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Effect of fibres on the interfacial shear strength of geopolymer concrete activated with water glass

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Abstract:
Cement, an important component of concrete, is used in construction. Unfortunately, the production of cement, releases considerable amounts of CO2 into the atmosphere. CO2 is the primary greenhouse gas responsible for global warming and finding alternatives to cement is essential to reduce CO2 emissions. Geopolymers are promising alternative binders that can completely replace ordinary Portland cement. Building large-scale structures with mass concrete leads to the formation of interfaces and joints, creating potential weak points that are prone to cracking. These connections may link concrete of different strengths or interface with different construction materials, such as steel. Ensuring cohesive performance in composite concrete structures requires a robust bond at these interfaces, which is usually achieved using shear ties. However, an excess of such ties can compromise the efficiency of the construction. To address these challenges in terms of design effectiveness and structural stability, this paper focuses on evaluating the interfacial shear strength of geopolymer concrete with and without the addition of polypropylene, steel and glass fibres. It was found that w the strength increased with the addition of fibres up to the threshold limit value and decreased thereafter. The test results show that the shear strength of steel fibre reinforced geopolymer concrete (GPC) the shear strength increment is maximum 72 %, increases by a maximum of 72 %, compared to 19 % for glass fibres.

Keywords:
compressive strength; shear strength; geopolymer concrete; GGBS; fly ash

1 Introduction

Over the last 30 years, the acceleration of global industrialisation and urban expansion has led to a significant increase in cement production. As a fundamental element in construction, cement has experienced rapid expansion owing to these trends. As a result, the cement sector has become the second-largest source of industrial CO_2 emissions globally and is responsible for approximately 25 % of total industrial CO_2 emissions [1]. To improve the quality of concrete and reduce the greenhouse gas (GHG) emissions associated with its production, fly ash serves as a substitute for ordinary Portland cement (OPC). This substitution improves concrete properties while concurrently reducing the environmental impact of GHG emissions [2, 3]. The ratio between fly ash and activator is a pivotal factor that significantly influences the strength of geopolymer concrete (GPC). A geopolymer made with fly ash showed remarkable performance when formulated with a Na_2SiO_3/NaOH ratio of 3,5 and exhibited a notably high compressive strength [4]. Increasing the H2O/Na2O ratio supported this polymerisation reaction. Observations show that the degree of reaction increases from 4,9-5,6 % within the 0-12-hour period at 60 °C [5].

Heating the fly ash-based GPC from 500-800 °C reduces the polymerisation process and reduces the strength [6]. Waterglass slag cement cured under standard conditions showed a higher compressive strength than Portland cement mortar. However, a notable disadvantage is the considerably greater drying shrinkage observed in alkali-slag cement compared to OPC [7]. The choice and number of activators are important for alkali-activated concrete. Elevating the activator dosage resulted in increased strength, whereas opting for a higher silicate modulus in the activator also contributed to higher strength [8]. Geopolymer concrete tends to be more brittle than conventional concrete. To overcome this brittleness, the addition of fibres is crucial. The introduction of fibres into GPC improves its overall performance [9].

The introduction of micro- and macro-steel fibres at the same total fibre volume resulted in substantial improvements in initial bond stiffness and bond strength [10]. Initial cracking in the fibre-reinforced concrete occurs due to bond slippage [11]. The water-to-binder ratio is important in determining the appropriate amount of fibre for optimal performance. Glass fibres, with their higher surface area, can impede the fluidity of the concrete and adversely affect it. Although the addition of glass fibres has not significantly increased the compressive strength, it has significantly improved the tensile and flexural strength as it effectively counteracts cracking [12]. The optimum fibre dose can be influenced by the water-to-binder ratio [13]. Initial scanning electron microscopy (SEM) observations indicated a notable increase in both pore size and quantity. This increase was primarily due to the combined effect of higher fibre content and water-to-binder ratio [14]. Analysis of the microstructures of fibre-reinforced concrete (FRC) shows that an increase in fibre dosage does not necessarily improve performance [15]. The SPFRC-C mixture, which contained crimped steel fibres showed the most significant increase in flexural strength. An impressive 120 % increase in the flexural strength was achieved with the SPFRC-C mix [16]. The addition of fibres to geopolymer concrete counteracts brittleness and improves overall performance. Both micro- and macro-steel fibres improved the bond stiffness and strength. Glass fibres improve the tensile and flexural capacities, but can affect the fluidity of the concrete. The water-to-binder ratio is critical for optimal fibre performance. The crimped steel fibres increased the flexural strength by 120 %, which showed significant improvement.

