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Effect of The Polypropylene Fiber Size and Alkaline Solution to Binder Ratio in GGBS-FA based Fiber Reinforced Geopolymer Concrete; Mechanical Properties and Fire Resistance

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Abstract

The increasing demand for sustainable construction materials has driven the exploration of alternative binders to reduce the environmental impact of conventional Portland cement. Geopolymer concrete (GPC), synthesized through the alkali activation of aluminosilicate materials such as fly ash (FA) and ground granulated blast furnace slag (GGBS), has emerged as a promising candidate due to its superior mechanical properties, lower carbon footprint, and resistance to aggressive environments. However, the brittle nature and susceptibility to explosive spalling under elevated temperatures remain critical challenges for GPC. This study investigates the influence of polypropylene (PP) fiber size (6, 12, and 18 mm) and Alkaline solution-to-binder (S/B) ratio (0.40, 0.425, and 0.45) on the mechanical and thermal properties of two-component geopolymer concrete (FA + GGBS). The results indicate that 12 mm PP fibers significantly enhance compressive strength, elastic modulus, and tensile strength, while 18 mm fibers provide superior crack-bridging effects but may lead to fiber clustering and reduced thermal stability. The optimal S/B ratio of 0.425 balances workability, fiber dispersion, and matrix bonding, resulting in improved mechanical performance and thermal resistance. At elevated temperatures, PP fibers melt, creating microchannels that reduce internal pressure and mitigate spalling risks, with 6 mm fibers offering the best fire resistance due to smaller, more uniform voids. This study provides critical insights into optimizing fiber-reinforced GPC formulations for high-performance, fire-resistant structural applications, offering a sustainable alternative to conventional cement-based composites.

Keywords: Geopolymer Concrete, Polypropylene Fiber, Post-fire Resistance, Alkaline solution, Fiber Reinforcement.

1. Introduction

The increasing demand for sustainable construction materials has driven researchers to explore alternative binders that reduce the environmental impact of conventional Portland cement. Among these alternatives, geopolymer concrete (GPC) has gained significant attention due to its superior mechanical properties, lower carbon footprint, and resistance to aggressive environments [1]. Geopolymer concrete is synthesized through the alkali activation of aluminosilicate materials such as fly ash (FA) and ground granulated blast furnace slag (GGBS), forming a three-dimensional aluminosilicate gel that serves as a binding phase. The incorporation of these industrial by-products not only enhances the sustainability of concrete but also improves its thermal resistance, making it a suitable candidate for high-temperature applications [2]. Despite the promising properties of GPC, its brittle nature and susceptibility to explosive spalling under elevated temperatures remain critical challenges [3]. The inclusion of polypropylene (PP) fibers has emerged as an effective strategy to mitigate these issues by improving the tensile strength, ductility, and fire resistance of the composite [4]. At high temperatures, PP fibers melt and create microchannels, facilitating vapor escape and reducing internal pressure buildup, thereby minimizing spalling risks [5]. However, the efficiency of fiber reinforcement is highly dependent on fiber size, length-to-diameter ratio, and distribution within the matrix [6].

A key factor influencing the behavior of fiber-reinforced geopolymer concrete is the solution-to-binder ratio (S/B), which defines the proportion of ground granulated blast furnace slag (GGBS) relative to the total binder content in the geopolymer system. The S/B ratio plays a crucial role in governing mechanical strength, setting time, durability, and high-temperature resistance [7]. Increasing the S/B ratio enhances the early-age strength and densification of the geopolymer matrix due to the higher calcium content in GGBS, which contributes to additional C-A-S-H (calcium-alumino-silicate-hydrate) and N-A-S-H (sodium-alumino-silicate-hydrate) gel formation [8]. However, excessive slag content may lead to higher shrinkage, increased brittleness, and reduced thermal stability due to the formation of denser structures with lower porosity, which can be detrimental under high-temperature exposure. Conversely, a lower S/B ratio (higher fly ash content) results in lower early-age strength but improved thermal resistance, as fly ash-based geopolymers exhibit superior performance at elevated temperatures due to their lower calcium content and enhanced formation of stable N-A-S-H phases [9, 10].

The interaction between polypropylene fiber size and the S/B ratio is a crucial yet underexplored aspect of fiber-reinforced geopolymer composites. A higher S/B ratio leads to a denser matrix, which may affect fiber dispersion, fiber-matrix bonding, and the overall mechanical performance of the composite [11]. In a high-S/B system, the presence of PP fibers could introduce microstructural discontinuities, influencing load transfer efficiency and thermal resistance. On the other hand, in a low-S/B system, the increased porosity may facilitate better fiber melting and void formation during high-temperature exposure, improving fire resistance but potentially compromising mechanical strength [12]. Despite extensive studies on fiber reinforcement and S/B variation separately, limited research has systematically examined their combined effect on the mechanical and thermal properties of GPC under high temperatures [13]. Therefore, this study aims to investigate the influence of polypropylene fiber size on the compressive strength, tensile strength, and thermal resistance of two-component geopolymer concrete (fly ash + slag) with varying S/B ratios. The findings will provide valuable insights into the optimization of fiber-reinforced GPC formulations for high-performance, fire-resistant concrete applications [14-16].

