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EFFECT OF POLYPROPYLENE FIBER ON THE STRENGTH PROPERTIES OF GEOPOLYMER CONCRETE ACTIVATED WITH WATER GLASS

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Abstract

Cement, which is a significant constituent in concrete, plays a crucial role in the construction industry. The manufacturing process of cement releases substantial amounts of CO_2, thereby contributing to environmental concerns. To address this issue, geopolymers have emerged as promising alternative substitutes to ordinary Portland cement. However, one of the challenges in utilizing geopolymer binders is the need for activators to initiate the polymerization process. Sodium silicate and sodium hydroxide solution are commonly used activators, but ground granulated blast-furnace slag (GGBS) reacts quickly with these activators and reduces the setting time. In order to arrest quick settings and enhance the efficiency of concrete production, "water glass" is used as an activator. The present study investigates the flexural and split tensile strength of geopolymer concrete by optimizing the dosage of polypropylene fibers for different mix proportions of GPC activated with water glass. The optimum dosage of fibers was obtained by the addition of different dosages of polypropylene fibers ranging from 0, 0.2%, 0.4%, 0.6% and 0.8%. The results from the investigation revealed a consistent augmentation in compressive strength with the incremental addition of fibers up to a threshold of 0.6%; beyond this point, the strength exhibited a dimin-ishing trend, while the flexural strength and split tensile strength were enhanced from 25% to 45% with the addition of an optimum dosage of polypropylene fibers. By optimizing the material formulations and mix proportions, it is possible to achieve a superior performance by minimizing the environmental impact on the construction industry.

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Key words

- Geopolymer concrete,
- Water glass,
- Compressive strength,
- Polypropylene fiber,
- Flexural strength.

NOMENCLATURE

GPC	Geopolymer concrete	WG	Water glass
OPC	Ordinary Portland cement	ITZ	Interfacial transition zone
GGBS	Ground granulated blast furnace slag	UHPFRC	Ultra-high-performance fiber reinforced concrete
FRC	Fiber-reinforced concrete	UHPC	Ultra-high-performance concrete
AFS	Alkali-activated fly ash slag	CS	Compressive strength
PPF	Polypropylene fiber	STS	Split tensile strength
SCC	Self-compacting concrete	FS	Flexural strength

1 INTRODUCTION

In the past thirty years, the world has witnessed a substantial increase in cement production, primarily driven by the forces of global industrialization and urbanization. Cement, a pivotal component in the construction industry, has undergone a remarkable expansion as a result of these trends. Consequently, the cement sector has now risen to become the second-largest source of industrial CO_2 emissions on a global scale, contributing approximately a quarter of the total industrial CO_2 emissions worldwide (Chen, C. et al., 2022). In an effort to enhance its properties and reduce the CO_2 emissions associated with cement production, cement replaced with fly ash has demonstrated its effectiveness in enhancing the attributes of concrete, while simultaneously addressing environmental concerns related to greenhouse gas emissions (O'Brien, K.R. et al., 2009). Fly ash and slag are by products of industry and pose significant challenges as they accumulate solid industrial waste on arable land and contribute to atmospheric pollution due to the limited management practices for industrial solid waste disposal (Qaidi, S.M.A. et al., 2022).

Geopolymer concrete, which is known for its cost-effectiveness, minimal energy consumption, thermal stability, ease of workability, environmental friendliness, absence of traditional cement, and durability, stands as a sustainable option (Verma, M. et al., 2022). Geopolymerization is a chemical reaction, which involves the formation of a strong alumina-silicate gel structure. This process utilizes the silica and alumina components present in binding materials like fly ash and slag, which are activated by an alkaline solution containing substances such as NaOH and Na_2SiO_3. The microstructure of interconnected geopolymer exhibits greater resilience when subjected to external environmental factors. In the geo-polymerization process, alkali metals play a crucial role in both the reaction rate and the resulting materials. Geopolymer is an inorganic polymer that exhibits an amorphous structure at elevated temperatures. Applying heat for curing accelerates the polymerization rate compared to curing at ambient temperatures (Davidovits, J., 1994).