To determine the shear strength of the concrete, beams with different span-to-depth ratios were considered. However, normal loading on a beam does not produce pure shear. A push-up test was performed to accurately calculate the shear strengths of the concrete specimens.

2 Methodology

2.1 Materials and methods

Class F fly ash conforming to IS 3812-2003 standards sourced from Ramagundam in Telangana was used in this study. Ground granulated blast furnace slag (GGBS) was procured from JSW, Hyderabad. The coarse aggregates and river sand were as per the specifications of IS 383:2016. The activator waterglass solution was procured from Kiran Global Solutions, Chennai, Tamil Nadu. The properties of these materials are listed in Table 1.

Table 1. 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

The coarse aggregates (CA) used were granite chips with a nominal maximum size of 10 mm, and fine aggregates composed of Zone II sand. Steel, E-glass, and polypropylene fibres were used to improve the mechanical properties of GPC. The properties of the materials are listed in Table 2. They were sourced from the fibre region in Chennai, Tamil Nadu. The glass fibre (GF) material consists of numerous extremely fine glass fibres, each of which is 12 mm long and has a density of 2500 kg/m³.

Polypropylene fibre (PPF) is a linear synthetic polymer fibre derived from propylene polymerisation, also 12 mm in length and with a density of 905 kg/m³. Steel fibre (SF), small discontinuous steel fragments that are specially manufactured, has a diameter of 0,75 mm and a length of 60 mm. The integration of these fibres into concrete improves its structural properties.

Table 2. Properties of the different types of fibres

Properties	Steel fibre	Glass fibre	Polypropylene fibre
density (kg/m³)	7850	2500	905
tensile strength (N/mm²)	1116	3445	400
length (mm)	60	12	12
diameter (mm)	0,75	0,60	0,60
aspect ratio	80	20	20

2.2 Mix proportions of GPC

The mix proportions for GPC were determined taking several factors into account: activator-to-binder ratio, binder content, aggregate-to-binder ratio, and water-to-water glass ratio. These calculations aimed to maximise the use of fly ash while achieving the target strength. Different ratios of fly ash to GGBS (60:40, 50:50, and 40:60) were investigated to formulate the mix proportions for different grades of GPC [17].

To increase the cost-effectiveness of GPC production, researchers have investigated the use of water glass as a substitute activator [18]. Mix proportions of GPC for different grades represented in Table 3.

Table 3. Materials used for the preparation of GPC in kg/m³

MIX-ID	GGBS	Fly ash	Coarse aggregate	Fine aggregate	Water - glass	Water
G1	140	220	950	905	165	32
G2	180	200	925	885	182	45
G3	190	190	935	875	200	60
G4	200	200	895	865	210	65
G5	210	190	885	860	220	75

2.3 Optimum dosage of fibres

When determining the optimal quantity of fibres, the aim is to evaluate their influence on the compressive strength of the GPC. For this purpose, different percentages of fibres are added to the concrete, ranging from 0,5-2,0 % for steel fibres, and from 0,2-1,0 % for polypropylene and glass fibres, and the resultant compressive strength is analysed.

2.4 Shear behaviour of geopolymer concrete

To analyse the shear strength of the GPC, push-off specimens were used consisting of two L-shaped blocks joined by a ligament to which a shear stress was applied. All specimens consisted of a longitudinal reinforcement with a diameter of 10 mm and 2 legged 6 mm diameter stirrups were used to safeguard against potential flexural failure. The specifications of the specimens are shown in Figure 1a. The shear strength can be measured using a universal testing machine, as shown in Figure 1b. The failure modes are illustrated in Figure 1c.

(a)

(b)

(c)

Figure 1. (a) reinforcement details of push-off specimen; (b) push-off specimen testing; (c) failure mode of specimen

3 Results and discussion

3.1 Compressive strength of GPC

Standard cubic specimens measuring 100 × 100 × 100 mm were prepared for compressive strength testing. 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 different WG/B ratios

In evaluating the compressive strength of GPC, the waterglass-to-binder ratio was adjusted from 0,40-0,65 at different ratios of fly ash to GGBS (50:50, 60:40, and 40:60). It is noteworthy that the strength of the GPC increased steadily with increasing waterglass-to-binder ratio up to 0,5. However, beyond this threshold, the strength began to decrease. The pattern of strength variation is shown in Figure 2.