Previous studies have demonstrated that short fibers contribute to crack bridging and enhance tensile strength [17], while longer fibers offer improved energy absorption and post-cracking ductility [18-21]. However, limited research has systematically examined the effect of polypropylene fiber size on the mechanical properties of geopolymer concrete, particularly in two-component geopolymer systems containing both fly ash and slag [22]. Given that GGBS contributes to early-age strength development and FA enhances long-term durability, their combined use in a geopolymer matrix may interact differently with PP fibers, influencing overall performance under elevated temperatures [23-25].

This study aims to investigate the influence of polypropylene fiber size on the compressive strength, tensile strength, and thermal resistance of two-component geopolymer concrete comprising fly ash and blast furnace slag. By evaluating the role of fiber dimensions in enhancing mechanical performance and fire resistance, this research provides insights into optimizing fiber-reinforced GPC formulations for high-temperature structural applications.

2. **Experimetal program**

2.1.Materials

2.1.1. Fibers

To prepare and develop polypropylene fiber-reinforced geopolymer concrete mixtures, aluminosilicate materials, alkaline solutions (sodium hydroxide and sodium silicate), aggregates (sand and gravel), and polypropylene fibers of 6, 12, and 18 cm in length (Fig. 1), supplied by Kimiax Tehran, were used. The properties of the fibers used in this study are presented in Table 1.

Table 1: Properties of Polypropylene Fibers

Length (mm)	6, 12, 18
Density (gr/cm3)	0.91
Tensile strength (MPa)	400
Water absorbency	No
Melting point	160

Fig. 1: PP fiber size

2.1.2. Supplemetary cementitous materials (SCMs)

The pozzolanic aluminosilicate materials used in the production of fiber-reinforced geopolymer concrete consisted of GGBS and FA**.** The blast furnace slag was obtained from *Esfahan Steel Company*, while the FA was sourced from *Arak*. The chemical composition of these pozzolanic materials is provided in Table 2.

Table 2: Chemical Composition of Pozzolanic Materials

Component	**FA**	**GGBS**
SiO_2	58.90	32.57
Al_2O_3	32.24	16.98
Fe_2O_3	2.84	1.26
CaO	0.73	34.07
MgO	0.89	9.69
SO_3	0.5	0.84
Na_2O	0.35	0.2
K_2O	1.12	0.08
Specific gravity	2.28	4.1

2.1.3. Alkaline solutions

The alkaline solutions used in this study include sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The sodium silicate solution was prepared in gel form, containing 54.1% water, 32.5% SiO_2, and 13.4% Na_2O. The sodium hydroxide solution was prepared at a concentration of 12 molar, using NaOH flakes with a purity of 95% dissolved in water. It is important to note that the NaOH solution must be prepared 24 hours before testing, allowing it to return to room temperature after the exothermic reaction.

2.1.4. Aggregate

For the production of fiber-reinforced geopolymer concrete samples, natural aggregates from *Amol* were used. Based on ASTM C33 [26], the grading of sand and gravel was performed in the laboratory, and the results are presented in Fig. 2. The water absorption percentage for fine and coarse aggregates was found to be 3.2% and 1.8%, respectively, while the specific gravity was 2.59 g/cm³ for fine aggregates and 2.63 g/cm³ for coarse aggregates.

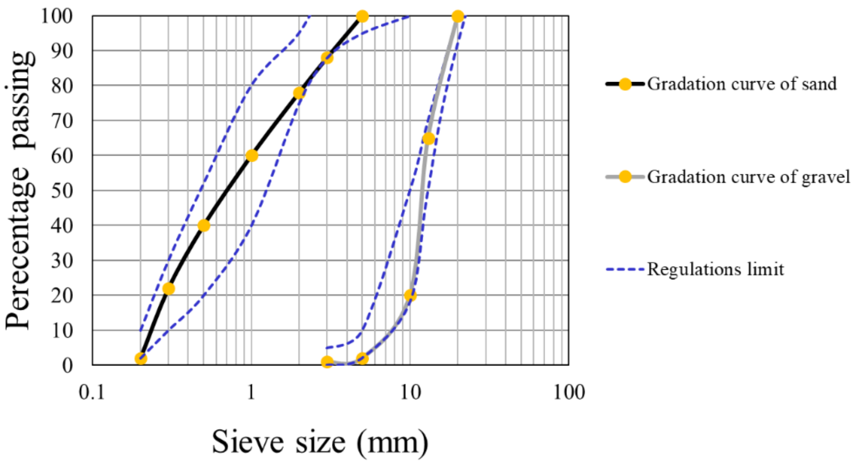

Fig. 2: Grading Curve of Aggregates

2.2. Mix Design

This experimental study investigates three different fiber-reinforced geopolymer concrete (FRGPC) mix designs, aiming to assess the effect of polypropylene fiber size (6, 12, and 18 cm) on mechanical properties. Fig. 3 is presented the experimental program of the GPC specimens.