Fly ash, which is abundant in silica and alumina components, exhibits pozzolanic traits and binding capabilities. When incorporated into geopolymer concrete, it imparts superior workability and offers higher solid-to-liquid ratios compared to other pozzolanic materials such as slag, metakaolin, and rice husk ash. This advantage arises from fly ash's small particle size, as well as its spherical and porous characteristics (Zhang, P. et al., 2020). When geopolymer concrete augments the quantity of ground granulated blast furnace slag, it has a diminishing effect on the mixture's workability. This decrease is attributed to the angular nature of the slag particles when compared to the spherical particles of fly ash. Additionally, the increased dosage of GGBS results in a reduction in the setting time at ambient temperatures due to the chemical reaction involving the calcium found in the slag (Rajashekar, S et al., 2023). When GGBS is combined with fly ash in GPC, it yields a compressive strength similar to that of water-cured ordinary Portland cement concrete. The rate of development of the strength in the specimens slows down after 28 days but continues to strengthen over the course of 180 days (Deb, P.S. et al., 2014).

The curing temperature significantly influences the setting and solidification of geopolymer concrete. When GPC samples are cured at elevated temperatures, they achieve concrete-like properties within just 4 hours at an ambient temperature. However, when the ambient temperature falls below 10 °C, it takes up to 4 days for fresh concrete to set without compromising its quality. GPC specimens subjected to higher-temperature curing achieve mechanical strength within a single day. In contrast, fresh concrete cured at ambient temperature displays a gradual increase in the quality of its strength, notably surpassing its gain in strength within the first 28 days. It is important to note that the duration of curing also plays a crucial role in achieving strength, especially when combined with variations in temperature (Hadi, M.N.S. et al., 2019). Geopolymer concrete exhibits a higher level of brittleness compared to conventional concrete. To mitigate this brittleness in geopolymer concrete, the incorporation of fibers has become essential. Fiber-reinforced concrete (FRC) has been increasingly preferred for real-world engineering applications owing to its exceptional tensile strength, flexural strength, durability, and fracture properties. The addition of fibers in GPC enhances its overall performance and makes it more suitable for practical engineering applications (Prasad, B.V. et al., 2023). The mortar made with alkali-activated fly ash slag (AFS) exhibits superior compressive strength, flexural strength, and lower water absorption compared to mortar samples composed of ordinary Portland cement. The hydration product in the AFS paste predominantly consists of amorphous components, and the higher content of fly ash results in reduced dimensional changes or variations in length (Chi, M.,2017).

In fiber-reinforced concrete, an initial crack is a result of a bond slip (Swamy, R.N. et al., 1974). The optimal fiber content can be influenced by the water/binder ratio. Based on the initial analysis of scanning electron microscope (SEM) observations, one of the primary factors is a significant rise in the size and quantity of pores, which arises from the combined effect of the increased water/binder ratio and fiber content (Yuan, Z. et al., 2021). Upon examining the microstructures of fiber-reinforced concrete, it becomes evident that augmenting the fiber dosage might not lead to an improved overall mechanical performance. Instead, it can result in the ineffective interweaving and agglomeration of the fibers, potentially increasing the occurrence of micro-cracks within the internal concrete structures (Xu, H. et al., 2020). A steel fiber-reinforced concrete (SFRC) mix, which incorporates crimped steel fibers, exhibits the most substantial increase in flexural strength. When using a SFRC mix, the flexural strength experiences a remarkable enhancement of 120% (Antarvedi, B. et al., 2023).

