



Mechanical Performance of Polypropylene Fiber-Reinforced Fly Ash and Metakaolin Geopolymers under Different Alkaline Molarities

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Abstract

This study evaluates the effect of polypropylene (PP) fiber addition on the mechanical performance of fly ash (FA)- and metakaolin (MK)-based geopolymer composites activated with 8M, 10M, and 12M sodium hydroxide. Mixes were cured at 60 °C for 24 h to obtain consistent early-age strength. Mechanical tests included compressive strength, three-point flexural strength, and splitting tensile strength. For FA-based mixes at 12M NaOH, PP fibers at 900 g/m³ substantially improved performance: compressive strength increased from 300 kg/cm² to 416 kg/cm², ($\approx 38.7\%$ gain), flexural strength increased from 33 kg/cm² to 62 kg/cm², and splitting tensile strength increased from 8.8 kg/cm² to 20.4 kg/cm². In contrast, MK-based mixes exhibited lower absolute strength and only limited gains after PP fiber addition. For MK-based geopolymers, adding PP fibers produced only limited gains in flexural and splitting tensile strength, indicating less efficient stress transfer between fiber and matrix compared with FA-based mixes. Monte Carlo simulations were employed to model the variability of compressive strength across the different mixes, providing probabilistic insight into performance reliability rather than relying solely on mean values. The statistical analysis indicates that FA-based geopolymer reinforced with PP fibers delivers both higher strength and higher reliability, supporting its viability as a structural alternative to Portland cement concrete in applications that demand improved flexural and tensile resistance. At the same time, the results show that MK-based systems are less responsive to PP fibers at the tested dosage, suggesting that improved reinforcement strategies (e.g., different fiber type, higher fiber content, or modified curing conditions) are required to enhance the mechanical efficiency of MK-based geopolymers. The results inform sustainable geopolymer binder design and elucidate how precursor chemistry governs the effectiveness of PP fibers at the fiber matrix interface.

Keywords: Environmental impact; Meta-Kaolin; Fly ash; Polypropylene Fibers; Geopolymer construction

1. Introduction

The exploration of geopolymer materials has significantly increased in recently due to their potential as sustainable alternatives to traditional Portland cement, whose production is responsible for nearly 8% of global CO₂ emissions and high energy consumption. By utilizing industrial by-products such as fly ash (FA) and calcined clays like metakaolin (MK), geopolymers not only reduce greenhouse gas emissions but also divert large volumes of waste from landfills, contributing to a circular economic approach in construction. Several life-cycle assessment (LCA) studies have confirmed that geopolymer binders can cut embodied CO₂ emissions by 40–80% compared to Portland cement, depending on precursor type and curing regime, while also lowering cumulative energy demand. These sustainability advantages underpin their growing consideration for structural and infrastructure applications.

Beyond their environmental benefits, extensive research has been dedicated to investigating the mechanical properties, durability, and reinforcement techniques of geopolymer composites, particularly those based on MK and FA. Fiber reinforcement, especially with polypropylene (PP) fibers, has emerged as an effective strategy for enhancing both performance and service life. Polypropylene fibers were selected due to their chemical stability in highly alkaline media, low cost, commercial availability for field repair mortars, and proven crack-bridging function in brittle cementitious matrices. High-modulus synthetic fibers such as polyethylene or PVA can provide higher tensile stiffness, but they are generally more expensive and may have different interfacial behavior in aluminosilicate gels. This study focuses on PP fibers as a practical, industry-used option for improving ductility in geopolymer repair and overlay applications. R. Y. Nkwaju et al. [1] highlighted the improvements in mechanical and durability characteristics of alkaline cement mortars reinforced with PP fibers, emphasizing their thermal and synthesis properties within phosphoric acid-based geopolymers utilizing MK.

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Similarly, B. Figiela et al. [2] demonstrated the effectiveness of fiber reinforcement in improving the performance of low-density MK geopolymers and basalt fiber-reinforced FA geopolymer composites under extreme conditions, such as simulated fire exposure.

R. Manimaran et al. [3] provided a comprehensive review of FA-based fiber reinforced geopolymer composites, noting their superior tensile and compressive properties and identifying a need for systematic structure-property correlations in the literature. FA is emphasized as an economical material that can be used to enhance concrete performance and has wide industrial applications. S. P. Arredondo et al. [4] further supported these findings by demonstrating how optimal PP fiber content in fly ash-based geopolymers significantly improves mechanical strength and reduces shrinkage, emphasizing the environmental advantages of these composite materials. And PP fibers addition increased splitting tensile strength by ~40% compared with unreinforced geopolymer mortar.

Additionally, [5] explored the enhancement of mechanical properties and durability in FA-based geopolymers by incorporating ground walnut shells, illustrating the importance of organic additives in promoting sustainable construction practices. This approach notably reduces micro-cracking and enhances the structural integrity and corrosion resistance of the material. R. Gailitis et al. [6] underscored the long-term benefits of fiber reinforcement, demonstrating its capability to reduce creep and shrinkage in FA based geopolymers, crucial for structural applications.

I. J. R. Dollente et al. [7] further expanded the practical applications of fiber-reinforced geopolymers, exploring their use in historical masonry restoration. They emphasized the adaptability of geopolymer composites for cultural heritage preservation due to their enhanced durability and mechanical performance. T. A. Hussein et al. [8] conducted an extensive review highlighting the synergistic effects of polyester fibers and nano silica on enhancing the chemical resistance and microstructural durability of geopolymer concrete and PP fibers specifically offer several benefits, including enhanced tensile strength, reduced shrinkage cracking, improved durability under environmental stresses, and increased resistance to impact and abrasion [9, 10]. And for higher NaOH molarity (10M–12M) improved compressive strength but also increased brittleness. For structural and repair applications, geopolymer materials must resist not only compressive loads but also crack initiation and crack propagation under bending and tension. Flexural and splitting tensile strength are therefore critical performance indicators for serviceability, ductility, and crack control in beams, overlays, and thin repair layers. Because geopolymers are typically brittle, fiber reinforcement is used to increase post-cracking load capacity and energy absorption [11].

In summary, prior studies show that fiber reinforcement is essential for improving the structural viability of geopolymer composites. The addition of polypropylene, polyester, steel, and natural fibers has been shown to increase flexural and tensile strength, enhance post-cracking behavior, and improve resistance to impact, shrinkage, and chemical attack. These mechanical and durability gains, combined with the lower embodied carbon of FA- and MK-based binders, position fiber-reinforced geopolymers as a promising class of eco-efficient, crack-resistant materials for structural repair and infrastructure applications. Despite these advances, there is still limited clarity on how fiber type, and mixture chemistry (e.g., FA vs. MK precursors and alkaline activator concentration) interact to control strength and ductility in geopolymer composites. The present study addresses this gap by evaluating the mechanical performance of polypropylene fiber-reinforced geopolymer mixes and examining their suitability for structural and repair applications.

1.1 Research Objective

This study aims to clarify the role of PP fibers in improving the mechanical response of geopolymer concretes produced from fly ash (FA) and metakaolin (MK) under different alkaline molarity levels (8M, 10M, and 12M). Unlike prior work that reports general improvements with fiber addition, this research focuses on the comparative effectiveness of PP fibers in FA-versus MK-based matrices, with emphasis on tensile performance, flexural capacity, and crack resistance. The objective is to determine whether PP fibers can compensate for the inherent brittleness of MK systems and to quantify the strength–ductility balance achieved in FA systems. Additionally, the study incorporates Monte Carlo simulations to model variability in compressive strength, thereby providing probabilistic insights into the reliability of fiber-reinforced geopolymers. By addressing both performance enhancement and variability, the research seeks to establish FA–PP composites as a credible structural alternative while identifying pathways to strengthen MK-based geopolymers.

1.2 Research Plan

This research employs PP fibers alongside MK and FA in the development of geopolymer concrete mixes activated by alkaline solutions of varying molarities (8, 10, 12). The study conducts a comprehensive evaluation of the resulting geopolymer mixes through mechanical tests, including compressive strength, flexural strength, and splitting tensile strength, as well as durability tests like water absorption and porosity. Advanced characterization techniques such as scanning electron microscopy (SEM), X-ray diffraction (XRD), X-ray fluorescence (XRF), and Transmission electron microscopy (TEM) are used to examine the microstructural properties of the geopolymer composites, providing insights into the bonding mechanism between PP fibers and the geopolymer matrix.