Fig. 3: Experimetal preparation of specimens.

To evaluate the fiber size effect, polypropylene fibers were incorporated at a ratio of 0.5% (50 g) per mix. The study considered three different alkaline solution-to-binder (S/B) ratios of 0.40, 0.425, and 0.45. The sodium hydroxide (NaOH) content was varied at 72, 58, and 54 kg/m³, while the sodium silicate (Na_2SiO_3) solution was used in amounts of 144, 146, and 162 kg/m³, respectively. Additionally, 0.25 kg of a carboxylate-based superplasticizer was included in the mix to enhance workability and facilitate proper compaction. A critical aspect of alkaline solution preparation is the highly exothermic reaction between NaOH and water, generating significant heat. Therefore, the alkaline solution must be prepared a day before casting, allowing it to cool to ambient temperature before use. Table 3 is presented the FRGPC mixture design which evaluated in this study.

Table 3: Mix Design of Geopolymer Concrete Samples

Sample	SCM		FA	CA	Na_2Sio3	NaOH	S/B	Na_2Sio3/NaOH
	Fly Ash	GGBS						
RGC	342	138	526	1158	144	72	0.4	2
GC1	342	138	526	1158	144	72	0.4	2
	342	138	526	1158	144	72	0.4	2
	342	138	526	1158	144	72	0.4	2
GC2	342	138	526	1158	146	58	0.425	2.5
	342	138	526	1158	146	58	0.425	2.5
	342	138	526	1158	146	58	0.425	2.5
GC3	342	138	526	1158	162	54	0.45	3
	342	138	526	1158	162	54	0.45	3
	342	138	526	1158	162	54	0.45	3

2.3. Sample Preparation, Casting and Curing

The fiber-reinforced geopolymer concrete (FRGPC) mixtures were prepared using a 50-liter pan mixer in a research laboratory. The mixing process followed these steps:

1. Aggregates (fine and coarse) were first added to the mixer and blended to ensure uniform distribution.
2. The pozzolanic materials (fly ash and GGBS) were introduced into the mixer and thoroughly mixed with the aggregates.
3. Polypropylene fibers were then gradually incorporated to ensure even dispersion within the dry mix.
4. The alkaline solution (a combination of NaOH and Na_2SiO_3) was added to the dry mixture, and mixing continued for 2 minutes to ensure proper homogenization.
5. After mixing, fresh concrete was tested, then cast into pre-oiled molds for curing.

Also, the Fig. 4 presented the preparation and oven curing condition at the 60 ^{0}C. The molded geopolymer concrete samples were cured in an oven at 60°C for 24 hours. After 24 hours, the samples were demolded and stored in laboratory conditions until the specified testing age. Based on observations, water curing had no significant impact on the compressive strength of geopolymer concrete, and storing the samples in water was found to reduce testing efficiency in this study [27].

Fig. 4: Mixer and heating oven of this study.

3. Result and Descussion

This section first examines the mechanical properties of each geopolymer concrete mix design at ambient temperature, evaluating the influence of polypropylene fiber size and length. Next, the performance of fibers and the effect of other parameters, such as the alkaline solution-to-binder ratio (S/B) and modulus of solution, at elevated temperatures are analyzed, and their impact on the mechanical properties of geopolymer concrete is discussed. Finally, the results of mechanical modeling and the error rate of each model, based on statistical error indices, are presented.

3.1. *Mechanical Properties*

3.1.1. Compressive Strength

The compressive strength test was conducted according to ASTM C109 [28] on 10 cm cubic specimens at 7 and 28 days. The mean compressive strength values for each fiber-reinforced geopolymer concrete (FRGPC) mix are presented in Fig. 5.

