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A COMPARATIVE STUDY: IMPACT OF FIBERS ON THE INTERFACIAL SHEAR STRENGTH OF GEOPOLYMER CONCRETE

Rajashekar SANGI[1*], Shesha Sreenivas BOLLAPRAGADA[2]

Abstract

Cement, which is a significant component of concrete, is used in construction. Unfortunately, during the manufacture of cement, considerable amounts of CO2 are released into the atmosphere. CO2 is the primary greenhouse gas responsible for global warming; finding alternatives to cement is essential to reduce CO2 emissions. Primarily due to its high carbon dioxide emissions, the environmental impact of OPC has prompted the search for sustainable alternative binders. Geopolymer concrete, an eco-friendly substitute, has gained attention for its potential to significantly reduce the carbon footprint associated with construction materials. Constructing large-scale structures with mass concrete leads to the formation of interfaces and joints, thereby creating potentially weak points prone to cracking. These connections may link concrete of various strengths or interface with diverse construction materials, such as steel. Ensuring a cohesive performance in composite concrete structures requires robust bonding at these interfaces, which is typically achieved using shear ties. However, an excess of these ties can hinder construction efficiency. To tackle these challenges concerning the effectiveness and structural stability of the construction, this study aims to assess the effects of polypropylene, steel, and glass fibers on the interfacial shear strength of geopolymer concrete by understanding how these different fibers influence the mechanical properties of geopolymer concrete. It was observed that with the addition of the fibers, strength was increased up to the threshold limit; after that, it was reduced. The results of the investigation showed that the shear strength increment of steel fiber-reinforced GPC is a maximum of 72%; for glass fiber, it was 19%.

Address

[1] Research Scholar, Dept. of Civil Engineering, Kakatiya University. Warangal, Telangana, India
[2] Professor Dept. of Civil Engineering, Kakatiya University, Warangal, India

[*] ***Corresponding author:*** srs.ce.ssc@gmail.com

Key words

- Compressive Strength,
- Shear Strength,
- Geopolymer Concrete,
- GGBS,
- Fly ash.

1 INTRODUCTION

During the past thirty years, the acceleration of global industrialization and urban expansion has significantly propelled an increase in cement production. As the fundamental element in construction, cement has undergone rapid expansion because of these trends. Consequently, the cement sector has risen as the second-largest source of industrial CO_2 emissions globally and is responsible for around 25% of the overall industrial CO_2 emissions (Chen et al., 2022). To improve the qualities of concrete and reduce the greenhouse gas (GHG) emissions associated with its production, fly ash serve as a substitute for OPC (Antarvedi et al., 2023). This substitution demonstrates its effectiveness in enhancing the properties of concrete, while concurrently lessening the environmental impact linked to GHG emissions (Yierlapalli et al., 2023). The ratio between fly ash and an activator stands as a pivotal factor, which notably impacts the strength of geopolymer concrete. Notably, a porous geopolymer made with fly ash exhibits a remarkable performance when formulated with a Na_2SiO_3/NaOH ratio of 3.5; it displays a notably high compressive strength (Temuujin et al., 2009). Raising the ratio of H_2O/Na_2O supports the polymerization reaction. Observations have indicated that within a 0 to 12-hour period at 60°C, the degree of reaction increased from 4.9% to 5.6% (Cui et al., 2023). Heating fly ash to 500°C and 800°C triggers the formation of geopolymerization (Abdullah et al., 2012). Water glass slag cements cured under standard conditions demonstrate higher compressive strength than Portland cement mortars. Yet, a notable drawback lies in the considerably greater drying shrinkage observed in alkali-slag cements compared to Portland cement (Krizan et al., 2023). The choice and amount of an activator are of significant importance in alkali-activated concrete. Elevating the activator dosage results in increased strength, while opting for a higher silicate modulus in the activator also contributes to achieving greater strength (Sangi R et al., 2024). Geopolymer concrete tends to be more brittle than traditional concrete. To address this brittleness, adding fibers becomes crucial. Introducing fibers to geopolymer concrete enhances its overall performance (Prasad et al., 2023).

