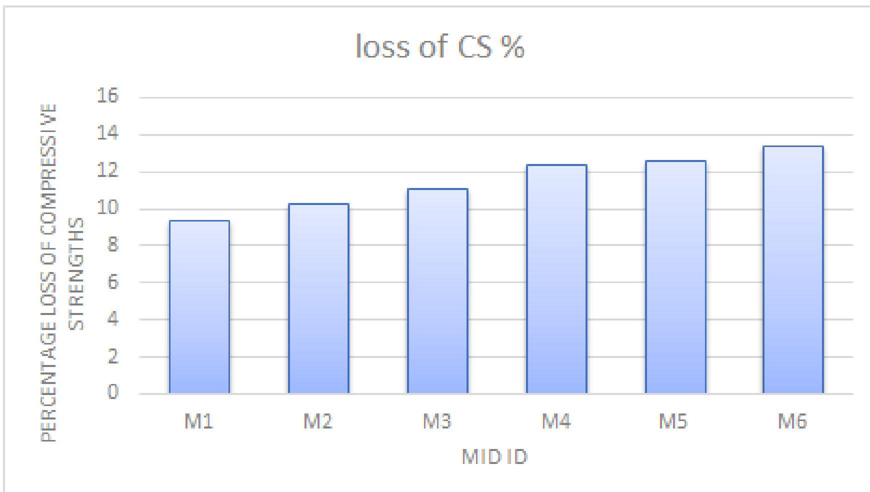

Figure.4 Percentage of CS loss due to acid attack

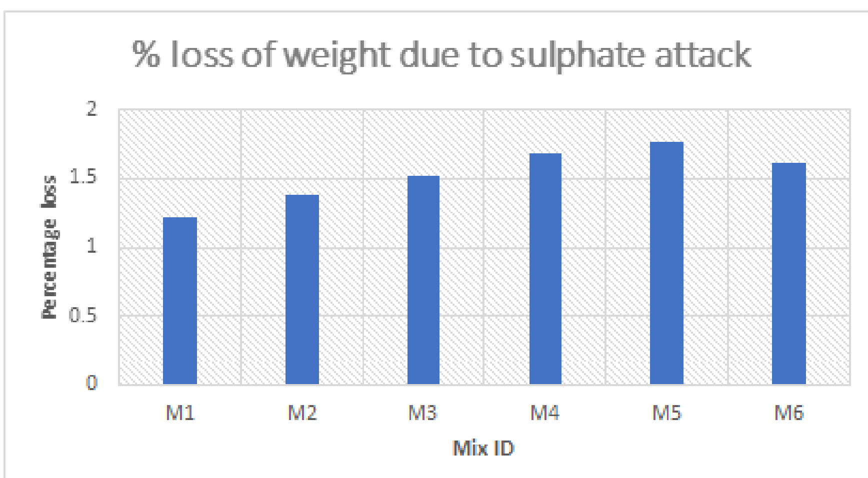

Figure.5 Percentage of weight loss due to sulphate attack

Table 4: Test results for sulphate attack

S. N o	%MK and %FA	Initial cube weight after 28days curing in grams	Final cubes weight after 90days curing in grams	% weight loss due to alkaline attack	CS of cube after 28days curing	CS of cubes after 90days curing	% CSloss due to alkaline attack
1	0%MK+100 %FA (M1)	2298	2270	1.22	29.6	26.51	10.44
2	20%MK+80 %FA (M2)	2424	2391	1.38	30.34	27	10.98
3	40%MK+60 %FA (M3)	2280	2245	1.52	31.26	27.72	11.32
4	60%MK+40 %FA (M4)	2368	2328	1.68	31.02	27.33	11.88
5	80%MK+20 %FA (M5)	2410	2368	1.76	30.62	26.82	12.4
6	1000%MK+ 0%FA (M6)	2340	2302	1.62	30.12	26.42	12.22

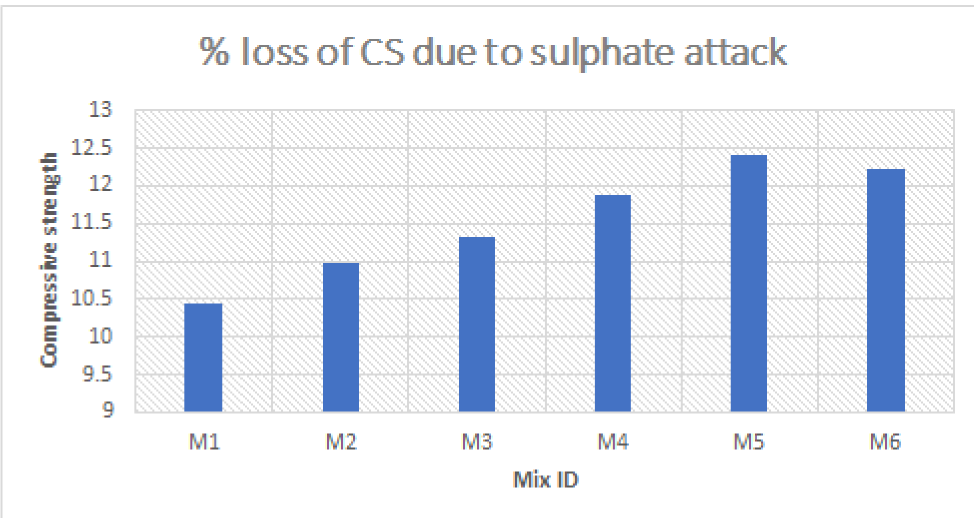

Figure. 6 Percentage of CS loss due to sulphate attack

IV. CONCLUSION

The study reached several conclusions about the properties and behavior of geopolymer concrete (GPC) using metakaolin (MK) and fly ash (FA). It was observed that under normal conditions, GPC typically does not exhibit significant physical changes at room temperature and can take up to 72 hours to fully set without leaving any residue on the surface. As the percentage of FA decreases and the percentage of MK increases, the slump value decreases, while the compaction factor value rises. An optimal mix of 40% MK and 60% FA was identified as yielding the maximum compressive strength (CS) at 7, 14, and 28 days. Additionally, concrete becomes more resistant to acid, alkaline, and sulfate attacks as the FA percentage decreases and the MK percentage increases.

The geopolymeric binder phase created from MK and FA effectively binds fine and coarse aggregates to form GPC, making it an eco-friendly material. The values of compressive, flexural, and splitting tensile strength (STS) increase with the mass ratio of NaOH to Na_2SiO_3. FA-based GPC with a higher concentration of NaOH solution exhibits higher CS, and concrete made with MK-based geopolymer also shows higher CS with an increased mass ratio of NaOH to Na_2SiO_3.

GPC's resistance to chemical attacks improves as the FA content decreases and MK content increases. This makes GPC a more resilient and durable construction material. The geopolymeric binder phase formed by MK and FA effectively binds fine and coarse aggregates, contributing to GPC's eco-friendly credentials.

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