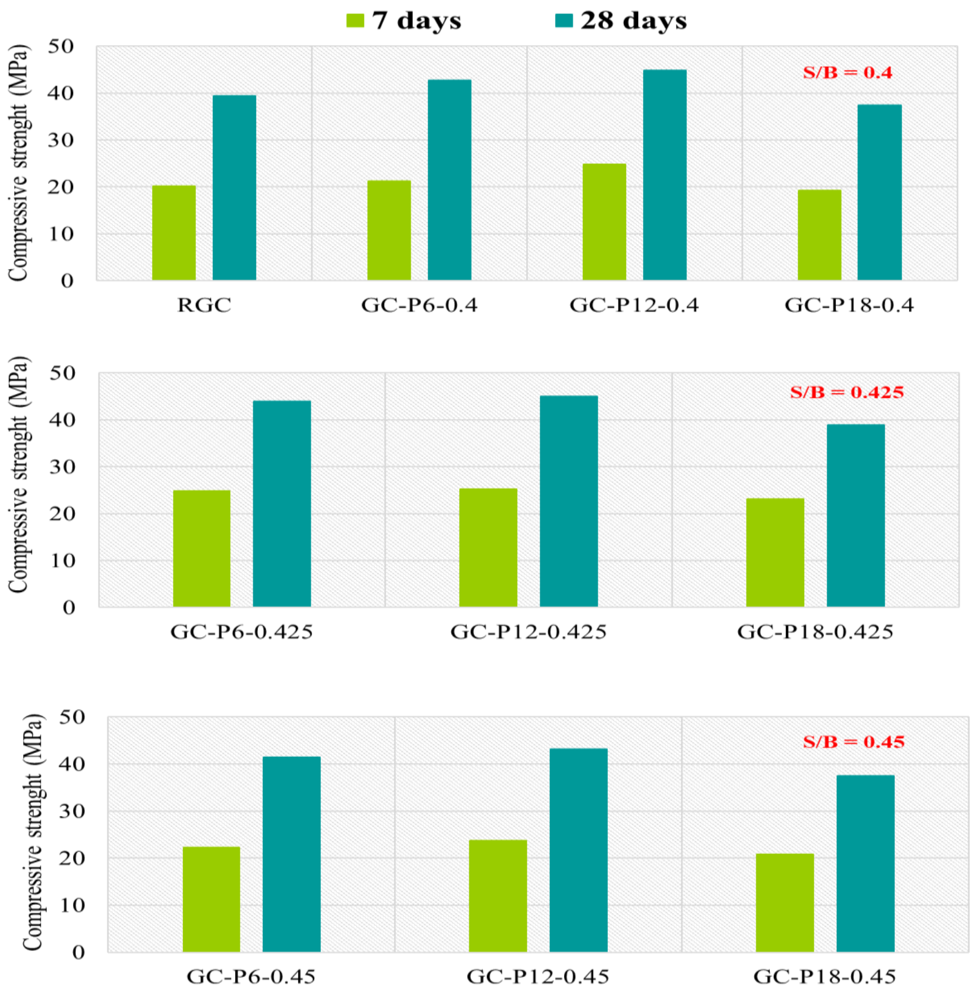

Fig. 5: Compressive Strength Results of 7- and 28-Day Fiber-Reinforced Geopolymer Concrete Samples

The inclusion of PP fibers can improve the tensile strength and toughness of concrete. The Fig. 5 likely show how different fiber sizes impact the compressive strength. For instance, longer fibers (P18) might provide better reinforcement compared to shorter fibers (P6), but this can vary based on the mix design.The S/B ratio influences the geopolymerization process, which in turn affects the strength development. A higher S/B ratio might lead to better workability but could also impact the final strength. The graphs should illustrate how different ratios affect the compressive strength at both curing periods.The findings align with prior research [29, 30], indicating that fiber content variation has minimal impact on compressive strength, whereas fiber length significantly affects the mechanical performance of geopolymer concrete.

Key Findings:

- The use of 12 mm fibers resulted in the highest compressive strength.
- Compared to samples reinforced with 6 mm and 18 mm fibers, the compressive strength of the 12 mm fiber-reinforced sample increased by 4.9% and 19.7%, respectively, at 28 days.

A comparative analysis of different S/B ratios (0.40, 0.425, and 0.45) reveals that samples with S/B = 0.425 exhibited the highest compressive strength at both 7 and 28 days. Since the binder (B) content was constant, increasing the alkaline solution up to an optimal level enhanced compressive strength. However, excessive solution content weakened the matrix, reducing compressive strength. Fig. 5 illustrates that increasing the S/B ratio from 0.40 to 0.425 resulted in no significant change in compressive strength, with the highest increase observed in 6 mm fiber-reinforced samples (2.8% improvement).

3.1.2. Elastic Modulus

The elastic modulus of each sample, considering various S/B ratios and fiber lengths measured based on ASTM C469 [31], is shown in Fig. 6. The results indicate a strong correlation between compressive strength and elastic modulus.

- 12 mm fibers produced the highest elastic modulus for all S/B ratios.
- For S/B = 0.40, the elastic modulus of 12 mm fiber-reinforced samples was 19% and 35% higher than samples with 6 mm and 18 mm fibers, respectively.
- Fibers longer than 12 mm significantly reduced the elastic modulus, suggesting that excessively long fibers negatively impact the mechanical behavior of geopolymer concrete.