2. Experimental Work

2.1 (Raw Materials for Geopolymer Concrete and Methods)

In-depth and comprehensive research is being planned to conduct practical trials focused on the utilization of waste materials, specifically pottery powder (MK) and FA, which are recognized as significant environmental challenges. These materials are often disposed of in rural areas, leading to numerous environmental problems. To address this time-sensitive issue, experimental investigations are currently underway, with a primary focus on the waste material derived from pottery production, known as meta-kaolin. This research, taking place in the industrial context of Egypt, aims to pave the way for innovative geopolymer solutions. The core of this research involves intentionally mixing MK and FA, all with the help of an alkaline solution an essential aspect of this study. A major focus of the study is the integration of PP fibers. The overall goal is to develop a comprehensive understanding of the interaction between MK and FA, and the addition of PP fibers. As shown in

Fig. 1, this research covers a broad range of materials crucial to the creation of geopolymers, highlighting the multifaceted nature of this groundbreaking field.

Justification of test methods. Compressive strength was selected to quantify fundamental load-bearing capacity; three-point flexural strength to assess crack initiation and post-cracking response in bending; and splitting tensile strength to evaluate tensile resistance and fiber-mediated load transfer. SEM/TEM and XRD were employed to correlate mechanical trends with matrix densification, porosity, and phase assemblage. A Monte Carlo simulation of compressive strength distributions was performed to assess performance reliability across precursor type, molarity, and fiber addition.

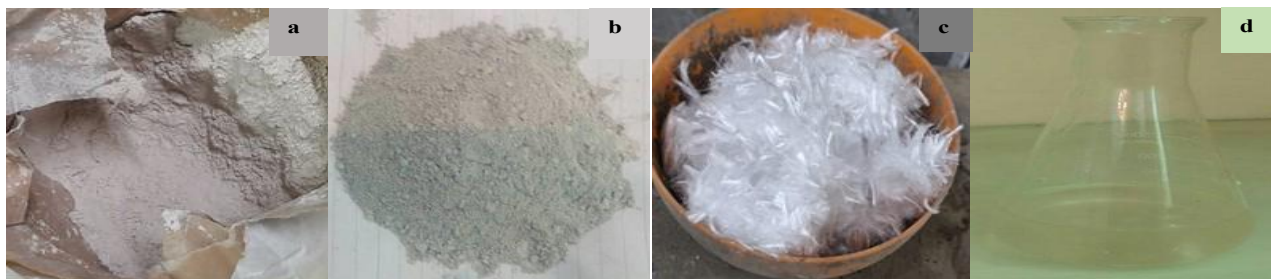


Fig. 1. Geopolymer Composite materials (a-Meta-kaolin, b-Fly ash, c-Polypropylene fiber, d-Alkaline Activator Solution)

2.2 Characteristics of Different Materials

The incorporation of materials that support the economical production of geopolymer concrete is highly significant in today's construction methods. The key ingredients utilized for this purpose involve a carefully chosen set of materials. The subsequent sections will explore the characterization of these materials in detail.

a. Meta-Kaolin Powder

MK, which is prepared by calcining kaolin at 800°C, significantly influences the pore structure of concrete. Its high dissolution rate in alkaline activator solutions and the ability to control the silicon-to-aluminum ratio, along with its brownish color, make it a preferred material for geopolymer production. Additionally, silica-rich kaolin has been used as a raw material for geopolymer concrete by “EL-GIARA”, (Thermal insulation factory, Asfour) in Old Cairo, Cairo.

b. Fly Ash Powder

The primary raw material for geopolymer concrete is FA sourced from coal-powered plants, Low-calcium FA (Class F) characterized by its spherical aluminosilicate particles and high oxide content. With 47.81% SiO_2 and 22.80 % Al_2O_3 , this fly ash is particularly suited for geopolymerization, enhancing both the structural and chemical properties of the resulting material. The fly ash powder was supplied by “Hemts Construction Chemicals”, located in El-Maadi, Cairo, Egypt.

c. PP Fibers

PP fiber is a widely used synthetic polymer due to its low cost, durability, and adaptability across industries, including construction and packaging. Its popularity stems from its ability to be customized using copolymers, additives, or fillers to meet specific application needs. However, the diverse properties of PP packaging waste create challenges in recycling, as the waste stream contains a mix of stiff, brittle, soft, and tough materials. PP fibers were incorporated at a dosage of 900 g per m^3 of concrete "PP fibers, supplied by the Egyptian European Steel Fiber Company (EESF, First Settlement, Cairo, Egypt), were added at a dosage of 900 g/ m^3 of concrete (equivalent to 0.225% of the binder weight). The fiber dosage of 900 g/ m^3 was selected based on the optimum range specified in the manufacturer's specifications for one cubic meter, which balances workability and compressive strength after crushing. Initial tests have indicated that fiber contents higher than this value result in reduced flowability without further increase in compressive strength.

d. Alkaline Activator Solution

The activation of this material blend is facilitated using alkaline activators, namely sodium silicate and sodium hydroxide with different molarities (8,10,12 Molars). The alkaline solution consists of sodium silicate (water glass) Na_2SiO_3 , available in liquid form, and sodium hydroxide NaOH, available in flakes. $\geq 98\%$ purity supplied by (El-Nasr Chemicals Company), located in Downtown, Cairo, Egypt.

e. Aggregates (Coarse and fine)

Fine aggregate with a maximum particle size of 4.75 mm was sourced from quarries near the Giza Pyramids, while dolomite based coarse aggregate with a nominal maximum size of 19 mm brought from “Ataqa area near Suez city” was also utilized. Standard tests were conducted to determine the absorption properties of the aggregates. Coarse aggregate showed an absorption rate of 0.65%, meeting the permissible range of (0.5% - 1%) [12]. For fine aggregate, the percentage of clay and other fine particles by volume was found to be 1.67%, remaining within the allowable limit of less than 3% [13].

2.3 Sieve Analysis

A comparison of the sieve analysis grading curve for the selected aggregates confirmed that the total weight of the coarse aggregate aligns with the values obtained from the sieve analysis curve. These results comply with the guidelines outlined in the Egyptian Code (Laboratory Testing Guide), [14]. Additionally, The Maximum Nominal Aggregate size was determined to be “19 mm”, as shown in Fig. 2.

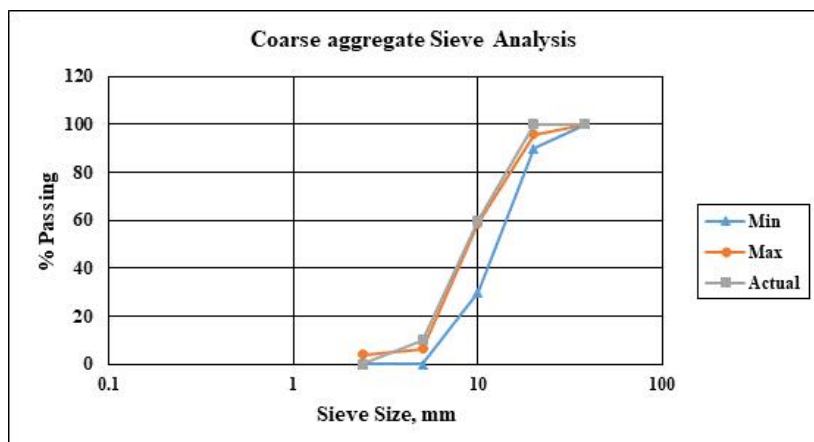


Fig. 2: Gradation Curve of Coarse Aggregate

2.4 Assessment of Precursor (Chemical Analysis of Precursor)

Table. 1 summarizes the average chemical composition of MK produced through the thermal processing of pottery powder waste, sourced from cyclones in the pottery industry at 800°C. Additionally, it highlights the chemical composition of fly ash formed during the combustion of pulverized coal in power plants. Both MK and FA were meticulously examined using X-ray fluorescence (XRF) and wavelength-dispersive X-ray fluorescence (WD-XRF) sequential spectrometry to determine their chemical makeup. The findings in Table 1 reveal that silica (Si) and aluminum (Al) are the predominant elements, with smaller amounts of sodium (Na), potassium (K), and calcium (Ca). Moreover, Tables 2 and 3 detail the physical properties of MK, fly ash, and PP fibers. Table (2) and Table (3) presented the physical properties of meta-kaolin, FA and PP fibers.