The incorporation of dispersed fibers represents a highly promising and extensively utilized technology for significantly enhancing concrete properties. Numerous researchers have explored the impact of randomly distributed fibers within concrete and consistently affirmed substantial improvements in both mechanical strength and durability (Paul, S.C. et al., 2020). Incorporating fibers into concrete enhances its post-peak performance (Sangi,R. et al.,2024; Aisheh, Y. et al., 2022). The presence of hybrid fibers effectively mitigates sudden failure and facilitates a transition to a softer state. The inclusion of 1% steel fibers and 0.1% polypropylene fibers in a GPC specimen result in a notable enhancement of the displacement ductility factor and energy absorption capacity. Specifically, these properties increase by 2.64 times and 2.09 times, respectively, when compared to specimens that do not incorporate any fibers (Sathish Kumar, V. et al., 2022; Sangi, R. et al., 2023).

2 MATERIALS AND METHODOLOGY

2.1 Materials

Class F fly ash and GGBS are used as binding materials; the chemical composition of these materials is detailed in (Tab. 1). Different combinations of fly ash and GGBS are used as binding materials; to activate these binding materials, water glass with a Na_2O/SiO_2 ratio of 1.99 is used as the activator, and natural river zone –II sand is used as a fine aggregate. Angular granite chips with a nominal maximum size of 10 mm are used as coarse aggregates. To understand the strength properties of GPC, different proportions of polypropylene fibers are used.

Tab 1. *Chemical composition of GGBS and fly ash (% mass)*

Chemical Composition	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	Na_2O	SO_3	LOI
Flay ash	60.12	26.35	4.21	1.26	4.1	0.23	0.35	3.25
GGBS	34.29	20.15	32.4	7.39	0.8	Nil	0.91	3.85

Polypropylene fiber (PPF) is a linear synthetic polymer fiber resulting from the polymerization of propylene. These fibers, which are 12 mm in length, exhibit a density of 905 kg/m³ and offer advantages such as being lightweight, robust, tough, and resistant to corrosion.

2.2 Methodology

The geopolymer concrete mix proportions were established through a comprehensive strength assessment of the GPC and by varying the activator-to-binder ratio, binder content, aggregate-to-binder ratio, and a fly ash-to-GGBS ratio. To assess the compressive strength, conventional cubic specimens of dimensions of 100 mm x 100 mm x 100 mm were prepared. These specimens were subjected to compression testing using a 3000 kN tester and adhered to the recommended standard load rate stipulated by IS 516. The optimum dosage of fibers can be identified based on the compressive strength of GPC by adding different percentages of fibers into the concrete mix. These fibers range from 0.2% to 0.8% for polypropylene fibers. Cylindrical samples of size 150 mm x 300 mm were cast and cured at an ambient temperature. The split tensile strength was examined for different grades of GPC with an optimum dosage of polypropylene fibers. The test was conducted as per IS: 5816-1999 and IS 456-2000. Prism specimens, each measuring 100 mm x 500 mm, were meticulously fabricated across various grades of GPC with an optimum dosage of polypropylene fibers. After being cured for a period of 28 days under ambient conditions, the test was conducted as per BIS 516.

3. RESULTS AND DISCUSSION

3.1 Compressive strength of GPC

By varying the water glass-to-binder ratios of 0.4, 0.45, 0.5, 0.55, 0.6, and 0.65, and using binder contents of 340 kg/m³, 360 kg/m³, 380 kg/m³, 400 kg/m³, 420 kg/m³, and 440 kg/m³, with different fly ash to GGBS combinations, different grades of GPC were produced. The mix proportions of the GPC are represented in (Tab. 2). Increasing the binder content enhances the strength of GPC, as a greater quantity of the binder fosters the formation of a more extensive geopolymeric gel, thereby improving the cohesion between the particles (Rajashekar, S. et al., 2023). Increasing the AG/B ratio diminishes the strength of the GPC, as a higher proportion of aggregates diminishes the available binder for the formation of geopolymeric gel, resulting in weaker inter-particle bonding (Sangi, R. et al., 2023). The highest compressive strength is associated with the utilization of ground granulated blast furnace slag; when this material is partially substituted with fly ash, silica fume, or metakaolin, a reduction in strength occurs. Conversely, there is an improvement in strength when GGBS replaces the primary pozzolanic material (Venu, M. et al., 2018). Substituting fly ash with ground granulated blast furnace slag presents a viable alternative to conventional oven curing, yielding nearly identical results.

