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An Examination of the Synergy of Steel, Polypropylene, and Glass Fiber Length and Content in Fiber-Reinforced Concrete: Performance and Economic Analysis

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Abstract

Concrete is a widely used material in construction due to its cost-effectiveness, strength, and compatibility. However, increasing its strength introduces limitations such as brittleness and low tensile and flexural strength. Fiber-reinforced concrete (FRC) was developed using materials like steel, glass, and polypropylene (PP) to resolve this issue. Each type of FRC, with varying specifications and fiber content, affects the performance and cost of concrete differently, necessitating thorough examination. This study investigates the impact of steel, glass, and PP fibers on the mechanical and economic performance of FRC mixtures, focusing on how the length and content of fibers influence properties such as compressive, tensile, flexural strength, flexural toughness, and economic efficiency index. To ensure better comparisons, a constant slump was maintained across all mixtures. The results show that while glass and PP fibers enhance tensile and flexural strength, their addition reduces compressive strength and modulus of elasticity. Moreover, increasing the content and length of glass and PP fibers further decreases compressive strength and modulus of elasticity. FRC with PP fibers improves tensile and flexural performance at a lower cost and CO_2 emissions. In contrast, despite higher costs and CO_2 emissions, FRC with steel fibers demonstrates superior mechanical improvements across all parameters.

Keywords: Fiber-reinforced concrete; Mechanical properties; Cost; Sustainability; Flexural toughness.

1. Introduction

In recent decades, growing populations and urban expansion have significantly increased the demand for infrastructure construction. Consequently, concrete, utilized in developing civil infrastructure and structures, has become one of the most widely used engineering materials and is considered an essential resource in civil engineering. Concrete is primarily characterized by its cost-effectiveness, substantial compressive strength, availability of abundant raw materials, ease of application, and excellent plasticity (Azmee and Shafiq 2018). Additionally, a significant advantage is adjusting its properties by using different materials (Mehdizadeh et al. 2023; Nouri et al. 2024) and mixed designs tailored to the project's environmental conditions to meet the specified requirements. In this context, various types of concrete have been created, including self-consolidating concrete (Kumar et al. 2021), high-strength concrete (Tahwia et al. 2021), and ultra-high performance concrete (Du et al. 2021). Despite its benefits, concrete can have limitations that restrict its application. These limitations include brittleness, low tensile strength, inadequate resistance to crack initiation and propagation, and limited ductility (Zhang et al. 2022; Chen et al. 2025).

To address these difficulties, various studies have been conducted. Research findings suggest that the addition of various fibers—such as steel (Magbool and Zeyad 2021), glass (Zhang et al. 2023), polypropylene (Tiwari and Singh, 2025), carbon (Guo et al. 2021), and basalt (Li et al. 2022)—improves the properties of concrete and eliminates the intrinsic deficiencies of ordinary concrete, leading to the development of fiber-reinforced concrete (FRC). A major challenge in achieving high-strength concrete was brittle fracture, which increases with increasing strength (Zhao et al. 2023). Consequently, using fibers in concrete has mitigated brittle fracture, transforming it into a ductile construction material known as FRC (Zhang, Pei, and Rong 2022). When considering FRC, the type and properties of fibers, such as length, diameter, and mechanical characteristics, are crucial in this domain (Zhao et al. 2023). To explore these factors in greater depth, it has been shown that raising the modulus of elasticity of the fibers reduces the creep and shrinkage of concrete. However, increasing the length-to-diameter ratio enhances the tensile strength (Zhao et al. 2023).

Steel fibers (SF) are the most prevalent and extensively used fibers in concrete. In 1908, B.JI.Некрасоъ was the first to utilize these fibers in concrete for the first time. Subsequently, H.F. Porter and Graham investigated the theory of enhanced strength due to their inclusion in concrete (Zhao et al. 2023). Typically, the dimensions of SF commonly used in concrete matrices include a length ranging from 10 mm to 60 mm and a cross-sectional diameter between 0.2 mm and 1 mm. Research has generally demonstrated the mechanical properties and ductility of steel fiber-reinforced concrete (SFRC). These enhancements include an increase in concrete's mechanical strength, ductility, and toughness (Zheng et al. 2024); energy absorption; prevention of crack initiation and propagation; and bridging between cracks (Wu et al. 2022).