Table 1: Chemical Analysis of (Meta-Kaolin, and Fly Ash)

%Compound	Meta-kaolin	Fly Ash
SiO ₂	57.16	64.71
TiO ₂	2	1.43
Al ₂ O ₃	26.15	25.42
Fe ₂ O ₃	4.79	4.19
MnO	0.02	0.03
CaO	4.44	1.12
Na ₂ O	0.03	0.02
K ₂ O	0.47	0.89
P ₂ O ₅	0.07	0.24
Cl	0.21	0.04
SO ₃	0.65	0.23
MgO	0.26	0.27
Loss of Ignition (LOI)	3.44	0.33

Table 2: Physical properties of (Meta-kaolin and Fly Ash)

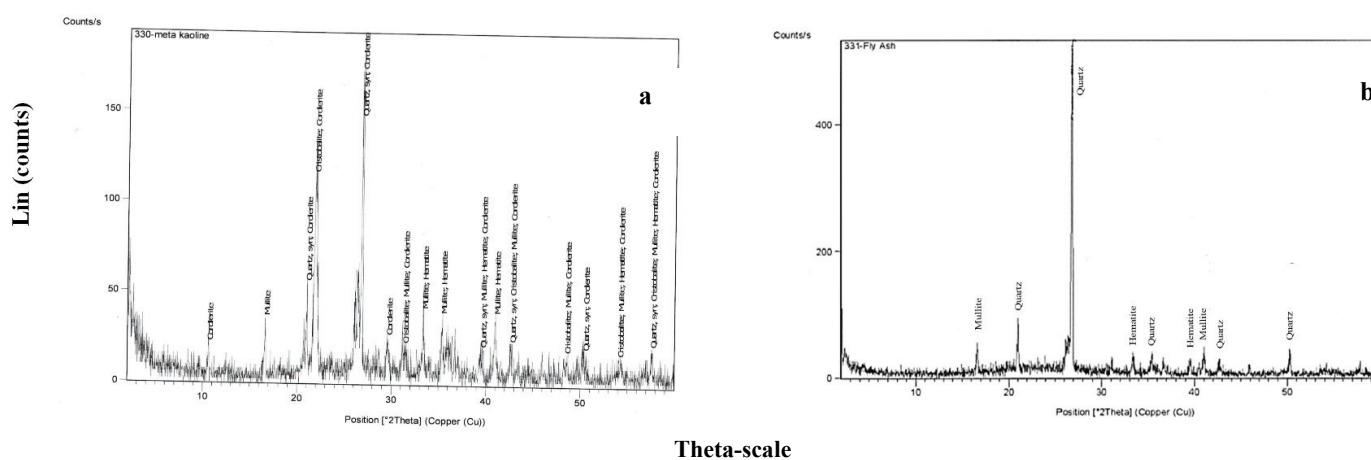
Physical properties	Fly Ash	Meta-kaolin
Presentation	Finely divided dry powder	Finely divided dry powder With Refractoriness = 1730°C
Colour	Light grey	Brownish
Bulk Weight	0.9 metric ton per cubic meter	Porosity ≤ 6%
Specific Density	2.3 metric ton per cubic meter	2.52 gm / cm ³
Particle Size	90% < 45 micron	< 50 nm = 0.5 % Max
Particle Shape	Spherical	Spherical

Table 3: physical properties of Polypropylene Fibers

Fiber Type	Tensile Strength (Mpa)	Young's Modules (Mpa)	Ultimate Elongation (%)	Length (L)	Diameter (D)
Polypropylene fiber	400 - 600	3.45	15 - 25	12 mm	30 μm

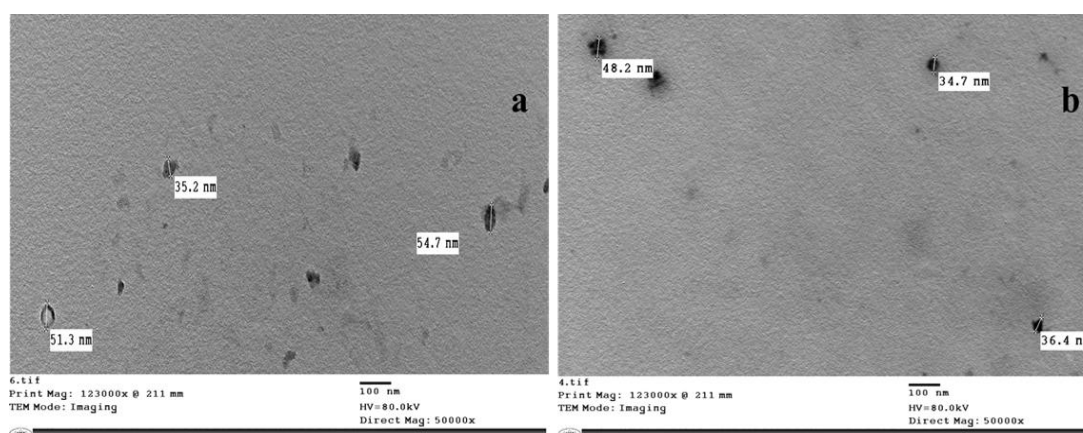
2.5 Mineralogical Analysis of Raw Materials

The examination of the crystalline phases in meta-kaolin powder and FA was conducted through X-ray diffraction (XRD) analysis of their chemical compositions. The results revealed the predominant presence of quartz and manganite in meta-kaolin and FA, as illustrated in Fig. 3 This observation signifies that both fly ash and meta-kaolin are predominantly composed of amorphous silica. "XRD patterns for FA-based mixes showed a broad amorphous hump between $\sim 20^\circ$ and 35° 2θ , consistent with formation of N-A-S-H gel, while MK mixes retained sharper residual crystalline features, suggesting incomplete dissolution and less uniform geopolymerization under the same curing conditions. This supports the lower mechanical efficiency observed in MK systems."

**Fig. 3: XRD Pattern of (a) Meta-Kaolin, and (b) Fly ash**

2.6 Transmission Electron Microscope (TEM)

TEM micrographs show that the MK particles are predominantly near spherical, but many are clustered into larger agglomerates. These clumps can hinder uniform dispersion in fresh concrete, weakening interfacial transition zones and overall mechanical performance. Fig. 4b shows that FA particles are still revealed near spherical. The FA is mostly discrete spheres spanning a wide range, such heterogeneity allows finer particles to pack into voids between larger ones, potentially densifying and strengthening the concrete matrix. Spherical geometry generally improves workability by lowering inter-particle friction, yet the observed size disparity and agglomeration indicate that it requires particle-size control and effective dispersion methods to fully exploit FA in high-performance concretes.

**Fig. 4: Transmission Electron Microscope (TEM) of (a) Meta-Kaolin, and (b) Fly ash**

2.7 Mix Proportion

Mixtures were carried out to impact the effects of incorporating various environmental pollutants into concrete. Alkaline activators are included in each mixture, acting as a dissolver in a (1:3) solution of Na_2SiO_3 and water. Three different concentrations of Na_2O (8, 10 and 12 Molar) were employed, and Water-To-Binder Ratio (W/B) was set to 0.35 as illustrated in Table. 4.