Tab 2. *Mix proportions of GPC.*

Mix ID	Fly ash (kg/m³)	GGBS (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)	Water Glass (kg/m³)	Compressive Strength (N/mm²)
G20	216	144	910	948	162	29
G30	240	160	882	918	180	39
G40	200	200	900	900	200	51
G50	210	210	884	884	210	62
G60	160	240	882	918	220	67

Fig. 1. *Different grades of a GPC cube*

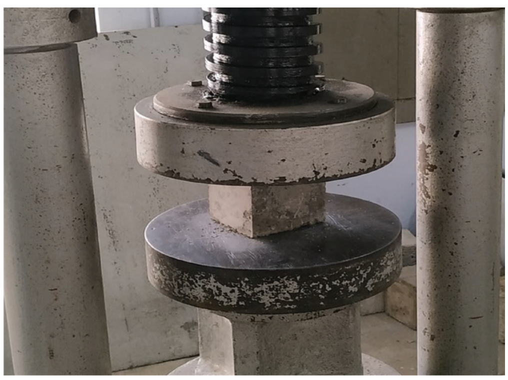

Fig. 2. *Testing of a GPC cube with CTM*

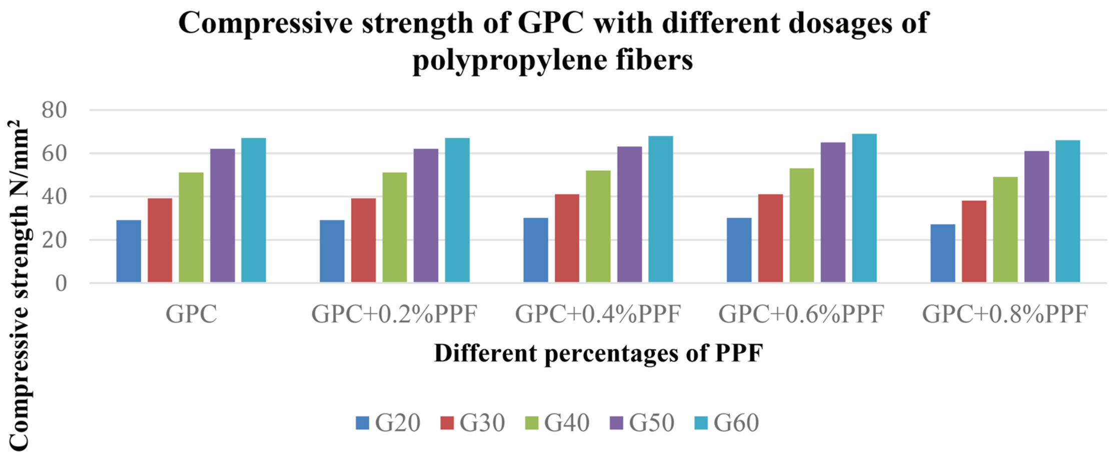

Fig. 3. *Optimum dosage of polypropylene fibers for different grades of GPC.*

3.2 Optimum Dosage of polypropylene fibers in GPC

Generally, fiber dosages are expressed as a percentage of the total volume of the concrete mixture. To enhance the strength attributes of geopolymer concrete, polypropylene fiber dosages of 0.2%, 0.4%, 0.6%, and 0.8% of the total volume of the geopolymer concrete mix were used. The addition of polypropylene fibers had less of an impact on the compressive strength; a modest increase was noted up to 0.6% of the fibers, followed by a subsequent decline. These compressive strength results are illustrated in (Fig. 1).The resistance level primarily relies on the mechanical properties of the fibers and the state of the contact between the fibers and the matrix, both of which are influenced by the alkaline environment and the fiber content. Thanks to the robust interface, the spring model can effectively represent the energy dissipation mechanism of BF-FGPC before it reaches the point of failure (Yang, S. et al., 2023).