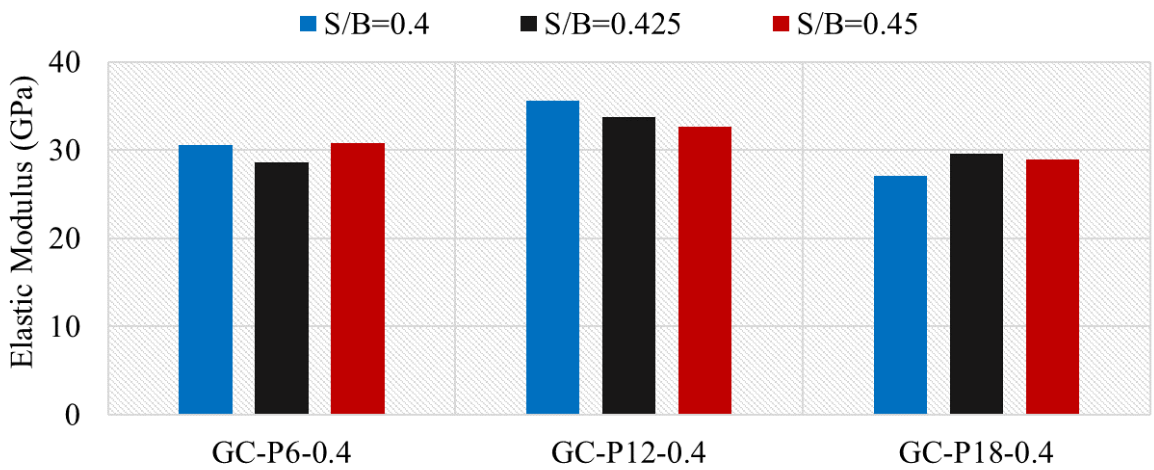

Fig. 6: Elastic Modulus of Geopolymer Concrete Containing Fibers of 6, 12, and 18 mm for S/B Ratios of 0.40, 0.425, and 0.45

3.1.3. Relationship Between Compressive Strength and Elastic Modulus

In conventional concrete, elastic modulus varies relative to compressive strength. However, in geopolymer concrete, elastic modulus increases proportionally with compressive strength, suggesting a strong dependency on mix design parameters. Several empirical equations exist for estimating elastic modulus based on compressive strength:

- ACI 318-14 [32]
- CEB-FIP Code 90 [33]
- Norwegian Standard NS 3473 [34]
- Al-Salman *et al.* [35]

Fig. 7 compares the calculated elastic modulus from this study with predictions from existing models. The CEB-FIP model exhibited the highest accuracy, while other models underestimated the experimental values.

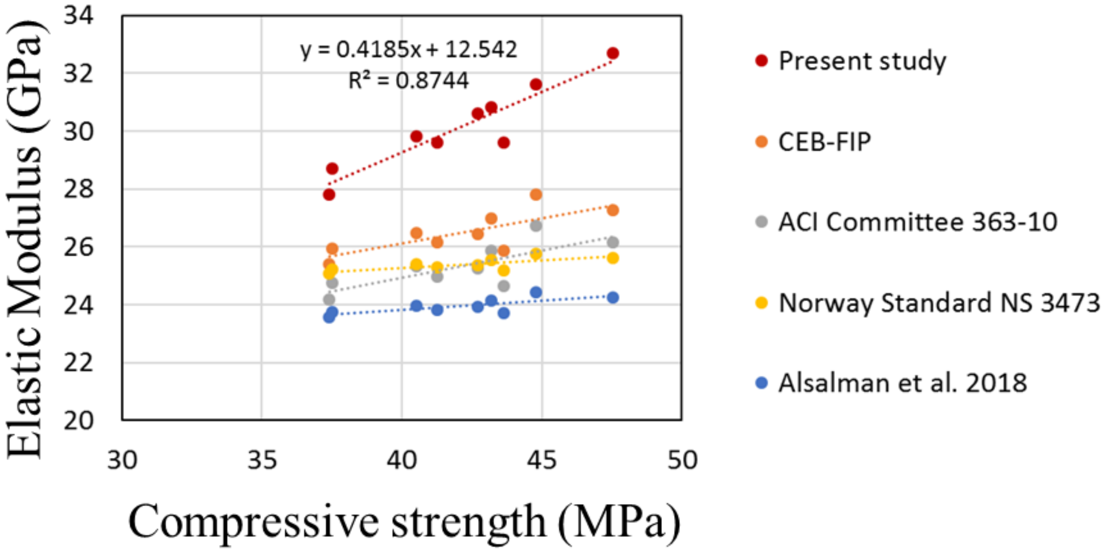

Fig. 7: Comparison of Elastic Modulus Predictions from This Study with Previous Research Models for 28-Day Geopolymer Concrete Samples

3.1.4. Tensile Strength

The **Fig. 8** illustrated the tensile strength results of FRGPC samples at 7 and 28 days for different alkaline solution-to-binder ratios (0.40, 0.425, and 0.45) and polypropylene fiber lengths (6 mm, 12 mm, and 18 mm).