Table 4: Mix proportions for samples per m^3

Mixes	No	FA (kg)	MK (kg)	Sand (kg)	Gravel (kg)	Na_2O (Molar)	Alkaline Ratio ($\text{NaOH}:\text{Na}_2\text{SiO}_3$)	NaOH (kg)	Na_2SiO_3 (kg)	Fibers PP (kg)	Age (days)	Water (L)
Mix	1	400	-	509.82	948.27	8	1:3	32.55	103.23	-	14+28	140
Witho	2	400	-	482.25	896.99	10	1:3	40.7	129	-	14+28	140
ut	3	400	-	455.5	847.25	12	1:3	48	154.8	-	14+28	140
Fibers	4	-	400	525.1	976.66	8	1:3	32.55	103.23	-	14+28	140
(contr	5	-	400	497.5	925.39	10	1:3	40.7	129	-	14+28	140
ol)	6	-	400	470.79	875.67	12	1:3	48	154.8	-	14+28	140
	1	400	-	509	947	8	1:3	32.55	103.23	0.9	14+28	140
Mix	2	400	-	481	895	10	1:3	40.7	129	0.9	14+28	140
With-	3	400	-	455	846	12	1:3	48	154.8	0.9	14+28	140
PP	4	-	400	524	975	8	1:3	32.55	103.23	0.9	14+28	140
Fibers	5	-	400	498	926	10	1:3	40.7	129	0.9	14+28	140
	6	-	400	470	874	12	1:3	48	154.8	0.9	14+28	140

Note: W/b = Water-To-Binder Ratio, MK= Meta-kaolin, FA = fly ash, PP = Polypropylene Fiber, NaOH: Na_2SiO_3 = Sodium hydroxide: Sodium Silicate, Fa: Ca = Fine aggregate (Sand): Coarse aggregate (Gravel), M= Molarity

3. Preparation, Curing, and Testing of Geopolymer Concrete

3.1 Preparation of Alkaline Solution

This experimental study examines the properties of geopolymer concrete using sodium hydroxide (NaOH) solutions with molarities of 8M, 10M, and 12M. For the 8M solution, 320 grams of NaOH pellets are dissolved in distilled water to achieve a one-liter concentration, maintaining a 1:3 ratio of sodium silicate to sodium hydroxide solution. The mixture is stored for 24 hours at $25 \pm 2^\circ\text{C}$ and 65% relative humidity to dissipate heat from the exothermic dissolution process, ensuring the solution reaches ambient temperature before being used in the concrete mix. The preparation of fiber-reinforced geopolymer concrete involves mixing dry materials (FA/MK, aggregates, and PP fibers) for approximately 2 minutes to ensure homogeneity, followed by the gradual addition of the alkali activator (NaOH and sodium silicate solution). Wet mixing is then continued for an additional 3–4 minutes until a uniform consistency is achieved, as explained in Fig. 5. The fresh mix is then cast and cured at elevated temperatures ($60\text{--}80^\circ\text{C}$) to enhance strength and durability. The following subsections will discuss the preparation of the curing process

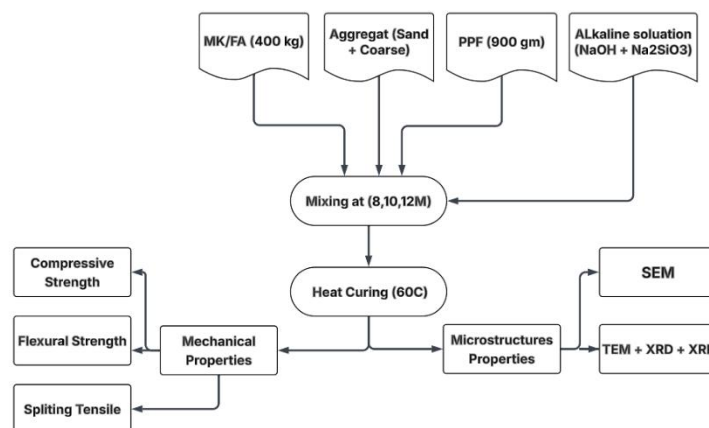


Fig. 5: Preparation Procedure of Geopolymer Concrete with Fibers.

3.2 Curing of GPC Specimens

The slump of fresh concrete was measured immediately after mixing. Standard molds were used to cast $150 \times 150 \times 150$ mm cubes (compressive strength), 150×300 mm cylinders (splitting tensile), and $100 \times 100 \times 500$ mm prisms (three-point flexural). For each mix and each property, six ($n = 6$) replicate specimens were tested. After casting, specimens were oven-cured at 60°C for 24 hours to accelerate geopolymerization and ensure adequate early strength development, a practice

widely reported in FA and MK based systems where ambient curing often results in incomplete reaction due to lower dissolution of aluminosilicate species [15]. Following oven curing, specimens were stored at room temperature until their designated curing ages of 14 and 28 days. Curing was carried out for 14 days because the geopolymer concrete mixtures, influenced by the alkaline activator solution, required a longer time to harden adequately. The presence of sodium hydroxide and sodium silicate tends to slow down the setting process in some mixes, especially at certain molarities, leading to delayed strength gain. Therefore, extending the curing period to 14 days ensured that the specimens achieved sufficient hardening and stable mechanical properties before testing. Although heat curing enhances mechanical performance and provides consistent results, it may limit the sustainability and practicality of large-scale applications. Therefore, this regime was adopted here primarily for research purposes to establish baseline mechanical behavior, while future work should investigate ambient or low energy curing methods to better align with sustainability goals. After oven curing at 60 °C for 24 h, specimens were demolded and stored at ambient laboratory conditions (25 ± 2 °C, relative humidity $\approx 60\%$) for 14 and 28 days before testing. This study used a 60 °C / 24 h curing regime to obtain a consistent mechanical baseline for fly ash- and metakaolin-based geopolymer mixes, with and without PP fibers. While this accelerated curing approach is common in laboratory geopolymer research, it is recognized that large-scale implementation can require ambient or mild curing. Previous studies have shown that geopolymer concretes can achieve acceptable mechanical performance and durability under ambient curing conditions, confirming the feasibility of low temperature curing for field applications [16], [17].

3.3 Slump (Fresh properties)

The results of the slump test conducted on the PP fiber-reinforced geopolymer concrete showed that the slump generally increased with higher alkali solution molarity (from 8M to 12M) for both FA and MK mixtures. This indicates that at higher molarities, the mixture becomes less viscous, improving workability. However, the incorporation of PP fibers reduced slump compared to mixes without fibers, as the fibers increased internal friction and acted as physical bridges that restricted flow. The highest slump value was recorded at the highest molarity of the alkali solution (12M), as shown on Fig. 6.

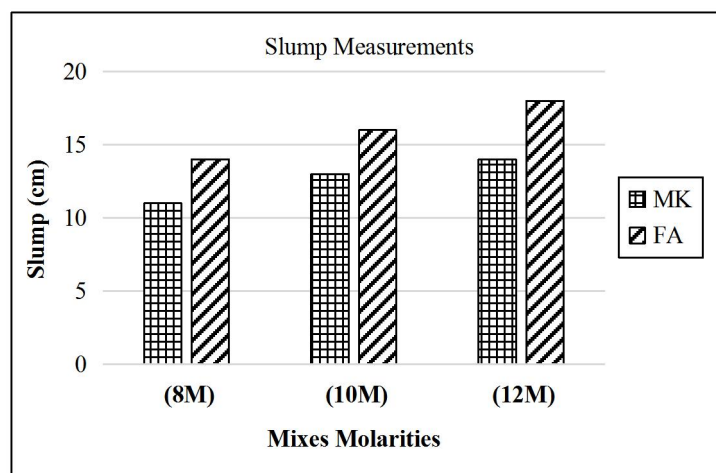


Fig 6: Sample Test Results of Slump

4. Results and Discussion (Mechanical Properties of Geopolymer)

4.1 Compressive Strength (f_c)

Fig 7. illustrates the 28-day compressive strength performance of geopolymer concretes formulated using FA and MK as aluminosilicate precursors, under three different sodium hydroxide molarities are (8M, 10M, and 12M) Subfigure 6a shows the compressive strength of geopolymer concrete without PP fibers, while subfigure Fig 7b presents the corresponding values with the inclusion of PP fibers. The results reveal that FA-based geopolymer concretes consistently demonstrate higher compressive strength compared to their MK-based counterparts across all molarity levels, both with and without fiber reinforcement.