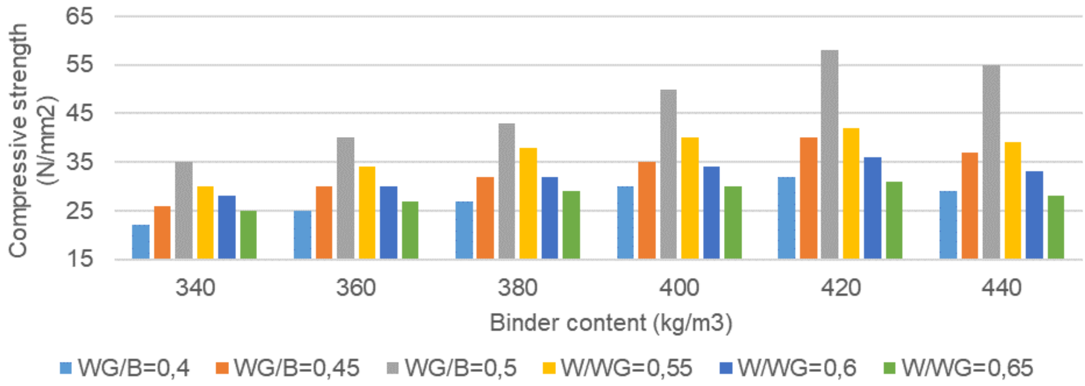

Figure 2. Compressive strength of GPC for different binder content and at a fly ash to GGBS ratio of 50:50

3.1.2 Compressive strength of GPC for different binder content

In evaluating the compressive strength of GPC the binder content was varied using different values: 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 50:50 ratio of fly ash to GGBS. The observations revealed a gradual increase in GPC strength with increasing binder content, peaking at 420 kg/m^3. However, beyond this threshold, the strength decreases.

3.1.3 Compressive strength of GPC for total AG/B ratio

In evaluating the compressive strength of GPC, the aggregate-to-binder ratio was manipulated. The highest compressive strength was achieved at an aggregate-to-binder ratio of approximately 4,21. Beyond this point, as the ratio exceeded 4,21 the GPC strength gradually decreased. The aggregate-to-binder ratio of the mixture was determined based on the binder content, as shown in Figure 3.

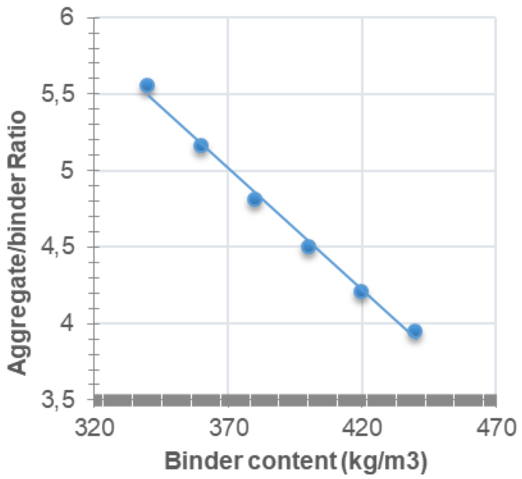

Figure 3. Variation of aggregate/binder ratio of GPC for different binder content

For different binder contents, the corresponding aggregate-to-binder ratios were calculated taking onto account the unit weight of the GPC of 2400 kg/m^3. The variations in strength with different aggregate-to-binder ratios are shown in Figure 4.