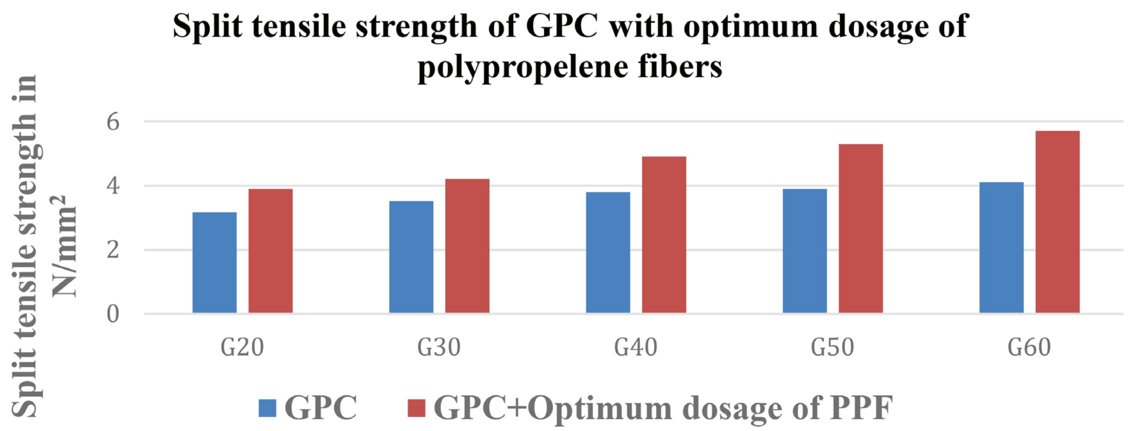

Fig. 4. *Split tensile strength of GPC with optimum dosage of fibers.*

3.3 Split Tensile Strength of GPC

The flexural strength (FS) and split tensile strength (STS) followed a similar path as the compressive strength of GPC. The analysis revealed a gradual increase in STS in accordance with the GPC grade. The corresponding split tensile results can be seen in (Fig. 2). Notably, the incorporation of fibers led to an increase in the split tensile strength. The most substantial enhancement was observed in the polypropylene fiber reinforcement, resulting in an impressive improvement in strength ranging from 20% to 30%. The polypropylene fibers (PPF) serve to reinforce and improve the integrity of the GP matrix, stopping the emergence of micro cracks and changing the path along which cracks propagate (Elsayed, M. et al., 2022). Incorporating a 2.25 percentage of SF into the standard concrete significantly increases the split tensile strength (STS) by 33%. However, in a 2SF-0.25PF blend, the replacement of PF leads to a 4.5% decrease in STS compared to the 2.25SF mix, whereas the introduction of PF increases STS by 1.9% when compared to the 2.0SF mix. These results suggest that the inclusion of PF in the 2.0SF mix has a positive influence on STS (Aisheh, Y.I.A. et al., 2022). The presence of fibers in specimens enhances tensile strength compared to those without fibers, primarily due to the bridging effect they exert on fractures (Ramezanianpour, A. A. et al., 2013).The interface between the PF and the matrix remains relatively weak, despite the fact that the bonding force increases as the embedded depth increases (Yang, S. et al., 2018).

3.3.1 Relation between split tensile strength (STS) and compressive strength (CS) of GPC with an optimum dosage of PF fibers

The rate at which the split tensile strength (STS) increases or decreases with the compressive strength (CS) of geopoly-

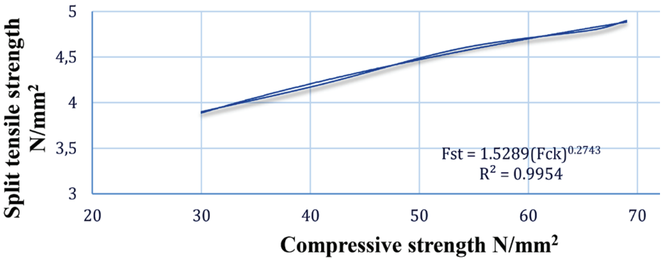

Fig. 5. *Relation between the compressive strength and split tensile strength of GPC*