Biryukovich first used glass fiber (GF) to enhance cement mortar, which has since emerged as one of the most prevalent and utilized fibers in this sector (Zhao et al. 2023). GF typically has a diameter of 10–16 micrometers and lengths ranging from 15 mm to over 50 mm. They are favored for their cost-effectiveness, lightweight nature, and high tensile strength, and they can help limit shrinkage (Wang et al. 2021). Glass fiber-reinforced concrete (GFRC) exhibits qualities similar to those of SF, with a slight difference in compressive strength (Nouri et al. 2025). Numerous studies indicate that incorporating GF enhances flexural and tensile strength, toughness, and ductility (Xue et al. 2019); nevertheless, inconsistent findings remain regarding the effect on compressive strength (Ahmad and Umar 2018).

Polypropylene fiber (PPF) is a material widely utilized in recent decades. These fibers were first used in the 1960s by the American Armed Forces Engineers Association to improve wear and impact resistance (Latifi et al. 2022), leading to the development of polypropylene fiber-reinforced concrete (PPFRC). The fibers' length ranges from 10 mm to 40 mm, while their diameter spans from 0.02 mm to 0.1 mm. Studies indicate that PPF exhibits exceptional resistance to chemical attacks (Kakooei et al. 2012). Moreover, synthetic fibers possess a significantly low specific weight and are cost-effective compared to metal fibers (Hosseinzadeh et al. 2023). These fibers have been conclusively shown to enhance ductility, flexural strength, energy absorption, and particularly tensile strength (Xue et al. 2019), while also mitigating plastic and drying shrinkage in concrete (Pelisser et al. 2010). Notably, PPF has minimal impact on compressive strength (Matar and Zéhil 2019).

Many factors can influence the effectiveness of FRC, including the type, content, shape, length, and diameter of the fibers (Mazaheripour et al. 2011). Each of these factors uniquely impacts the characteristics of reinforced concrete. They also affect both the properties and cost of FRC. For example, the total cost of FRC rises with increased fiber content and decreases with shorter and thinner fibers. Roshan et al. (Roshan et al. 2023) assessed the cost of concrete using two types of SF (engineered and recycled) at a 0.5% dosage, both individually and in a hybrid form. The recycled fibers had diameters of 0.3 mm and lengths ranging from 11 mm to 75 mm, while the engineered fibers were 50 mm long with a 0.8 mm diameter. The results suggested that mechanical properties were not only improved but also that the overall cost was reduced compared to using only engineered fibers due to the inclusion of recycled fibers. SFRC can enhance the mechanical properties of concrete pavements, allowing for a reduction in the amount of concrete needed by decreasing pavement thickness (Ali et al. 2021).

Technological advancements have led to uniquely featured structures, with FRC gaining particular relevance due to its superior mechanical properties and ductility. Previous studies have strongly emphasized the importance of investigating how fiber length and quantity affect these properties. This research explores the mechanical properties and ductility of three common types of FRC reinforced with steel, PP, and glass fibers while considering economic factors. The study examines the impact of fiber content and length on FRC, maintaining a consistent slump while adopting an economic perspective and documenting ideal outcomes for use in the construction sector. The characteristics studied include compressive strength, tensile strength, flexural strength, elastic modulus, and flexural toughness. Finally, the ratio of each property to cost was analyzed to determine the most cost-effective and sustainable mixture design. Exploring the impact of increasing the length and content of fibers in FRC mixtures, using three types of fibers—steel, PP, and glass—on mechanical properties along with the cost and CO_2 emissions increase from adding fibers can aid in making technical, economic, and sustainability decisions for the industrial production of FRC.