In the absence of PP fibers, Fig. 7a, FA based systems exhibited a steady increase in compressive strength with increasing molarity, reaching 214 kg/cm², 250 kg/cm², and 300 kg/cm² for 8M, 10M, and 12M solutions at the age of 28 days, respectively (1 MPa = 10.1972 kg/cm²). In contrast, MK-based systems showed substantially lower strength values under the same conditions, with only 28 kg/cm² at (8M), 61 kg/cm² at 10M, and 110 kg/cm² at 12M at the age of 28 days. These findings indicate that FA is more reactive and conducive to geopolymerization under alkaline activation, leading to the development of stronger and denser matrices. This trend aligns with the findings of Temuujin et al. [15], who reported a marked increase in compressive strength of FA based geopolymers with increased alkali molarity, due to the enhanced dissolution of silica and alumina species facilitating polycondensation reactions

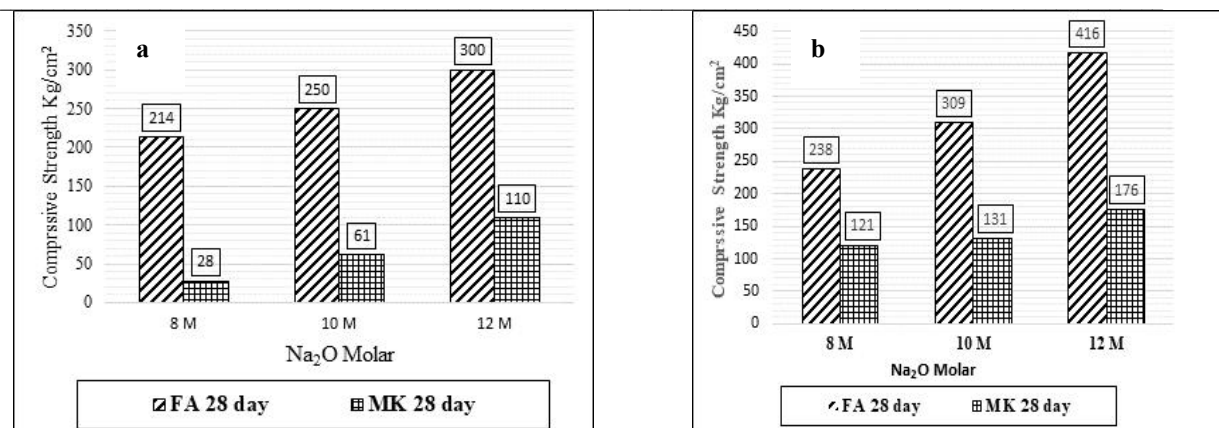


Fig 7: Compressive strength values for FA and MK (a) Without PP fiber, (b) With PP Fiber

In subfigure 7b, the addition of PP fibers significantly improves the compressive strength of both FA and MK geopolymer concretes. For MK, the strength rises from 121 kg/cm² at 8 M to 176 kg/cm² at 12 M, while for FA, it increases from 238 kg/cm² to 416 kg/cm². The incorporation of PP fibers likely enhances the tensile properties and crack resistance of the geopolymer matrix, leading to improved compressive strength by mitigating micro-crack propagation. Additionally, Ranjbar et al. [18] demonstrated that the addition of PP fibers to geopolymer concrete can increase compressive strength by up to 30%, consistent with the observed trends in subfigure 6b. The more pronounced improvement in MK samples with PP fibers may be attributed to better fiber-matrix bonding in the denser MK geopolymer structure. These findings align with existing research. A study by J. L. Provis et al. [19] reported that FA-based geopolymers typically exhibit higher compressive strength than MK-based ones due to differences in their aluminosilicate composition and reactivity. The effect of molarity on strength development is also supported by [20], who noted that higher alkali concentrations enhance the dissolution of aluminosilicate precursors, leading to stronger geopolymer networks.

T. Porpadham et al. [21] reviewed the effect of fiber reinforcement in geopolymer concrete and found that adding up to 0.8% PP fibers increased compressive strength in FA based geopolymer concrete, although the improvement was less pronounced than with steel fibers. They also noted that the enhancement in compressive strength is most significant at optimal fiber contents, typically below 2% by volume. R. Abufarsakh et al [22] reported that the inclusion of PP fibers (optimal at 0.5% by volume) in geopolymer concrete led to an increase in compressive strength compared to mixes without fibers. Their results confirm that fiber reinforcement, especially with polypropylene, can enhance the mechanical properties of geopolymer concrete.

4.2 Flexural Strength

Fig. 8 presents the flexural strength values of FA and MK geopolymer concrete tested using the four-point bending method at 8M, 10M, and 12M alkali molarity. The results are categorized into two subfigures. Fig. 8a shows the Flexural strength of FA and MK without PP fibers, while Fig. 8b represents Flexural strength of FA and MK with PP fibers. The results indicate that FA-based geopolymers exhibit significantly higher flexural strength compared to MK-based geopolymers across all molarities. In Fig. 8a, without fibers, FA geopolymer shows a steady increase in flexural strength with molarity, reaching a peak of 33 kg/cm² at 12M, while MK geopolymer remains significantly lower, achieving only 5.5 kg/cm² at 12M. In Fig. 8b with PP fibers, FA geopolymers show an even more pronounced increase in flexural strength, with the 12M sample reaching 62 kg/cm², almost double the fiber-free equivalent. MK geopolymer, on the other hand, experiences only a minor increase in flexural strength after fiber inclusion, with the 12M sample reaching 9 kg/cm².

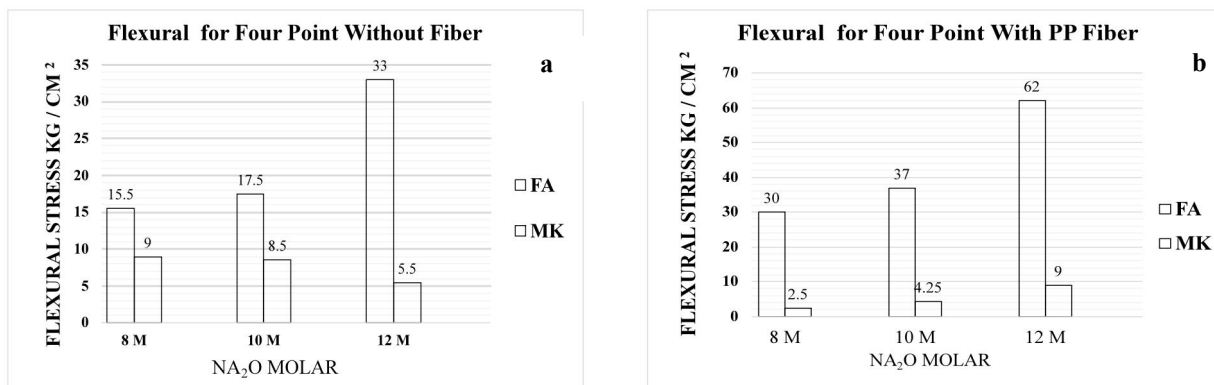


Fig 8: Flexure strength ultimate load values for FA and MK (a) Without PP fiber, (b) With PP fiber

The results highlight the contrasting effects of PP fibers on FA and MK geopolymers. In FA-based geopolymers, the addition of PP fibers greatly enhances flexural strength, particularly at higher molarity levels. The increase in flexural strength with molarity can be attributed to stronger geopolymerization reactions at higher alkaline concentrations, which improve matrix integrity and fiber adhesion. Similar findings have been reported by [23], who demonstrated that higher molarity levels contribute to better fiber-matrix interaction, improving flexural properties in fiber-reinforced geopolymer composites. In contrast, MK-based geopolymers show limited improvement in flexural strength with PP fiber reinforcement. The minor increase in strength suggests that PP fibers do not form strong bonds with the inherently porous MK matrix, resulting in weak interfacial adhesion and ineffective load transfer. Studies such as [24] have shown that MK geopolymers require alternative reinforcement strategies, such as surface-treated fibers or hybrid fiber systems, to achieve significant flexural strength improvements. The inverse trend observed in MK geopolymers, where flexural strength increases with fiber addition but remains relatively low, is likely due to the brittle nature of MK geopolymer networks, which limits their ability to sustain tensile stress effectively. The findings also indicate that flexural strength is more sensitive to fiber reinforcement than compressive strength, particularly in FA-based geopolymers. The improvement in flexural properties with PP fibers aligns with observations in conventional fiber-reinforced concrete, where fibers contribute more significantly to tensile and bending resistance rather than compressive performance. According to [22], fiber-reinforced composites typically show a 30–80% increase in flexural strength, depending on fiber content and matrix properties. The 100% increase in FA-based geopolymer flexural strength at 12M (from 33 kg/cm² to 62 kg/cm²) suggests that PP fibers are highly effective in enhancing flexural performance in well-compacted matrices.