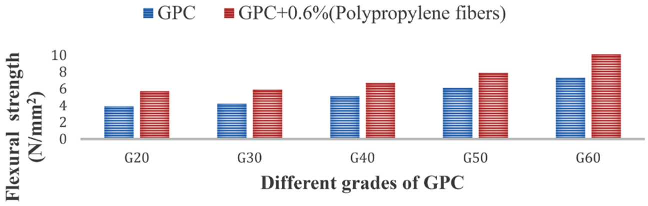

Fig. 6. *Flexural strength of GPC with optimum dosage of fibers.*

mer concrete (GPC) was observed. Substituting fly ash with GGBS has a comparatively lower impact on flexural strength and split tensile strength compared to its effect on compressive strength. (Fig. 5) shows the variations in the compressive strength and split tensile strength. The relationship between compressive strength and split tensile strength with the optimum dosage of polypropylene fibers is indicated by the two equations derived from the test data.

The following power equation was derived to describe the scatter in all the data points:

$$f_{st} = 1.5289(f_{ck})0.2743 \quad (1)$$

Here, both the f_{st} = split tensile strength, and fck= compressive strength, are expressed in MPa. The coefficient of determination (R^2) for this equation was found to be 0.9954, which is relatively high, thereby underscoring the effectiveness of the analysis.

3.4. Flexural strength of GPC

An incremental rise in flexural strength was noted in correlation with the GPC grade. The most substantial augmentation in flexural strength was observed in the context of the polypropelene fiber reinforcement, which led to a remarkable improvement of approximately 20% to 30%. Among the mixes tested, the G60-PF blend exhibited the highest flexural strength, i.e., 10.1MPa. The inclusion of 0.6% of PF resulted in a remarkable 21% increase in strength compared to the control mix. These notable enhancements in flexural strength can be seen in (Fig. 4). Introducing PF into the 2.0-SF-0.25-PF mix slightly reduced the strength by 1.75% compared to the 2.25-SF mix (Aisheh, Y.I.A. et al., 2022). PPF fibers are more susceptible to breakage, and in a specific case, PF fibers were extracted from the mortar without causing any damage to the contact surface (Abbas, S. et al., 2015). The split tensile strength, hardness, and flexural strength of UHPC are influenced by factors such as the fiber surface characteristics, bonding strength, and surface roughness between the mortar and aggregate. Polypropylene fibers (PPF) play a pivotal role in fortifying and improving the GP paste matrix, stopping the formation of micro cracks, and changing the configuration of crack propagation (Elsayed, M. et al., 2022). According to IS 456:2000, the recommended maximum strain for specimens subjected to flexure is 0.0035. However, recent test results conducted on HTGPC specimens suggest that a strain of 0.004 is conservative (Sathish Kumar, V. et al., 2022).

3.4.1 Relation between CS and FS of GPC with an optimum dosage of PF fibers

Upon the replacement of fly ash with slag, the flexural strength increased from 15% to 20%, indicating that this modification led to an improvement in compressive strength (Sangi, R. et al., 2023). The addition of PPF not only enhances flexural strength but also contributes to increased compressive strength. This is due to the improved bonding between the fibers and the concrete matrix, which helps to prevent crack propagation and improve the overall load-bearing capacity. Polypropylene fibers primarily enhance flexural strength by resisting bending stresses; they also contribute to improving the overall structural integrity of the concrete, leading to higher compressive strength. The relationship between compressive strength (CS) and flexural strength (FS) follows a pattern closely similar to that observed in the splitting tensile strength analysis. The equations obtained from the regression analysis display a significant similarity, indicating a consistent correlation between these different measures of strength in the geopolymer concrete.