- **Effect of Fiber Length on Tensile Strength**

The results demonstrate that the tensile strength of geopolymer concrete increases with fiber incorporation, indicating that polypropylene fibers effectively improve tensile behavior. Among all fiber lengths, the 18 mm fiber-reinforced samples exhibited the highest tensile strength across all S/B ratios. The 12 mm fiber-reinforced samples showed slightly lower tensile strength than 18 mm fibers but higher than 6 mm fibers, suggesting an optimal fiber bridging mechanism at this length. The 6 mm fiber-reinforced samples had the lowest tensile strength among fiber-reinforced mixes, likely due to their limited crack-bridging capability compared to longer fibers (based on ASTM C469 [31]).

- **Influence of S/B Ratio on Tensile Strength**

S/B = 0.425 resulted in the highest tensile strength across all fiber lengths at both 7 and 28 **days.** Increasing the S/B ratio to 0.45 slightly reduced tensile strength, particularly in longer fiber-reinforced samples (12 mm and 18 mm). This decrease could be attributed to excessive liquid content, leading to a weaker bond between fibers and the geopolymer matrix. The 0.40 S/B ratio samples exhibited lower tensile strength compared to 0.425 S/B. This suggests that an insufficient alkaline solution led to incomplete geopolymerization, limiting matrix strength development.

- **Tensile Strength Development Over Time**

A significant increase in tensile strength is observed between 7 and 28 days, highlighting the progressive polymerization and densification of the geopolymer matrix over time. The tensile strength gain is most pronounced in 12 mm and 18 mm fiber-reinforced samples, particularly at S/B = 0.425, supporting the idea that a well-balanced matrix-fiber interaction is key to tensile enhancement. The 6 mm fiber-reinforced samples exhibited the lowest relative strength gain from 7 to 28 days, suggesting that shorter fibers contribute less to long-term strength improvement.

- **Comparison with Plain Geopolymer Concrete (RGC Sample)**

The plain geopolymer concrete (RGC) exhibits the lowest tensile strength, confirming the well-established issue of brittle failure in fiber-free geopolymer concrete. The incorporation of fibers significantly enhances tensile properties, demonstrating the crack-bridging role of polypropylene fibers and their ability to delay crack propagation.

- **Effect of PP Fiber Size on Microstructural Properties**

a) Pore Structure and Fiber Distribution

- 6 mm PP fibers:

  - Short fibers are more uniformly distributed within the geopolymer matrix.
  - They create smaller microvoids but less effective crack bridging due to their limited length.
  - The fiber-matrix interface is relatively stronger, improving overall cohesion.

- 12 mm PP fibers:

  - These fibers provide an optimal balance between dispersion and reinforcement.
  - They fill voids effectively and promote a dense geopolymer matrix, improving mechanical strength.
  - SEM images typically show fewer interconnected pores, indicating better compaction.

- 18 mm PP fibers:

  - Longer fibers tend to cause agglomeration, leading to fiber clustering.
  - This creates localized weak zones with increased porosity and microcracks due to non-uniform stress distribution.
  - However, at elevated temperatures, they leave behind larger voids as they melt, which can reduce structural integrity.

b) Fiber-Matrix Bonding and Interface Transition Zone (ITZ)

- The ITZ is a crucial factor in defining the performance of fiber-reinforced GPC.
- 6 mm fibers: Show a stronger ITZ with the geopolymer matrix due to their smaller size and better dispersion.
- 12 mm fibers: Exhibit good adhesion with the matrix, forming a densely packed ITZ that enhances mechanical strength.
- 18 mm fibers: Show a weaker ITZ due to fiber clumping, increasing microcracks and voids in the structure.

c) Crack Propagation and Toughness Mechanism

- Shorter fibers (6 mm) provide some resistance but are less effective in bridging wider cracks.
- 12 mm fibers are the most efficient in crack bridging, allowing for better stress transfer and crack deflection.
- 18 mm fibers, while improving toughness, can cause non-uniform stress distribution, leading to early failure in some regions.