2. Experimental program

2.1. Materials

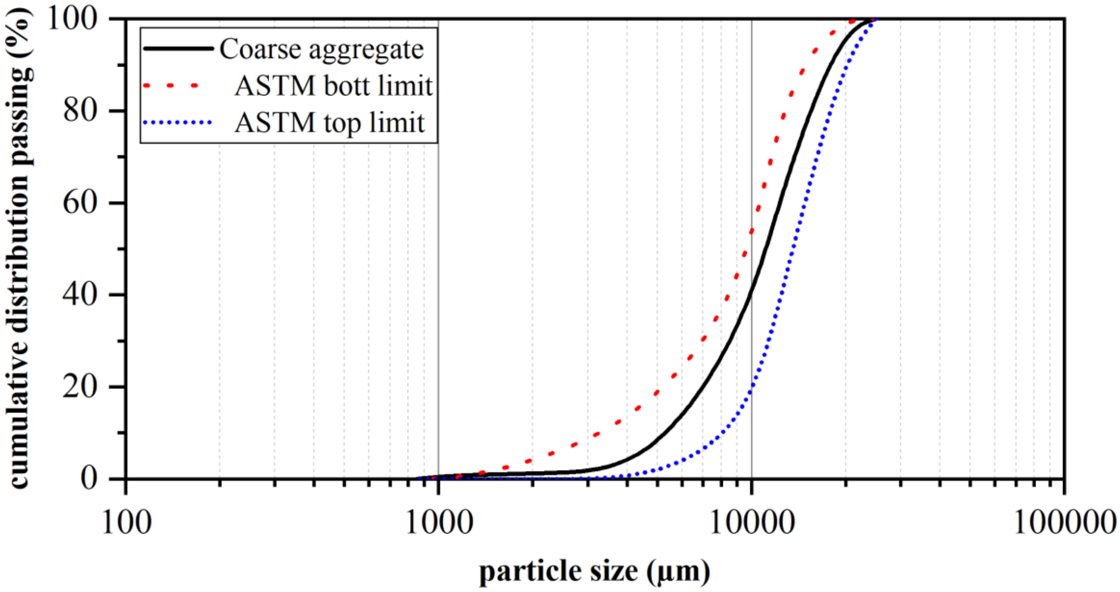
Fiber-reinforced concrete (FRC) was prepared using the following ingredients: Type II Portland cement, silica fume, limestone powder (LP), coarse and fine aggregates, hooked-end steel fiber, polypropylene (PP) fiber, glass fiber, superplasticizer (SP), and water. The chemical compositions and physical properties of the cement are detailed in Table 1. The silica fume used in this study has a particle size of less than 2 µm, a density of 2.214 kg/m^3, and a specific surface area of 143,100 cm^2/g. Table 2 summarizes the chemical compositions of the silica fume. Fig. 1 shows the gradation of aggregates. The fine aggregate has a diameter ranging from 0 to 6 mm, and the maximum size of coarse aggregate is 25 mm. Table 3 illustrates the properties of the polycarboxylate superplasticizer.

Table 1. Characterization of Type II Cement: Physical Properties and Chemical Composition