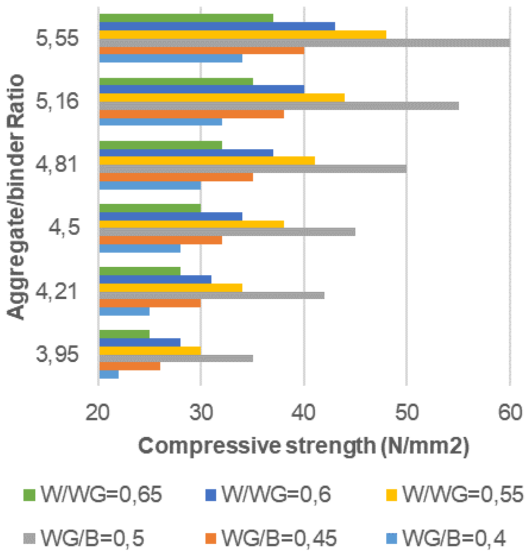

Figure 4. Compressive strength of GPC for different aggregate to binder ratio and for the fly ash: GGBS 50:50

3.1.4 Optimum dosage of fibres in GPC

The ideal fibre quantity in GPC can vary depending on the type used and is usually given as a percentage of the total concrete mix volume. To improve the strength of the concrete, adjustments were made within defined ranges: 0,5 %, 1,0 %, 1,5 %, and 2,0 % by volume for steel fibres, and 0,2 %, 0,4 %, 0,6 %, 0,8 %, and 1,0 % for polypropylene and glass fibres. It was observed that increasing the fibre content gradually improved the strength until a specific threshold was reached. Beyond this point, the strength began to decrease. Specifically, the addition of polypropylene fibres improved the strength by up to 0,6 % of the fibre dosage, whereas for glass fibres, the strength increased by up to 0,8 % with glass fibres. The steel fibres showed an optimal improvement at a dosage of 1,5 % [19].

3.2 Shear strength of GPC

Determining the exact shear strength of concrete is complex and requires thorough consideration of several factors. The shear strength of concrete stems from the diverse mechanisms and elements within its composition and structure. Aggregate interlocking and coarse aggregate particles play a critical role as they interlock within the cement paste and resist the shear forces. Their irregular shapes and rough surfaces create frictional forces that resist shear movements.

The improvement in shear strength is based on mechanisms such as aggregate interlocking, dowel action between adjacent concrete elements, and the formation of diagonal cracks, which can be prevented from widening by incorporating shear reinforcements such as stirrups or other types of reinforcement. In the push-up test, a force is applied vertically to the face of a specimen to measure its shear strength directly. However, performing direct shear tests on is a challenge as it is difficult to prepare sufficiently large specimens and the complexity involved in applying pure shear stresses. The push-off test is a simpler method of investigating shear transfer processes using a push-off specimen. The specimen consisted of two L-shaped blocks connected by a junction to apply shear stress. The push-off specimens were used to estimate the shear strength. Each specimen contained a 10 mm diameter longitudinal reinforcement to prevent possible flexural failure, complemented by two-legged 6 mm diameter stirrups. The specimen dimensions were 340 × 200 × 100 mm. A schematic representation of the reinforcement is shown in Figure 1a.

Shear strength assessments can be conducted across various concrete grades and fibre types such as steel, glass, and polypropylene. Casting and curing were performed for 28 d. The shear strength is calculated according to the following formula, where *τ* is a shear strength in N/mm^2:

$$\tau = F/A \quad (1)$$

Where *F* is the shear force in and *A* is the shear area of specimen.

The observations revealed that the shear strength increased with the GPC grade. Notably, the highest increase was observed in steel fibre-reinforced GPC, with a 17 % improvement in shear strength. The shear strength results are shown in Figure 5. The shear strength of GPC due to aggregate interlocking and resistance from the uncracked concrete is shown in Figure 6. Shear failure is a critical concern in reinforced-concrete structures as it occurs suddenly and its brittle characteristics.

Owing to their complexity, various design methods and models have been developed to analyse shear strength. Push-off models are frequently used for this purpose. There is still a gap in the understanding of the shear capacity of FRC [20]. When comparing fibres across the crack, aggregate interlock, and dowel action, the analysis revealed that the contribution of concrete in the compression zone was on average the largest, whereas the contribution from the dowel action was the smallest [21]. The shear slip behaviour observed in polypropylene and steel fibre reinforced concrete (SFRC) results in a reduced fracture opening and increased compressive strength [22]. Steel fibres influence the fracturing behaviour and shear strength significantly more than other fibre types [23].