4.3 Indirect Tension Strength (Splitting Tensile Strength)

Fig. 9 presents the Indirect Tension Strength (Splitting Tensile Strength) test results for FA and MK based geopolymer concrete under two conditions: without PP fibers (Fig 9a) and with PP fibers (Fig 9b). The results are plotted for three different molarity levels (8M, 10M, and 12M). The y-axis represents the splitting tensile strength in kg/cm², while the x-axis shows the molarity levels. The bars illustrate the performance of FA-based and MK-based geopolymer concrete, with separate markers indicating their respective strengths. From Fig. 9a, the splitting tensile strength without PP fibers is relatively low for both FA and MK samples, with FA showing higher values than MK at all molarity levels. The tensile strength increases slightly with molarity, peaking at 8.8 kg/cm² for FA at 12M, while MK remains below 2 kg/cm². In contrast, Fig. 9b demonstrates a significant improvement in tensile strength with the inclusion of PP fibers, particularly for FA-based geopolymer concrete. The highest recorded strength reaches 20.4 kg/cm² FA with 12M with PP fibers, while MK-based geopolymer also sees an increase, with a maximum of 4.9 kg/cm² at 12M.

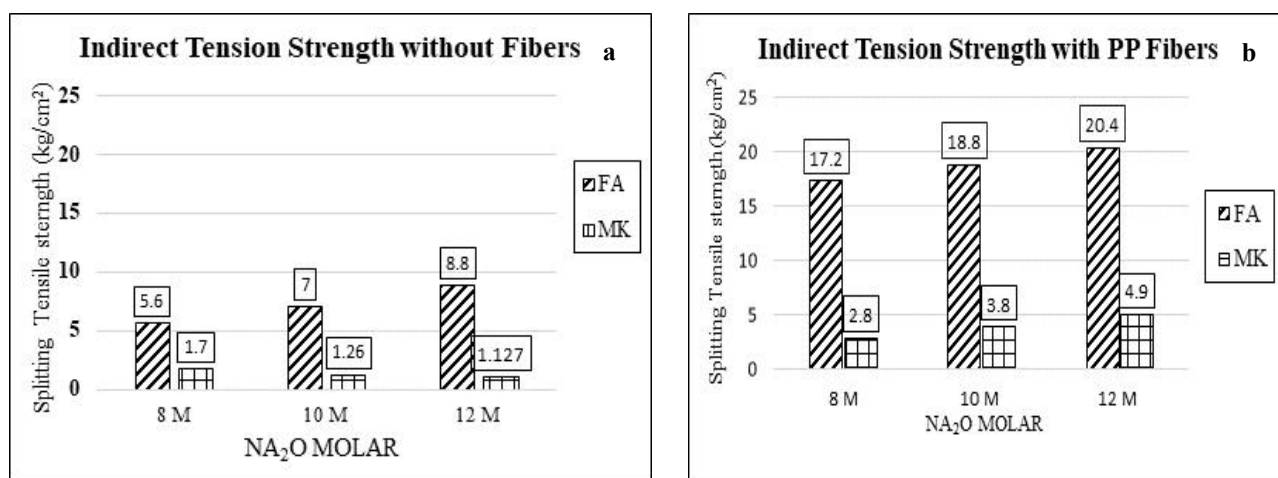


Fig. 9: Indirect Tension Strength values for FA and MK (a) Without PP fiber, (b) With PP fiber

The results of the splitting tensile strength tests confirm that FA based geopolymer concrete consistently outperforms MK-based geopolymer concrete, both with and without PP fibers. This indicates that FA-based geopolymers tend to form a more cohesive matrix, enhancing tensile resistance. The gradual increase in tensile strength with molarity suggests that higher Na₂O concentrations promote better geopolymerization, leading to stronger bond formation and improved tensile capacity [23, 14]. The addition of PP fibers significantly improves the splitting tensile strength for both FA and MK samples, particularly in FA-based geopolymer concrete. The FA sample with 12M - Na₂O exhibits a 2.3× increase in tensile strength (8.8 kg/cm² → 20.4 kg/cm²) with PP fibers, highlighting the beneficial role of fiber reinforcement in crack bridging and stress distribution [26]. This improvement can be attributed to the ability of PP fibers to control microcracks, delaying crack propagation and thus enhancing tensile resistance. For MK-based geopolymer concrete, although PP fibers increase the splitting tensile strength, the absolute values remain considerably lower than those of FA-based samples. The highest recorded strength for MK at 12M with PP fibers (4.9 kg/cm²) is still lower than that of FA at 8M without fibers (5.6 kg/cm²). This

suggests that MK-based geopolymer concrete has a more brittle nature, with lower tensile resistance due to its denser microstructure and weaker fiber-matrix interaction. This observation aligns with findings from previous research [27], which emphasize that MK-based geopolymers require additional modifications, such as hybrid fiber reinforcement or alternative curing methods, to achieve substantial tensile improvements. FA-based systems outperformed MK-based systems across all metrics, particularly when PP fibers were added. This behavior is attributed to two coupled factors first Low-calcium (Class F) FA typically contains a high proportion of amorphous aluminosilicate glass, which dissolves readily under high-alkaline activation (10M–12M NaOH), producing a continuous sodium aluminosilicate hydrate (N-A-S-H) gel. This dense gel phase improves load transfer and supports effective crack bridging by PP fibers. Second MK-based systems, while reactive, often develop a more heterogeneous matrix with local micro voids and early microcracking under the same curing regime, which reduces the efficiency of fiber anchorage and limits gains in flexural and splitting tensile strength.

5. Statistics Analysis of Compressive Strength Results (Monte Carlo Simulation Method)

To assess the reliability of the experimental results and capture variability beyond average values, a Monte Carlo simulation was applied using the experimental compressive strength data of FA- and MK-based geopolymer concretes reinforced with PP fibers. The simulation was performed by fitting the experimental strength results at each molarity (8M, 10M, 12M) to a normal distribution and then generating 10,000 random samples for each case. Compressive strength was selected as the key parameter because it is the most widely adopted performance criterion for structural concrete and showed the clearest distinction between FA and MK systems in the experimental programme. And Probabilistic modeling is particularly valuable in the context of geopolymer concretes, where reaction kinetics are highly sensitive to activator molarity and precursor chemistry, leading to variability that cannot be fully captured by average values alone. Monte Carlo simulation was implemented using Python (NumPy random sampling over 10,000 iterations) to model compressive strength variability based on the experimental mean $\pm$ standard deviation. The probability distribution allowed estimation of the confidence level associated with achieving target strength, providing a quantitative measure of structural reliability.