While maintaining the same total fiber volume, the introduction of both micro and macro steel fibers results in substantial improvements in initial bond stiffness and bond strength (Chu et al., 2023). Initial cracks in fiber reinforced concrete occur due to a bond slip (Sangi et al., 2024). The water-to-binder ratio holds significance in determining the right amount of fiber for optimal performance. Glass fibers, with their higher surface area, can impede the ability to flow of concrete, thus adversely affecting it. While the inclusion of glass fibers did not notably boost compressive strength, it significantly improved the tensile and flexural capacity of concrete by effectively resisting cracking (Gao et al., 2023). The optimum fiber dose can be impacted by the water-to-binder ratio. An initial analysis through scanning electron microscope (SEM) observations indicates a notable increase in both the size and quantity of the pores, which is primarily due to the combined effect of higher fiber content and the water-to-binder ratio (Yuan et al., 2021). Upon analyzing the microstructures of FRC, it is apparent that increasing the fiber dosage might not enhance the performance (Xu et al., 2020). The SPFRC-C mix, which contains crimped steel fibers, demonstrates the most significant boost in flexural strength, i.e., an impressive 120% increase (Sangi et al., 2024).

2 EXPERIMENTAL DETAIL AND METHODOLOGY

2.1 Materials

Our research employed Class F fly ash, which meets IS 3812-2003 standards and was sourced from Ramagundam in Telangana. The GGBS was obtained from JSW in Hyderabad, India. The coarse aggregates and river sand complied with IS 383:2016 specifications. The activator water glass solution was procured from Kiran Global Solutions in Chennai, Tamil Nadu. The steel fibers, E-glass fibers, and polypropylene fibers were acquired from Chennai, Tamil Nadu.

Tab. 1 *Properties of fibers.*

Sl. No	Material	Properties	Value
1	Steel fiber	Type of fiber	Hooked
		Density	7850 kg/m^3
		Aspect ratio	60
		Diameter	0.5 mm
		Length	30 mm
		Tensile strength	1116 N/mm^2
2	Glass fiber	Density	2500 kg/m^3
		Length	12 mm
		Diameter	25 µm
		Tensile strength	2560 N/mm^2
3	Polypropylene fiber	Density	905 kg/m^3
		Length	12 mm
		Diameter	20 µm
		Specific gravity	0.91

The coarse aggregates (CA) used were granite chips with a nominal maximum size of 10 mm; the fine aggregate comprised zone-II sand. The glass fiber (GF) material consists of numerous extremely fine glass fibers; each one is 12 mm long, with a density of 2500 kg/m^3. Polypropylene fiber (PPF) is a linear synthetic polymer fiber derived from propylene polymerization; it is also 12 mm in length and with a density of 905 kg/m^3. The steel fibers (SF), which were small, discontinuous steel fragments, have a diameter of 0.3 mm and a length of 30 mm. The integration of these fibers into the concrete improved its structural properties.

Tab. 2 *Properties of materials.*

Sl. No	Material	Properties	Value
1	Fly ash	Colour	Greyish white
		Specific gravity	2.16
		Consistency	30%
2	GGBS	Colour	White
		Specific gravity	2.73
		Consistency	42%
3	Coarse aggregate	Specific gravity	2.72
	Fine aggregate	Specific gravity	2.64
	Water glass	PH	13

2.2 Mix Proportions of GPC

The mix proportions for the geopolymer concrete were established by taking into account various factors: i.e., the activator-to-binder ratio, binder content, aggregate-to-binder ratio, and water-to-water glass ratio. These calculations aimed to maximize the utilization of fly ash while achieving the targeted strength. Various ratios of fly ash to GGBS (60:40, 50:50, and 40:60) were evaluated to formulate the mix proportions for the different grades of the geopolymer concrete (Sangi et al., 2023).

2.3 Optimum dosage of fibers

Determining the optimal amount of fibers involves evaluating their effect on the compressive strength of GPC. This entails adding different percentages of fibers to the concrete i.e., 0.5%, 1%, 1.5%, and 2% of the steel fibers, and 0.2%, 0.4%, 0.6%, 0.8%, and 1% of the polypropylene and glass fibers.

2.4 Shear behavior of geopolymer concrete

Push-off specimens were used to examine the shear strength of GPC. A push-off specimen is composed of two L-shaped blocks joined by a ligament to which shear stress is applied. All the specimens consisted of longitudinal reinforcement with a 10 mm diameter; 2-legged 6 mm diameter stirrups are used to safeguard against potential flexural failure. The size of the specimen was 340 mm x 200 mm x 100 mm. The shear strength could be obtained for G20, G30, G40, G50 and G60 grades of the GPC concrete and the optimum dosage of the fibers.