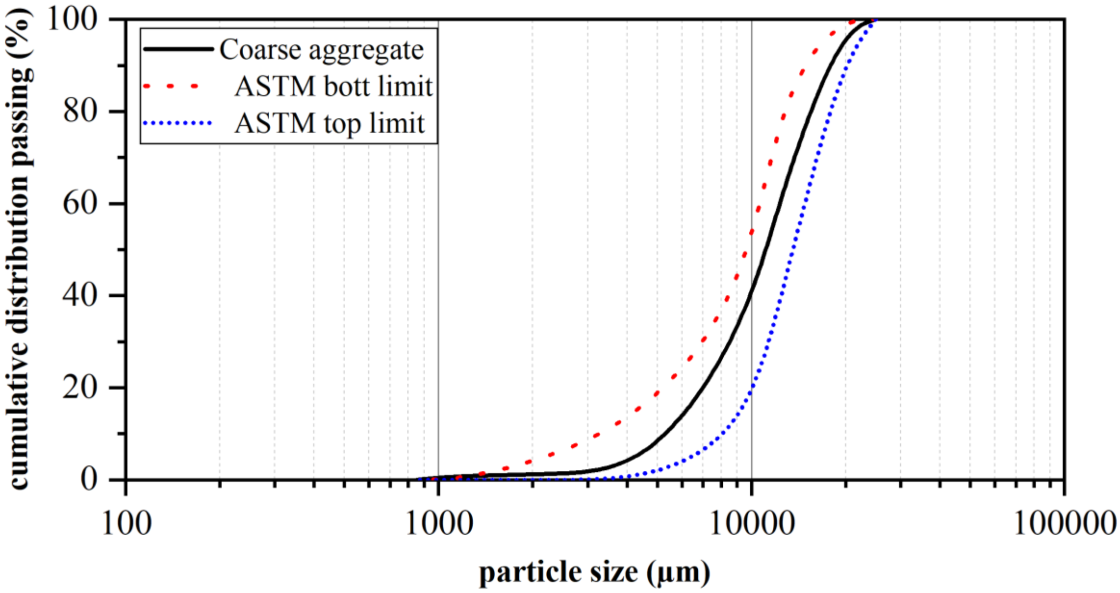
Description		Value
Fineness (Blaine Test, cm^2/gr)		3081
Retained on Sieve #170 (90 µm)		5.7
Initial Setting Time (minutes)		153
Final Setting Time (minutes)		212
Compressive Strength (MPa)	2 days	16
	3 days	20.8
	7 days	33.3
	28 days	49.2
Silicon Dioxide (SiO_2)		20.79
Aluminum Oxide (Al_2O_3)		4.76
Ferric Oxide (Fe_2O_3)		3.86
Calcium Oxide (CaO)		62.28
Magnesium Oxide (MgO)		3.22
Sulfur Trioxide (SO_3)		1.89
Sodium Oxide (Na_2O)		0.37
Potassium Oxide (K_2O)		0.68

Table 2. Chemical properties of silica fume

Compound	L.O.I	Al_2O_3	SiO_2	Na_2O	SO_3	CaO	TiO_2	MgO	Fe_2O_3
Weight (%)	1.56	0.748	92.41	0.294	0.19	0.44	N.D.	0.902	0.829



a) Gradation of coarse aggregate



b) Gradation of fine aggregate

Fig. 1. Gradation of aggregates used to prepare high-performance concrete; (a) coarse aggregate, and (b) fine aggregate

Table 3. Specification of the superplasticizer

Type of product	LG- HE 310
Physical state	Liquid
Color	Brown
Specific gravity	1.1 gr/cm^2
Ion chloride	No

Table 4 demonstrates the mechanical properties of the PP, glass, and steel fibers used in this study. This study aims to evaluate the performance of three types of fiber commonly used in the industry, considering both small and large lengths. These selections are based on common values found in the literature and available in the industry. They have been chosen to allow a practical comparison of the performance of three different types of FRC, enhancing the ability to make an appropriate choice. Fig. 2 shows the appearance of these three types of fibers.

This study utilizes fibers derived from natural and industrial basic materials. Significantly, all these materials can be recycled or repurposed as waste products. These components can be recovered, processed, and integrated into concrete mixtures, enhancing sustainability by diminishing waste, saving natural resources, and lowering environmental impact. This method encourages transitioning to resource-efficient building approaches aligned with international sustainability objectives (Svazas et al. 2023; Hristova et al. 2024; Ma et al. 2024).

Table 4. Characteristic of fibers

Fiber type	Glass	Polypropylene	Steel
Fiber Shape	Strand	Strand	Hooked-end
Unit weight (kg/m^3)	2600	910	7850
Tensile strength (MPa)	1000	400	1200
Elastic modulus (GPa)	70	2.7	160
Length (mm)	15, 30	12, 30	20, 60
Diameter (mm)	0.1	0.05	0.5

(a) (b) (c)

Fig. 2. Different types of used fibers: (a) polypropylene, (b) glass, and (c) steel fibers

2.2. Mix Proportions and specimen preparation

This study planned thirteen different test mixture fractions to study the impact of various contents and lengths of three types of fibers on FRC. The water-to-cementitious materials (W/CM) ratio was set at 0.32, and the silica fume-to-cementitious materials ratio was 0.1. The values were derived from laboratory experiments, indicating that this ratio attains a desirable solution between workability and strength for FRC mixtures. Table 5 provides detailed information on the concrete mixing schemes used in the study. It is important to note that adding less than 0.5% of fibers does not necessarily change the volumetric design of the mixture. This study investigates the impact of including three types of fibers with two different lengths on the mechanical behavior of FRC. In Table 5, LL means long length, and SL means short length of fibers.