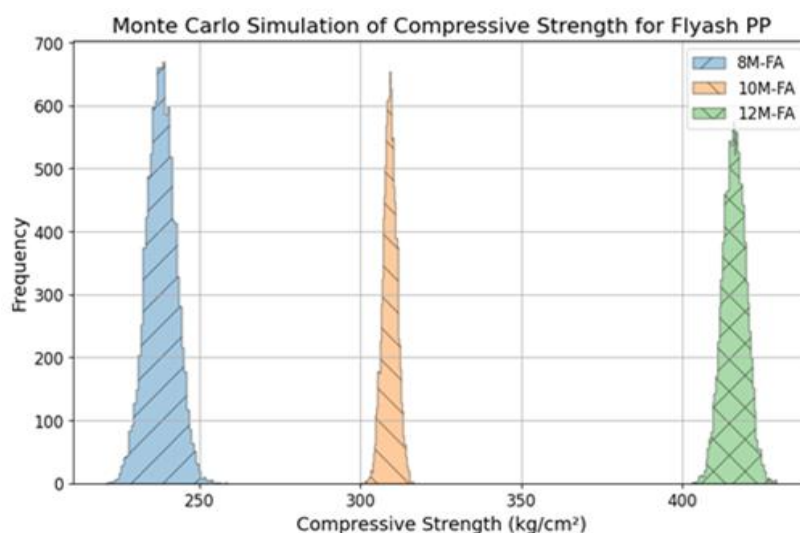


Fig 10: Monte Carlo Compressive Strength for FA – PP

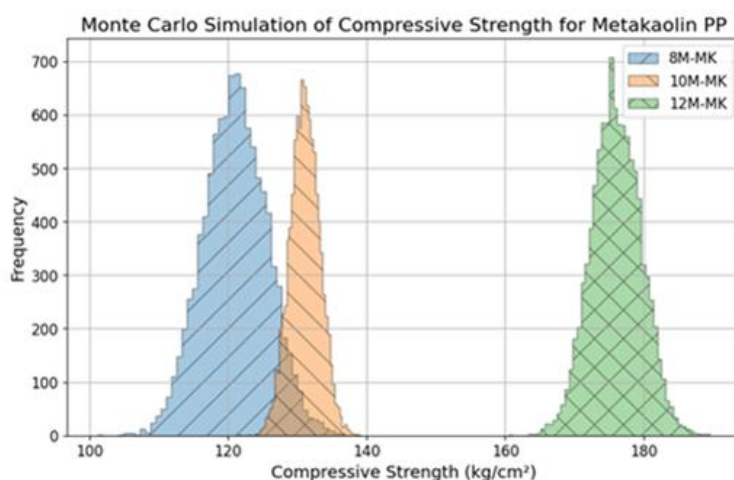


Fig 11: Monte Carlo Compressive Strength for MK – PP

The simulation was performed by fitting the experimental strength results at each molarity (8M, 10M, 12M) to a normal distribution and generating 10,000 random samples for each case. Compressive strength was selected as the key parameter because it was the most widely adopted structural performance criterion and showed the clearest distinction between FA and MK systems in the experimental program. The resulting probability distributions Fig. 10,11 highlight differences in performance stability. For FA-based mixes Fig. 10 the 8M system showed a narrow distribution (200–240 kg/cm²), reflecting consistent performance with low variability. At 10M, the distribution widened slightly (300–310 kg/cm²), while the 12M mix achieved the highest strengths ($\approx$ 400–420 kg/cm²) but with greater spread, indicating increased variability due to stronger but less uniform reaction kinetics. In contrast, MK-based systems Fig. 11 consistently showed lower compressive strength ranges (120–180 kg/cm²) with broader overlapping distributions, confirming their weaker reactivity and higher uncertainty compared to FA mixes. Probabilistic modeling complements deterministic testing by quantifying reliability. For instance, the 12 M FA–PP mix showed > 90% probability of exceeding 400 kg/cm², confirming its suitability for structural applications. This statistical approach provides insights directly relevant to practical applications, as it quantifies the likelihood of achieving a target compressive strength at a given molarity. It demonstrates that FA-based systems not only achieve higher mean strength but also greater reliability at lower molarity levels (8M), while MK-based systems exhibit larger uncertainty regardless of molarity. Moreover, it highlights that while higher molarity increases strength, it may also increase variability, which has implications for mix design optimization and quality control in real-world construction. Future studies should extend this probabilistic modeling to other mechanical properties (flexural and tensile strength) and incorporate durability data, providing a more comprehensive reliability assessment of fiber-reinforced geopolymers.

6. SEM Analysis

The SEM images presented in Fig. 12a, 12b and Fig. 13a, 13b illustrate the microstructural characteristics of MK and FA geopolymer matrices with and without PP fibers reinforcement at 12M molarity.

- **Metakaolin (MK) Geopolymer:**
 - The SEM image of MK without PP fibers shows a porous and heterogeneous structure, with visible micro-cracks and loosely packed particles.
 - The image of MK with PP fibers exhibits a denser microstructure with better particle bonding and reduced visible cracks, suggesting improved matrix integrity.
- **Fly Ash (FA) Geopolymer:**
 - The SEM image of FA without PP fibers depicts a more compact structure compared to MK, but some micro-cracks and voids are still present.
 - The FA with PP fibers image shows a further densified matrix, with PP fibers potentially bridging micro-cracks and improving the continuity of the geopolymer network.

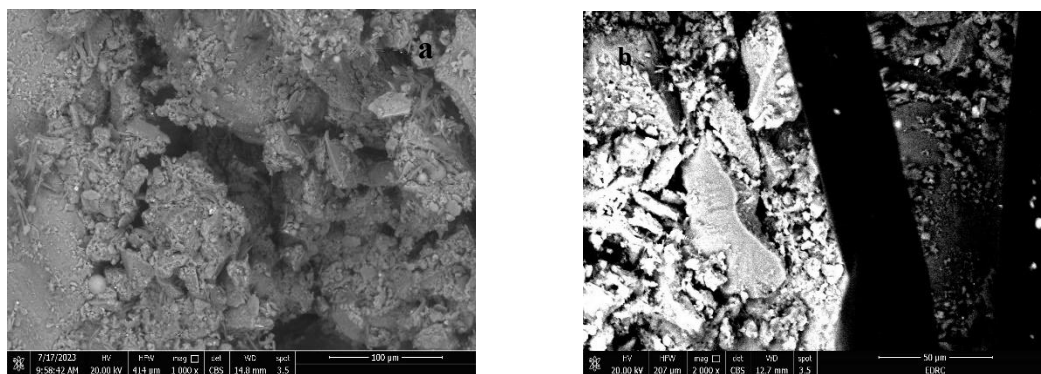


Fig. 12: SEM 12M (a) MK-Without PP, (b) MK-With PP

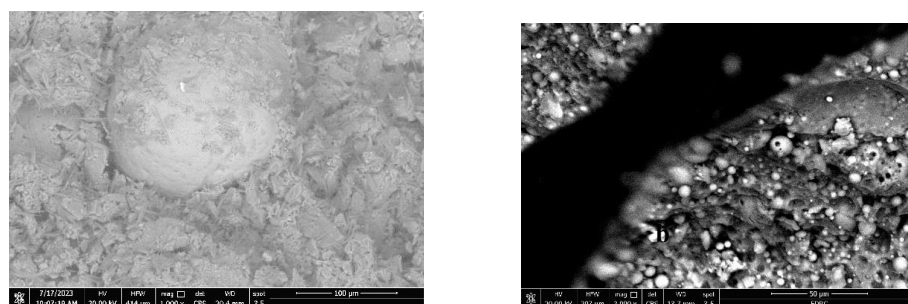


Fig. 13: SEM 12M - (a) FA-Without PP, (b) FA-With PP

The experimental findings indicate that PP fibers have contrasting effects on the compressive strength of FA and MK geopolymer concretes. The SEM analysis of MK-based geopolymers without fibers reveals a porous and fragmented structure, contributing to its relatively low compressive strength of 110 kg/cm². However, the introduction of PP fibers led to a significant increase in strength to 176 kg/cm², which is reflected in the denser microstructure observed in the SEM images. The improved compressive strength can be attributed to the fiber-bridging effect, which helps restrain crack propagation and enhance load transfer within the geopolymer matrix. Similar findings have been reported by [23], who observed that fiber incorporation in MK-FA-based geopolymer composites improves strength and durability due to crack confinement and better stress distribution within the matrix.

In contrast, FA-based geopolymers exhibit a different response to PP fibers reinforcement. The compressive strength of FA geopolymer without fibers was 300 kg/cm², which is significantly higher than MK-based samples, aligning with the SEM images that show a compact and well-structured matrix. However, the addition of PP fibers resulted in an increase in compressive strength to 416 kg/cm². This rise can be explained by the good bonding between the hydrophobic PP fibers and the geopolymer matrix, which improves stress transfer and decreases localized defects. Studies such as [24] have highlighted similar benefits of PP fibers incorporation, noting that fibers improve ductility and crack resistance.

The differing behavior of MK and FA based geopolymers can be explained by their distinct microstructural characteristics. FA geopolymers naturally exhibit better compaction and lower porosity due to the spherical shape of FA particles, whereas MK geopolymers tend to form more heterogeneous and porous matrices. As a result, PP fibers contribute positively to MK and FA samples by enhancing cohesion and increasing strength. These findings emphasize that the effectiveness of fiber reinforcement is highly dependent on matrix composition and fiber-matrix interaction. Future work could explore surface treatments or alternative fiber types to improve the fiber-matrix bonding in MK-based geopolymers, ensuring optimal mechanical performance.