During push-off stress tests, the interfacial shear transmission in a reinforced engineered cementitious composite (ECC) was studied. These findings indicate that the ECC initially achieved the highest shear resistance before failing along the shear plane [24]. Direct shear tests were conducted to evaluate the shear behaviour. Novel empirical equations were developed to anticipate the shear stress-slip correlation in ultra-high-performance concrete (UHPC), considering the ratios of stirrups and steel fibre volumes. It was found that a higher steel fibre volume ratio increases the shear strength and slip while the shear fracture width decreases [25]. The shear capacity of GPC-reinforced beams made from fly ash was assessed and compared with that of Response 2000. The GPC beams exhibited crack formation similar to that of the OPC beams [26]. The results of uncracked interface testing revealed that the ultimate shear transmission strength (STS) increased with increasing clamping force applied along the interface [27]. GPC specimens can withstand higher shear stresses than conventional concrete [28]. Under both dynamic and static loading conditions, there was an increase in the peak shear stress corresponding to higher strain rates [29, 30]. The effect of steel-fibre reinforcement on the concrete shear behaviour in the SFRC specimens showed improved shear stiffness compared to RC. The ability of a reinforcement to traverse the shear plane is critical to the performance of the fibres during diagonal fracturing [31]. The compressive strength has a significant influence on the ultimate shear strength but only a minor influence on fracturing [32]. In recycled aggregate concrete (RAC), the stress-slip relationship and fracture propagation closely resemble those of natural aggregate concrete. GPC exhibits limited workability when a 100 % alkaline activator is used [33]. The relationship between compressive strength (f_{ck}) and shear strength (τ) of concrete is not a direct correlation. These properties are distinct and depend on several factors.

$$\tau = 0{,}9(f_{ck})^{0{,}5} \text{ (MPa)} \quad (2)$$

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

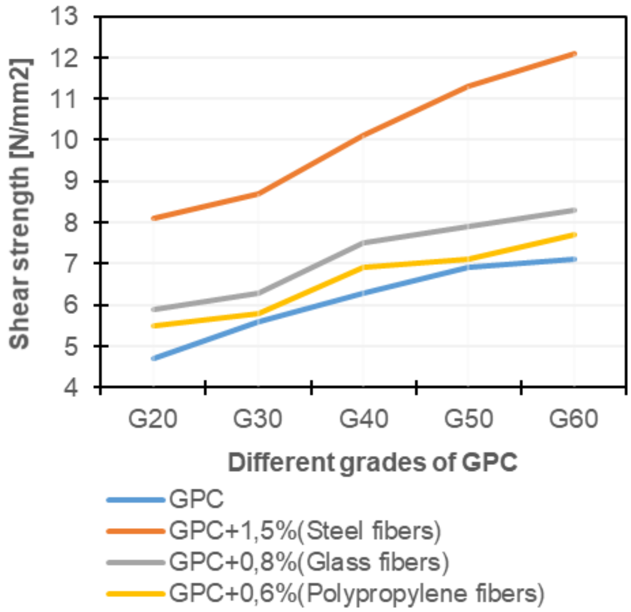

Figure 5. Shear strength of GPC with optimum dosage of fibres

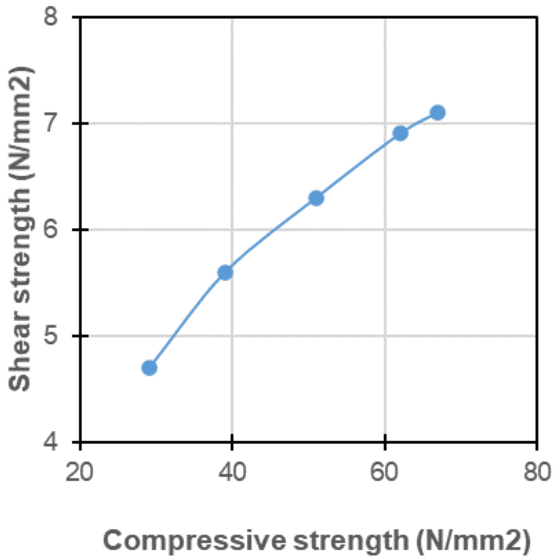

Figure 6. Comparison of shear and compressive strength

3.3 Effect of fibres on shear strength of GPC

In plain GPC, the shear strength primarily stems from aggregate interlocking and the resistance of uncracked concrete. In fibre-reinforced GPC, aside from the previously mentioned mechanisms. Shear resistance arises from mechanical action, and the frictional resistance between the fibres and concrete increases the shear strength. The shear strength develops only due to the frictional resistance between the fibres and the concrete, as shown in Figure 7. This additional aspect can be assessed by comparing the shear strengths of plain concrete and fibre-reinforced concrete.