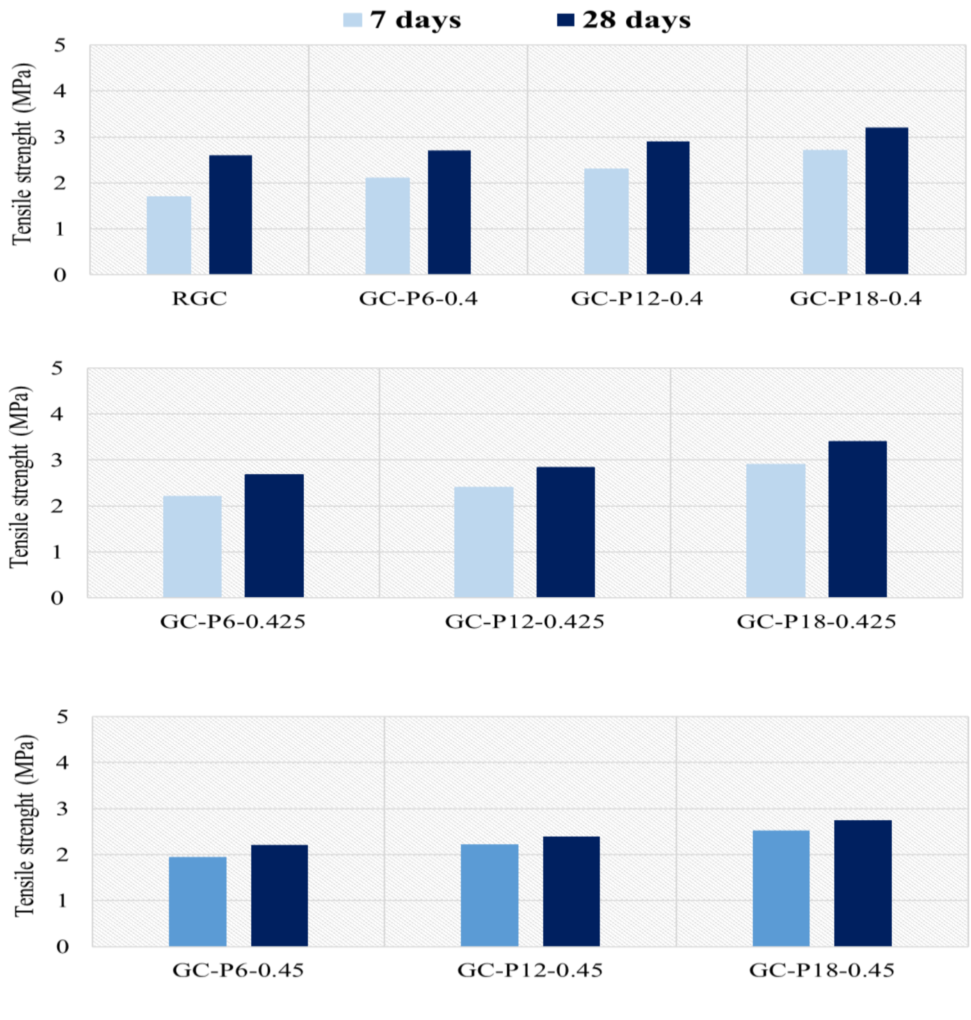

Fig. 8: Tensile Strength Results of 7- and 28-Day Fiber-Reinforced Geopolymer Concrete

3.2. Post-fire residual Strength

The compressive strength of 28-day geopolymer concrete samples containing polypropylene fibers (6, 12, and 18 mm) at temperatures ranging from 26°C to 700°C evaluated based on ACI216 [36] and shown in Fig. 9.

- At room temperature (26°C), the compressive strength ranged between 37 and 48 MPa.
- At 200°C, compressive strength increased, attributed to additional geopolymerization and polymerization of unreacted aluminosilicates, leading to a denser microstructure.
- Beyond 400°C, the compressive strength declined due to microcracking and thermal degradation of aggregates.
- Polypropylene fibers melt at 200°C, reducing fire resistance and creating voids, which weaken the matrix at higher temperatures.
- At 700°C, the greatest strength loss was observed in 18 mm fiber-reinforced samples, followed by 12 mm fibers, while 6 mm fiber-reinforced samples exhibited the least degradation.