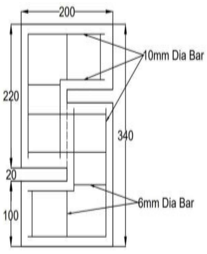

Fig. 1 *Reinforcement details of push-off specimen*

Fig. 2 *Testing push-off specimen*

Fig. 3 *Failure mode of specimen*

Tab. 3 *Mix proportions for different grades of GPC*

Mix ID	Fly ash (kg/m^3)	GGBS (kg/m^3)	Fine Aggregate (kg/m^3)	Course Aggregate (kg/m^3)	Water glass (kg/m^3)
G20	216	144	910	948	162
G30	240	160	882	918	180
G40	200	200	900	900	200
G50	210	210	885	885	210
G60	160	240	885	885	220

3 RESULTS AND DISCUSSION

3.1 Compressive strength of GPC

Standard cubic specimens, which measured 100 mm x 100 mm x 100 mm, were specifically prepared for testing the compressive strength. A 3000 KN tester was used to apply the load at a rate consistent with the guidelines outlined in the IS 516 standards.

3.1.1 Compressive strength of GPC for the different WG/B ratios:

The evaluation of the geopolymer concrete's compressive strength involved adjusting the water glass-to-binder ratio from 0.4 to 0.65 across the different fly ash to GGBS ratios (50:50, 60:40, and 40:60). Notably, the strength of GPC showed a consistent increase with a rising water glass-to-binder ratio of up to 0.5. However, beyond this threshold, the strength started to decline. This trend in the strength variations is depicted in [Fig. 4].

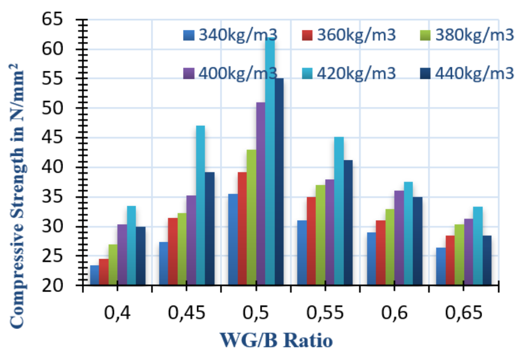

Fig. 4 *Compressive Strength of GPC for different liquid to binder ratios and the fly-ash to GGBS ratio 50:50.*

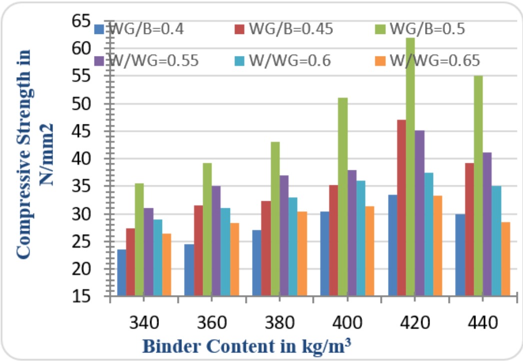

Fig. 5 *Compressive Strength of GPC for different binder contents and for fly ash to GGBS ratio of 50:50.*

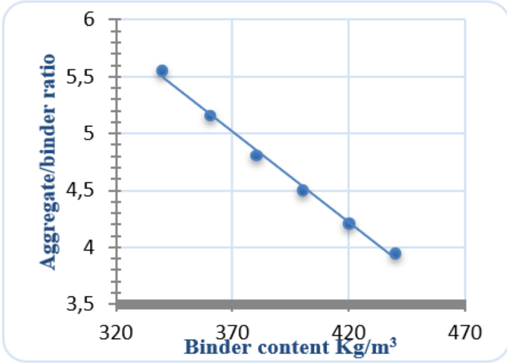

Fig. 7 *Variations of aggregate/binder ratio of GPC for different binder contents.*

3.1.2 Compressive strength of GPC for different binder contents:

The evaluation of the geopolymer concrete's compressive strength involved varying the binder content across different values, i.e., 340 kg/m^3, 360 kg/m^3, 380 kg/m^3, 400 kg/m^3, 420 kg/m^3, and 440 kg/m^3, while maintaining a fly ash to GGBS ratio of 50:50. The observations revealed a gradual increase in the GPC strength with the ascending binder content, which peaked at 420kg/m^3. However, beyond this threshold, the strength declined. This pattern of strength variations is illustrated in [Fig. 5].