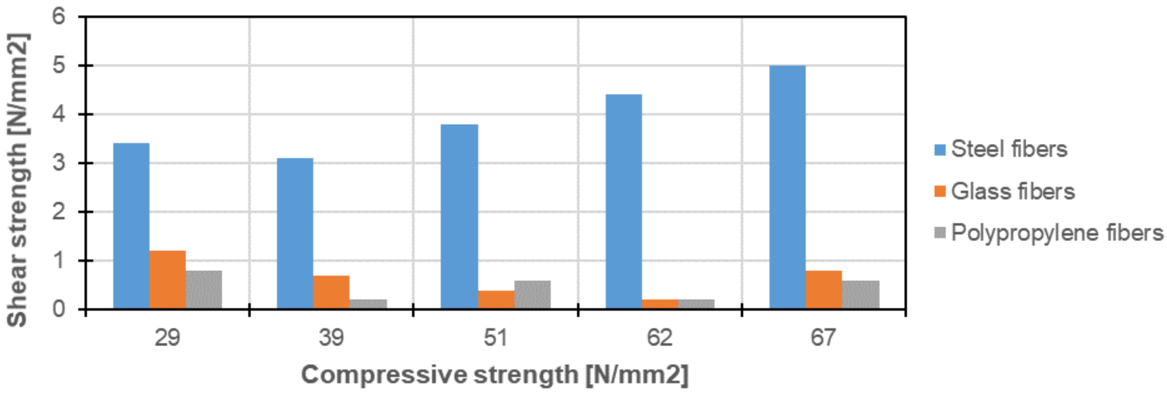

Figure 7. Development of the shear strength due to frictional resistance of fibres and concrete matrix

The analysis revealed that the shear strength in steel fibre-reinforced GPC, increased by a maximum of 72 % compared to plain GPC. Steel fibres contributed to an increase in the shear strength of steel fibre-reinforced concrete by approximately 65 %, whereas the increases for glass fibre and polypropylene fibre-reinforced GPC were approximately 19 % and 8 %, respectively.

(a) (b) (c)

Figure 8. Failure patterns of the GPC specimens: (a) without shear reinforcement; (b) with shear reinforcement and fibres; (c) without shear reinforcement, with fibres

The failure patterns of the GPC specimens are shown in Figure 8. In the samples without steel fibres, the cracks first appeared near the top and bottom notches. With increasing load, 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 occurring with no warning before falling apart. The specimens with steel fibres behaved similarly to those without steel fibres. However, the presence of steel fibres delayed the appearance of cracks. Instead of immediate cracking, multiple small diagonal cracks appeared, which gradually joined together to form a crack band along the shear plane. Ultimately, the specimens broke in half. The inclusion of shear ties at the interface prevented the specimen from breaking into two parts, and the use of steel fibres also slowed the crack growth. This shifts the failure mode from brittle to ductile.

4 Conclusions

The strength of GPC is influenced by several factors, including the water glass-to-binder ratio, amount of binder content, aggregate-to-binder ratio, and fly ash to GGBS ratio. By adjusting these proportions, GPC mixtures of different grades were formulated.

The ideal fibre quantities were determined by varying the compressive strength by adjusting the fibre percentages in GPC. The optimal dosage of steel fibre, polypropylene, and glass fibre, was found to be 1,5 %, 0,6 %, and 0,8 %, respectively.

The observations revealed a gradual increase in shear strength with the GPC grade. Furthermore, the addition of steel fibres to GPC resulted in a greater increase in shear strength compared to glass and polypropylene fibres.

For plain GPC, the shear strength results primarily from aggregate interlocking and the resistance offered by the uncracked concrete. However, in fibre-reinforced GPC, shear resistance is augmented by the mechanical action and frictional resistance between the fibres and the concrete.

The steel fibre reinforced GPC exhibited a remarkable 72 % increase in the maximum shear strength. In comparison, the glass fibre reinforced concrete showed an improvement of approximately 19 %, whereas the polypropylene fibre-reinforced concrete showed an improvement in shear strength of approximately 8 %.

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