Table 5. Specification of mixed designs

No	Mix	Type of fibers	Length of fibers (mm)	Fiber volumes (%)	Cement (kg/m^3)	Silica fume (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	LP (kg/m^3)
1	Control	-	-	-	495	55	849.3	772	176	94.4
2	GF-SL	Glass	15	0.25	495	55	849.3	772	176	94.4
3	GF-LL	Glass	30	0.25	495	55	849.3	772	176	94.4
4	GF-SL	Glass	15	0.5	495	55	849.3	772	176	94.4
5	GF-LL	Glass	30	0.5	495	55	849.3	772	176	94.4
6	PP-SL	Polypropylene	12	0.25	495	55	849.3	772	176	94.4
7	PP-LL	Polypropylene	30	0.25	495	55	849.3	772	176	94.4
8	PP-SL	Polypropylene	12	0.5	495	55	849.3	772	176	94.4
9	PP-LL	Polypropylene	30	0.5	495	55	849.3	772	176	94.4
10	SF-SL	Steel	20	0.25	495	55	849.3	772	176	94.4
11	SF-LL	Steel	60	0.25	495	55	849.3	772	176	94.4
12	SF-SL	Steel	20	0.5	495	55	849.3	772	176	94.4
13	SF-LL	Steel	60	0.5	495	55	849.3	772	176	94.4

To ensure the reliability of the experimental results, all specimens were prepared and tested using consistent methodologies. After mixing, the process continued for 5 minutes before molding. To reduce the effect of fiber orientation on the technical characteristics of this study, all the mixtures were considered in fixed slumps between 70 and 90 mm by adjusting the amount of superplasticizer. This target slump is suitable for industrial FRC mixture production. There was approximately 6-8 kg/m^3 of superplasticizer in the mixtures, depending on the type, length, and content of the fibers.

During the mixing process, the fresh performance of FRC mixtures, particularly when incorporating different fibers, was closely monitored to adjust the workability empirically. Consequently, this study did not examine the varying workability associated with different fibers. The primary objective of this study was to compare the performance of various fibers under a fixed slump condition to reduce the influence of workability-related factors. Although different fibers can negatively impact the mixture's fresh performance (Vivek et al. 2022), these effects were mitigated by adding superplasticizers. For example, mixtures containing longer fibers or higher fiber contents required increased superplasticizer dosages to achieve the target slump. Despite these adjustments, the relatively low fiber content in the mixtures helped minimize mixing, separation, and fiber packing issues.

Furthermore, casting direction and the duration of external vibration were constant in all specimens. Compressive strength tests used 150×150×150 mm cube specimens. Tensile strength and elasticity modulus tests used 300×150 mm cylindrical specimens. Flexural strength tests used 500×100×100 mm prism beams. All concrete mixtures were prepared and cured in accordance with ASTM C192/C192M-22, which delineates defined processes for mixing, molding, and curing concrete test specimens under laboratory conditions. Complying with this criterion assures consistency, reproducibility, and reliability of the experimental results.

3. Experiments

3.1. Compressive strength

Following BS 1881-120, the tests were conducted using 150 mm specimens under a compressive load capacity of 300 tons (Fig. 3). Compressive strength tests were performed on specimens cured in lime-saturated water for 7 and 28 days.

Fig. 3. Compressive strength test.