3.1.3 Compressive strength of GPC for total AG/B ratio:

The evaluation of the geopolymer concrete's compressive strength involved manipulating the aggregate-to-binder ratio. It was observed that the highest compressive strength was attained at an aggregate-to-binder ratio of around 4.21. Beyond this point, as the ratio exceeded 4.21, the strength of the GPC gradually decreased. The aggregate-to-binder ratio in the mix was determined based on a GPC density of 2400 kg/m3. For the different binder content values, the corresponding aggregate-to-binder ratios were calculated, and this strength variation is depicted in [Fig. 6].

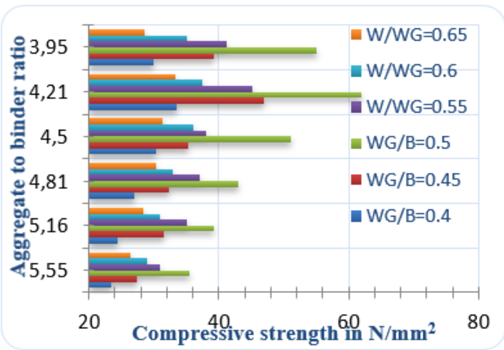

Fig. 6 *Compressive strength of GPC for different aggregate to binder ratios and for the fly ash: GGBS 50:50.*

3.1.4 Optimum Dosage of fibers in GPC

The ideal quantity of fiber in geopolymer concrete can vary based on the type used, which is typically expressed as a percentage volume of the total concrete mix. Adjustments were made within defined ranges, i.e., 0.5%, 1%, 1.5%, and 2.0% by volume for the steel fibers, and 0.2%, 0.4%, 0.6%, 0.8%, and 1% for the polypropylene and glass fibers to improve the concrete's strength properties. It was observed that increasing the fiber content gradually improved the strength until reaching a specific threshold. Beyond this point, the strength began to decline. Specifically, adding polypropylene fibers improved strength up to 0.6% of the fiber dosage, while for the glass fibers, the strength increased up to 0.8%. The steel fibers showed optimal enhancement at a dosage of 1.5% (Sangi et al., 2023).

3.2 Shear strength of GPC

Determining the precise shear strength of concrete is intricate and requires a thorough consideration of multiple factors. The shear strength of concrete stems from diverse mechanisms and elements within its composition and structure. The aggregate interlock, and the coarse aggregates particles play a pivotal role by interlocking within the cement paste, thereby their offering resistance against shear forces. Their irregular shapes and rough surfaces create frictional forces that resist shear movements.

Enhancements to the shear strength involve mechanisms such as the aggregate interlock, the dowel action between the adjacent concrete elements, and the formation of diagonal cracks, which can be prevented from widening by incorporating shear reinforcements such as stirrups. The pushup test entails exerting a force perpendicular to a specimen's face to directly measure its shear strength. However, performing direct shear tests on concrete poses challenges due to the intricacy of preparing sufficiently large specimens and the complexity involved in applying pure shear stresses.

The push-off test, which uses a push-off specimen, stands as one of the simpler methods for investigating shear transfer processes; this specimen consists of two L-shaped blocks connected by a junction to apply shear stress. To estimate the shear strength, push-off specimens are utilized. Each specimen includes a longitudinal reinforcement with a 10 mm diameter to prevent potential flexural failure and is complemented by two-legged 6 mm diameter stirrups. The specimen dimensions measure 340 mm x 200 mm x 100 mm. Shear strength assessments can be conducted across various concrete grades and different fiber types, e.g., steel, glass, and polypropylene fibers. Casting and curing are carried out for a duration of 28 days. The shear strength calculations are performed using the formula:

$$\tau = F/A \tag{1}$$

Where:

τ = Shear strength N/mm2

Tab. 4 *Shear strength of GPC with the optimum percentage of fibers*

Mix ID	GPC	GPC+1.5%SF	GPC+0.8%GF	GPC+0.6%PPF
G20	4.32	6.5	4.9	5.4
G30	4.7	7.1	5.5	5.8
G40	5.1	7.8	5.9	6.4
G50	5.7	8.3	6.2	6.9