“SEM images of FA-12M + PP fiber show fibers spanning microcracks and embedded in a dense matrix with limited porosity, indicating effective crack bridging and stress redistribution. In contrast, SEM images of MK-12M + PP fiber show more voids around the fibers and discontinuities in the surrounding gel, suggesting weaker interfacial stress transfer. This correlates with the observed mechanical response, where FA + PP at 12M more than doubled flexural and splitting tensile strength, whereas MK + PP produced only marginal improvement.”

7. Correlation Between Compressive and Flexural Strength

The relationship between compressive strength (FC) and flexural strength (FT) for both FA and MK geopolymer samples, with and without PP fibers, is illustrated in Fig. 14a, 14b. The figure presents two separate trends for geopolymer concrete reinforced with PP fibers and without fibers. The equations derived from the empirical trend illustration indicate that the flexural strength increases with compressive strength in a non-linear fashion for FA-based geopolymer concrete, whereas MK-based geopolymer concrete exhibits a different trend. The R² values in the figure suggest a strong correlation in both cases, with FA-based geopolymer concrete showing a higher dependency of flexural strength on compressive strength compared to MK-based geopolymer concrete.

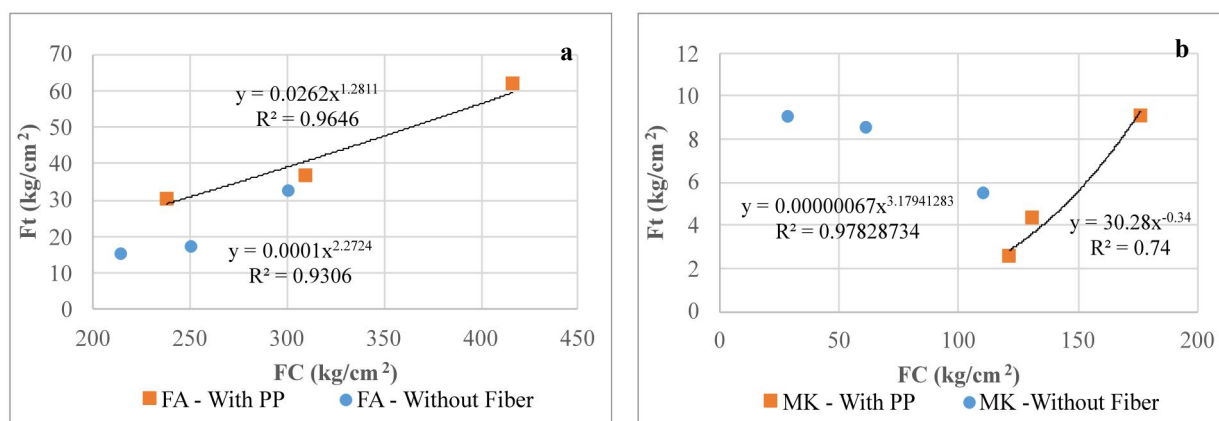


Fig 14: Correlation Between Compressive and Flexural Strength (a) FA-Without /With PP, (b) MK-Without /With PP

For FA-based geopolymer concrete, the addition of PP fibers significantly enhances flexural strength, as evident from the steep curve and high R² value (0.9646). The incorporation of fibers provides improved crack-bridging mechanisms, leading to enhanced tensile resistance and improved ductility, which agrees with previous studies on fiber-reinforced geopolymer composites [28]. On the other hand, FA-based geopolymer concrete without fibers also demonstrates a strong correlation, but the trend follows a different pattern, suggesting that matrix composition and fiber reinforcement have distinct effects on flexural performance [29]. For MK-based geopolymer concrete, the effect of fibers is less pronounced. The presence of PP fibers shows a non-linear relationship with compressive strength (R² = 0.74), while MK-based geopolymer concrete without fibers exhibits a different trend, with an R² value of 0.9783. These findings align with the work of [30], who reported that the

mechanical properties of geopolymer concrete are highly dependent on binder type and curing conditions. The incorporation of PP fibers plays a crucial role in improving flexural strength, particularly in FA-based geopolymer concrete. This improvement can be linked to the ability of PP fibers to arrest microcracks and enhance energy absorption during loading. Similar behavior has been reported by [31], where fiber reinforcement improved flexural toughness and ductility, making the material more resistant to cracking and failure. Consequently, these results highlight the effectiveness of PP fibers in enhancing the flexural performance of geopolymer concrete, making it a viable alternative for applications requiring high tensile and flexural resistance.

8. Conclusion

This study evaluated the mechanical performance of FA and MK based geopolymer concretes reinforced with PP fibers under varying alkaline molarity levels (8M, 10M, and 12M). The findings can be summarized as follows:

- 1- This study experimentally evaluated the mechanical performance of fly ash (FA)- and metakaolin (MK)-based geopolymer composites activated with 8M, 10M, and 12M NaOH, with and without polypropylene (PP) fibers at a dosage of 900 g/m³. Mechanical characterization included compressive strength, three-point flexural strength, and splitting tensile strength after heat curing at 60 °C for 24 h.
- 2- FA-based geopolymers showed a strong positive response to PP fiber addition, particularly at 12M NaOH. In the FA-12M mix, PP fibers increased compressive strength from 300 kg/cm² to 416 kg/cm² (≈38.7% gain), flexural strength from 33 kg/cm² to 62 kg/cm² and splitting tensile strength from 8.8 kg/cm² to 20.4 kg/cm². This indicates that, for FA matrices, PP fibers are effective in enhancing both load-bearing capacity and crack resistance.
- 3- MK-based geopolymers developed lower absolute strengths than FA-based mixes under the same curing and activator conditions. In addition, the same PP fiber dosage produced only limited improvements in flexural and splitting tensile strength for MK systems. This suggests less efficient stress transfer between PP fibers and the MK matrix at the tested dosage.
- 4- The comparative results demonstrate that PP fiber reinforcement is markedly more effective in FA-based geopolymers than in MK-based geopolymers. This difference is attributed to the combined influence of precursor type and alkaline activation level, which governs matrix consolidation, crack-bridging efficiency, and the contribution of fibers to post-cracking behavior.
- 5- Monte Carlo simulations were applied to the compressive strength data to evaluate performance reliability in probabilistic terms rather than relying only on mean values. The FA-based geopolymer with PP fibers exhibited both higher strength and higher reliability, indicating that it can be considered a viable structural alternative to conventional Portland cement concrete in applications where flexural and tensile resistance, crack control, and early mechanical stability are critical (e.g. repair layers, overlays, thin structural elements).
- 6- MK-based geopolymers did not achieve comparable performance under the same PP fiber dosage and curing regime. This identifies a development need: MK systems may require alternative reinforcement strategies (for example, different fiber types with higher stiffness, increased fiber volume, surface-treated fibers, or modified curing chemistry) to obtain similar gains in flexural and tensile behavior.
- 7- The curing regime used in this work (60 °C for 24 h) was selected to obtain consistent, high early-age strength for comparative assessment between FA and MK systems. While this approach is widely adopted in laboratory geopolymer research to ensure reproducible polymerization, it is energy intensive. Future work should investigate ambient or low-energy curing routes to improve practical deploy ability and sustainability while maintaining mechanical reliability. This study establishes FA–PP geopolymers as a viable structural alternative to Portland cement concrete for applications that require high strength, ductility, and fracture resistance.

Overall, this work defines a baseline performance map for FA- and MK-based geopolymers reinforced with PP fibers under controlled conditions. The results highlight FA-based PP fiber geopolymer as the more structurally efficient and reliable system within the tested matrix–fiber–activator combination, and they clarify that MK-based systems will require targeted optimization before they can deliver comparable tensile and flexural enhancement.

9. Nomenclature

FA: Fly ash

MK: Metakaolin

PP: Polypropylene fibers

GPC: Geopolymer concrete / geopolymer composite

NaOH: Sodium hydroxide

Na₂SiO₃: Sodium Silicate

SEM: Scanning Electron Microscopy

XRD: X-ray Diffraction

TEM: Transmission Electron Microscopy

XRF: X-ray fluorescence

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