Fig. 7. *Testing of GPC beams with UTM*

Fig. 8. *GPC beams after testing*

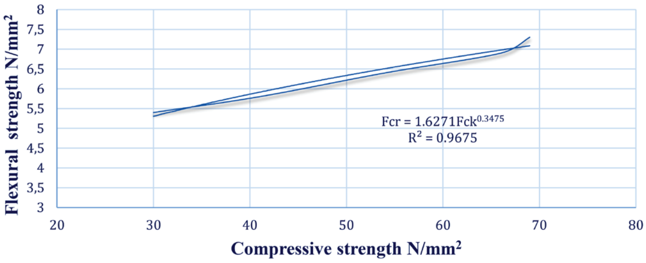

Fig. 9. *Relation between compressive strength (CS) and flexural strength (FS) of GPC*

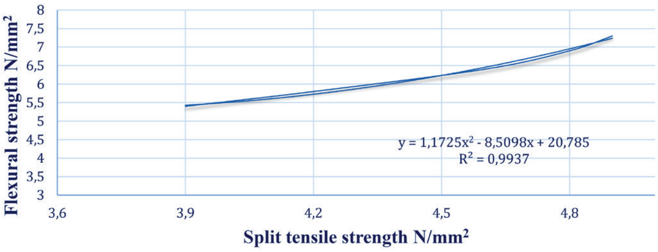

Fig. 10. *Relationship between FS and STS of GPC with the addition of PF fibers*

The presence of PP fibers can enhance the compactness of the ITZ, which means that the space between the aggregate particles is filled more effectively by the cementitious matrix. The improved compactness reduces the porosity of the ITZ, which in turn enhances the bond between the aggregate and the matrix. A denser and better-bonded ITZ is less prone to crack initiation and propagation. PP fibers act as a reinforcement within the concrete matrix. When cracks form, these fibers help to distribute stresses and restrain crack propagation. By bridging across cracks and absorbing energy, the fibers slow down the progression of cracks, thereby improving the durability and toughness of the concrete.

3.4.1 Relation between compressive strength (CS) and flexural strength (FS) of GPC

Relationship between FS and STS of GPC with the addition of PF fibers

This slowdown in crack propagation is particularly beneficial in the ITZ, where cracks often initiate and propagate.

$$f_{cr} = 1.6271(f_{ck})^{0.3475} \quad (2)$$

where f_{cr} = flexural strength (N/mm^2) and f_{ck} = compressive strength (N/mm^2). In this equation, a relatively high coefficient of determination (R^2 = 0.9675) was obtained, thereby highlighting the effectiveness of the regression analysis. The mechanical properties of the GPC matrix within the ITZ are closely tied to its density. A denser matrix typically exhibits higher compressive and flexural strength. The inclusion of PPF, which enhances the compactness of the ITZ, can therefore indirectly improve the mechanical properties of the matrix within this zone. This results in a concrete mix with an overall improved mechanical performance.

4 CONCLUSIONS

- The strength attributes of GPC are significantly influenced by several factors, including the water glass-to-binder ratio, the aggregate-to-binder ratio, the binder content, and the ratio of fly ash to GGBS. To investigate this impact, these proportions were systematically modified in the formulation of geopolymer concrete with grades of G20, G30, G40, G50, and G60.
- The mechanical properties of GPC depend on the type and dosage of fiber; the optimal dosage of fiber for various grades of GPC were evaluated based on the compressive strength. By adjusting the fiber percentage in geopolymer concrete, it was found that the ideal dosage for polypropylene fibers was 0.6%.
- The flexural strength and split tensile strength displayed a gradual increase corresponding to the GPC grade. Notably, the flexural strength and split tensile strength were enhanced by 25% to 45% with the addition of an optimum dosage of fibers.
- The mechanical properties of the geopolymer concrete (GPC) were correlated with its compressive strength by examining the relationships between the split tensile strength and compressive strength, as well as between the flexural strength and compressive strength. Regression equations were developed from these relationships.
- The inclusion of suitable quantities of PP fibers enhanced the compactness of the interfacial transition zone (ITZ) and slowed down the crack propagation. The mechanical properties of the matrix are closely tied to the density of the matrix within the ITZs.

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