The interfacial shear strength of fiber-reinforced GPC was detailed in [Table 4]. The observations revealed that the shear strength increased with the GPC grade. Notably, the highest increase was observed in steel fiber-reinforced GPC, with a 17% improvement in the shear strength. The shear strength results were reported in [Fig.8]. Shear failure stands as a critical concern in reinforced concrete structures due to its sudden occurrence and brittle characteristics. Owing to its complexity, various design methods and models have been developed to analyze shear strength. The push-off model is frequently employed for this purpose. There is still a gap in understanding shear capacity in FRC (Alimrani et al., 2024). When comparing fibers across a crack, aggregate interlock, and dowel action, the analysis revealed that, on average, the concrete's contribution in the compression zone is the most significant, whereas the contribution from the dowel action is the least significant (Sangi et al., 2024). The shear slip behavior observed in polyolefin and steel fiber reinforced concrete (SFRC) result in reduced fracture openings and enhanced compressive strength (Picazo et al., 2021). Steel fibers notably affect fracturing behavior and shear strength more than the other fiber types (Tran et al., 2020).

During push-off stress tests, the interfacial shear transmission in a reinforced engineered cementitious composite (ECC) was studied. The findings indicate that ECC initially achieves highest shear resistance before experiencing failure along the shear plane (Peng et al., 2020). Direct shear tests were employed to evaluate the shear behavior. Novel empirical equations were developed to anticipate the shear stress-slip correlation in ultra-high performance concrete (UHPC), considering the ratios for stirrups and steel fiber volumes. Higher steel fiber volume ratios were found to elevate shear strength and slip, while diminishing shear fracture width (Wu et al., 2019). The shear capacity of GPC reinforced beams made from fly ash was assessed and compared with Response 2000. It was observed that the GPC beams displayed a crack formation similar to OPC beams (Yacob et al., 2019). The results from testing the uncracked interfaces revealed that the ultimate shear transmission strength (STS) rises with an increase in the clamping force applied along the interface (Ahmad et al., 2015). Geopolymer concrete (GPC) specimens can endure higher shear stresses compared to traditional concrete with stresses (Navarro et al., 2016). In both dynamic and static loading, the conditions showed an increase in peak shear stress corresponding with higher strain rates (French et al., 2017). The impact of steel-fiber reinforcements on the shear behavior of concrete in the SFRC specimens demonstrates improved shear stiffness compared to RC. The reinforcement's ability to traverse the shear plane is crucial for the performance of fibers during diagonal fracturing (Kang et al., 2017). The compressive strength greatly influences the ultimate shear strength, but it has a minimum effect on fracturing (Rahal et al., 2016). In recycled aggregate concrete (RAC), the stress-slip relationship and fracture propagation closely resemble those observed in natural aggregate concrete. Geopolymer concrete exhibits limited workability when utilizing a 100% alkaline activator (Xiao et al., 2012).

The relationship between the compressive and shear strength of concrete is not a direct correlation; these properties are distinct and depend on various factors.

$$S = 0.919(_{fck})^{0.4883} \tag{2}$$

Where S and f_{ck} are both measured in MPa.

A higher compressive strength in concrete often indicates a better ability to resist shear forces; the relationship is complex and influenced by multiple factors.

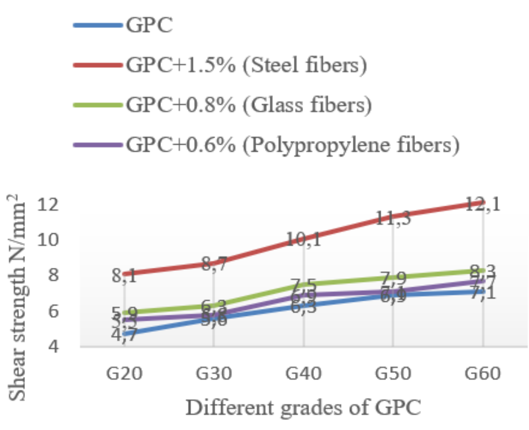

Fig. 8 *Shear strength of GPC with optimum dosage of fibers*

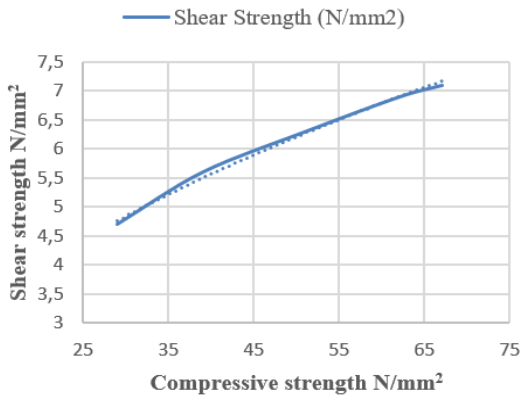

Fig. 9 *Shear strength developed due to aggregate interlocking and resistance from the uncracked concrete*