3.2. Splitting tensile strength

An indirect tensile test (Brazilian test) was conducted following the ASTM C496 using 150×300 mm cylindrical specimens at ages 7 and 28 days (Fig. 4). The cylindrical specimen was positioned under the pressure jack so that the force applied by the jack acted along the height and on the side surface of the specimen. The jack's load was incrementally increased until the specimen split in half. The device then recorded the final breaking load. Eq. (1) represents the splitting tensile strength.

$$T = \frac{2P}{\pi LD} \tag{1}$$

Where T is the tensile strength (MPa), P is the maximum load (N), and L and D are the height and diameter of cylindrical specimens (mm), respectively.

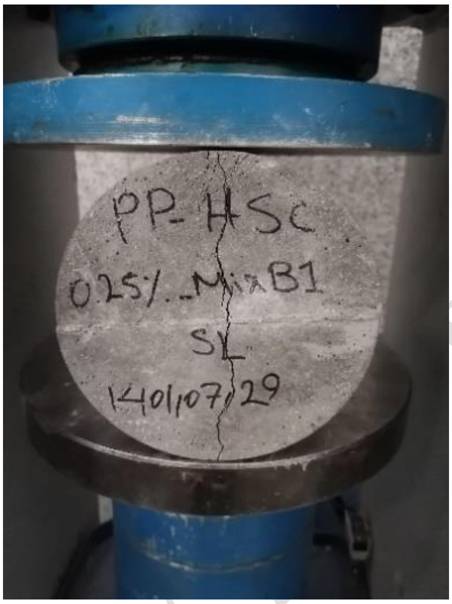


Fig. 4. Splitting tensile strength test (Brazilian test).

3.3. Elastic modulus test

The modulus of elasticity test was conducted according to the ASTM C469. As per this standard, the loading speed was set to 1.25 mm/min, equivalent to 0.021 mm/s, as input into the testing device (Fig. 5). The specimen dimensions specified by the standard were 150 mm in diameter and 300 mm in height. The modulus of elasticity value was derived by converting the force-displacement diagrams into a stress-strain diagram. Subsequently, Eq. (2) was applied to calculate the modulus of elasticity.

$$E = \frac{(S_2 - S_1)}{(\varepsilon_2 - 0.000050)} \tag{2}$$

Where E represents the elastic modulus (MPa), S_2 denotes the stress at 40% of maximum load (MPa), S_1 signifies the stress at 0.00005 of strain (MPa), and ε_2 corresponds to S_2.

Fig. 5. Elastic modulus test.

3.4. Flexural strength & toughness test

A uniform loading test was conducted on a beam-shaped specimen with dimensions of 500 × 100 × 100 mm, following ASTM C1018 (Fig. 6) to measure the flexural strength.

$$T = \frac{3PL}{2bd^2} \tag{3}$$

Where *T* is the flexural Strength (MPa), *P* is the maximum load (N), *L* is the beam length (mm), *b* is the average width of the specimen at the fracture section (mm), and *d* is the average depth of the specimen at the fracture section (mm).

Fig. 6. Flexural strength test.

According to ASTM C1018, flexural toughness, which is determined by the area under the load-displacement curve, serves as a measure of the flexural ductility of concrete. Fig. 7 illustrates the flexural toughness values of the FRC mixture as calculated by the area under the load-displacement diagram.

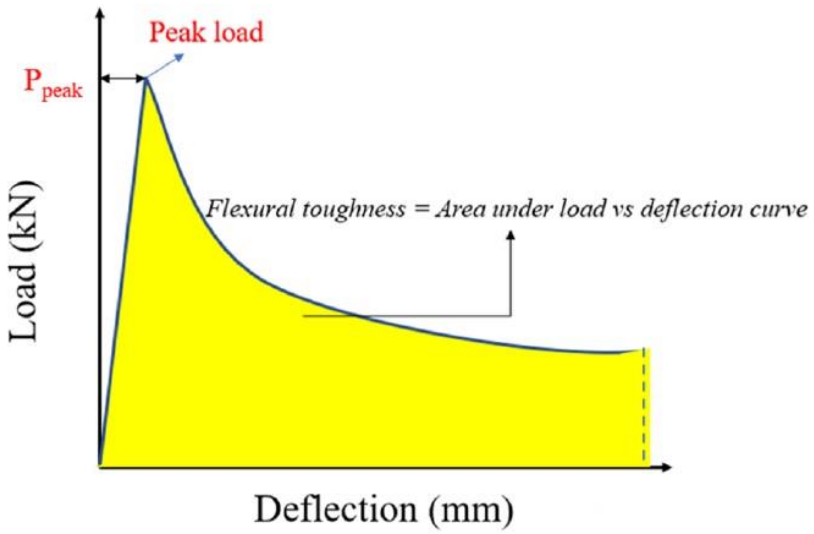


Fig. 7. Typical load-deflection behavior of FRC.