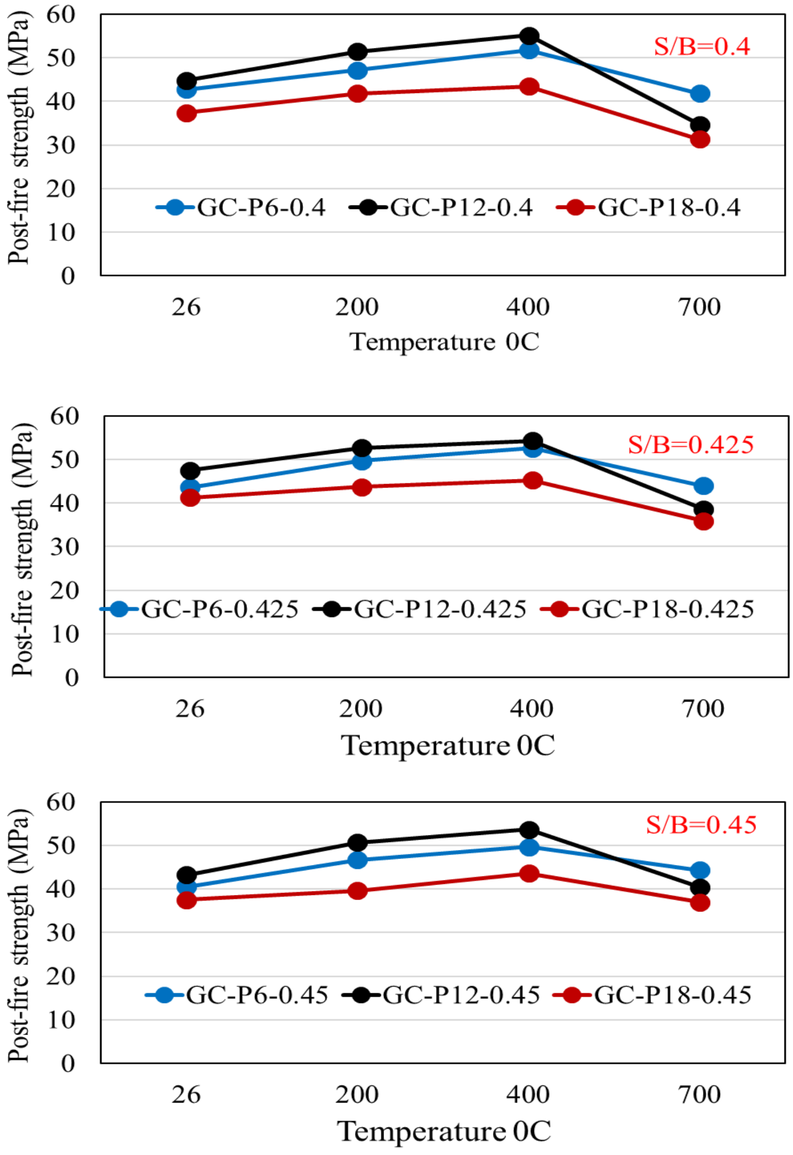

Fig. 9: Compressive Strength Variation of Fiber-Reinforced Geopolymer Concrete at Elevated Temperatures

4. Conclusion

This study comprehensively investigated the effect of polypropylene (PP) fiber size on the mechanical properties and microstructure of geopolymer concrete (GPC) containing blast furnace slag (BFS) and fly ash under ambient and high-temperature conditions. The findings provide critical insights into optimizing fiber reinforcement for improved performance.

4.1. Influence of PP Fiber Size on Mechanical Properties

- Tensile Strength: The incorporation of PP fibers significantly enhanced the tensile strength of GPC, with 18 mm fibers exhibiting the highest strength due to their superior crack-bridging effect. However, excessive fiber length led to agglomeration, reducing tensile efficiency.
- Compressive Strength: Fiber addition had a marginal effect on compressive strength, as fibers primarily improve tensile properties. Nonetheless, the 12 mm fibers contributed to a denser microstructure, resulting in a slight compressive strength increase.
- Flexural Strength: The presence of longer fibers (12 mm and 18 mm) notably enhanced flexural strength, reinforcing the material's resistance to bending-induced cracking.

4.2. Effect of Alkaline Solution-to-Binder (S/B) Ratio on Performance

- The optimal S/B ratio was identified as 0.425, balancing workability, fiber dispersion, and matrix bonding.
- A higher S/B ratio (0.45) led to increased porosity, negatively affecting mechanical strength and fiber-matrix bonding.
- A lower S/B ratio (0.40) resulted in incomplete geopolymerization, producing a weaker matrix structure.

4.3. Microstructural Insights and Fiber-Matrix Interactions

- Scanning Electron Microscopy (SEM) analysis revealed that PP fiber size significantly influenced the interfacial transition zone (ITZ) and pore distribution.
- 12 mm fibers provided the most refined microstructure, reducing porosity and enhancing fiber-matrix adhesion.
- 18 mm fibers caused fiber clustering, leading to localized weaknesses, microcracking, and increased void formation.
- 6 mm fibers, while improving uniformity, had a limited effect on crack resistance due to their shorter length.

4.4. Performance Under Elevated Temperatures

- At elevated temperatures, PP fibers melted, leaving behind voids that influenced post-fire mechanical behavior.
- 6 mm fibers contributed to smaller, more uniform voids, improving fire resistance by preventing explosive spalling.
- 12 mm fibers provided a balance between crack resistance and thermal stability.
- 18 mm fibers, while effective at ambient conditions, left larger voids post-melting, reducing thermal resistance.

4.5. Practical Implications and Future Research

- Optimizing fiber length (12 mm) and S/B ratio (0.425) significantly enhances the durability and mechanical properties of GPC.
- Future studies should explore hybrid fiber systems (combining different fiber sizes) to further optimize mechanical performance.
- Thermal behavior beyond 800°C should be investigated to evaluate the long-term fire resistance of fiber-reinforced GPC.
- Nano-modification of the geopolymer matrix could further enhance fiber-matrix bonding and reduce porosity.

4.6. Final Remarks

This research highlights the critical role of fiber length in tailoring GPC properties for structural applications. The findings provide a scientific basis for selecting polypropylene fiber sizes to optimize strength, durability, and thermal performance in geopolymer concrete, offering a sustainable alternative to conventional cement-based composites

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