3.3 Effect of fibers on the shear strength of GPC

In plain GPC, shear strength primarily stems from the aggregate interlocking and resistance from the uncracked concrete (Sangi et al., 2024). In fiber-reinforced geopolymer concrete, aside from the previously mentioned mechanisms, shear resistance arises from the mechanical action and frictional resistance between the fibers and the concrete. This additional aspect can be assessed by comparing the shear strength between plain concrete and fiber-reinforced concrete

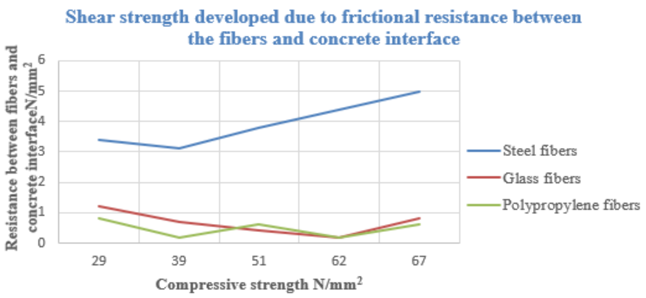

Fig. 10 *Shear strength developed due to frictional resistance*

The analysis revealed that in steel fiber-reinforced GPC, the maximum increase in shear strength reached 72%. Steel fibers contribute to approximately 65% enhancement in shear strength for steel fiber-reinforced concrete, whereas for glass fiber and polypropylene fiber-reinforced geopolymer concrete, the increase is around 19% and 8%, respectively. In samples without steel fibers, cracks first showed up near the top and bottom notches. As the load got heavier, these cracks spread towards the middle. Another crack formed on the side and moved toward the notch. When the load reached its highest point, the specimens broke into two parts along the middle with a sudden, brittle failure; there was no warning before they fell apart. The specimens with steel fibers behaved similarly to those without them. However, the presence of steel fibers delayed the appearance of cracks. Instead of cracking immediately, multiple small diagonal cracks emerged and gradually combined to create a band of cracking along the shear plane. Ultimately, these specimens also broke into two halves. The inclusion of shear ties at the interface prevented the specimen from breaking into two parts, and the use of steel fibers there also slowed down the crack growth. This alteration shifted the failure mode from brittle to ductile.

5 CONCLUSION

- The strength of geopolymer concrete is influenced by several factors; i.e., the water glass to binder ratio, the amount of binder content, the aggregate to binder ratio, and the fly ash to GGBS ratio. By adjusting these proportions, different grades of GPC mixtures were formulated.
- The ideal fiber quantities were established through variations in the compressive strength by adjusting the fiber percentages in the geopolymer concrete. The optimal dosages for the steel fiber, polypropylene fiber, and glass fiber were identified as 1.5%, 0.6%, and 0.8%, respectively.
- The observations revealed a gradual increase in shear strength with the grade of GPC. Furthermore, the addition of steel fibers in GPC demonstrated a higher increment in shear strength compared to the glass and polypropylene fibers.
- Shear strength primarily arises in plain GPC from the aggregate interlocking and the resistance offered by the uncracked concrete. However, in fiber-reinforced geopolymer concrete, the shear resistance is augmented by the mechanical action and the frictional resistance between the fibers and the concrete.
- The steel fiber-reinforced geopolymer concrete exhibited a remarkable increase of 72% in maximum shear strength. In comparison, the glass fiber-reinforced concrete showed enhancements of around 19%, while the polypropylene fiber-reinforced concrete demonstrated an approximate 8% improvement in shear strength.

The fiber reinforcement in GPC significantly improves its interfacial shear strength compared to conventional geopolymer concrete. The fibers bridge the cracks and distribute the stress more evenly, thereby enhancing the material's ability to resist shear forces. Engineers and designers can take advantage of the enhanced shear strength and ductility of fiber-reinforced geopolymer concrete to design efficient structural elements without compromising safety. With the enhanced properties of fiber-reinforced geopolymer concrete, the construction industry can achieve more durable, efficient, and sustainable structures, thereby addressing both performance and environmental concerns effectively.

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