3.5. Scanning Electron Microscopy analysis

The microstructure of the interfacial transition zone (ITZ) between fibers and the cementitious matrix was examined using a scanning electron microscope (SEM). For SEM analysis, concrete specimens from fiber-reinforced concrete (FRC) mixtures underwent a three-step preparation process: Initially, one surface of the 150 × 150 mm cubic specimens was ground and polished with diamond polishing pads ranging from 200-grit to 3000-grit. Subsequently, the specimens were cut using a diamond blade saw to produce 10 mm cubes. Lastly, the polished specimens were coated with a thin layer of gold for SEM analysis.

4. Results and discussion

In this section, the results obtained from the experiments are presented and discussed, offering an in-depth analysis of their interpretation and significance within the study context.

4.1. Compressive strength

Fig. 8 illustrates the effect of contents and lengths of three types of fibers on the compressive strength results of each type of FRC. These results indicate that the increase in length and content of glass and PP fibers leads to a reduction in compressive strength. Glass and PP fibers are often poorly distributed in large quantities, which may be contributing to this issue. Furthermore, increasing the length of fibers has decreased the compressive strength of mixtures. In the case of long-length fibers, the entanglement of the fibers increases, making it impossible to control and operate cracks during compression stress. These findings align with previous studies (Yan et al. 2021) and highlight a time-dependent phenomenon, where long-term mechanical characteristics, including compressive strength, may diminish over time (Hussain et al. 2020).

Generally, as shown in Fig. 8, incorporating glass and PP fibers into fiber-reinforced concrete (FRC) has decreased compressive strength at both 7 and 28-day cure ages. The extent of strength reduction varies based on fiber length and content. The maximum observed reduction in compressive strength can reach approximately 20% for glass fibers, while for PP fibers, it can be up to about 30%. Conversely, including steel fibers can enhance compressive strength by approximately 7%. Specifically, the mixture with 0.5% steel fibers with a length of 20 mm (SF-SL-0.5) exhibited the maximum compressive strength at 104.1 MPa, whereas the mixture containing 0.5% PP fibers with lengths of 30 mm (PP-LL-0.5) showed the minimum compressive strength at 70 MPa.

The mechanisms underlying the strength reduction associated with PP and glass fibers can be attributed to several factors. In the case of glass fibers, the texture and smooth surface characteristics may lead to lower adhesion with the cementitious matrix, potentially reducing the interfacial bond strength between the fibers and the concrete. This hypothesis is further supported by scanning electron microscopy (SEM) observations (as seen in Fig. 9), which reveal that the transition zone at the interface (ITZ) between the glass fibers and the matrix exhibits microcracks and a less cohesive bond than mixtures containing steel fibers. Fig. 9 shows steel fibers have fewer microcracks than PP and glass fibers.

Similar results were observed for PP fibers, indicating that their lower adhesion with the cement matrix contributes to the overall strength reduction. The lower compressive strength of FRC mixtures containing these fibers, as observed in Table 4, coupled with their lower modulus of elasticity than steel fibers, further exacerbates the situation. The dispersion of PP fibers during mixing can lead to potential agglomeration, increasing the likelihood of microcrack initiation within the concrete and further diminishing compressive strength.

In contrast, the benefits of steel fibers, including their ability to delay crack formation and propagation, have been documented. Steel fibers create fewer microcracks than glass and PP fibers due to their higher rigidity and modulus of elasticity. Moreover, hooks in steel fibers significantly enhance the physical bond strength between the fibers and the cementitious matrix, contributing to superior compressive strength compared to mixtures containing glass fiber and PP fiber.

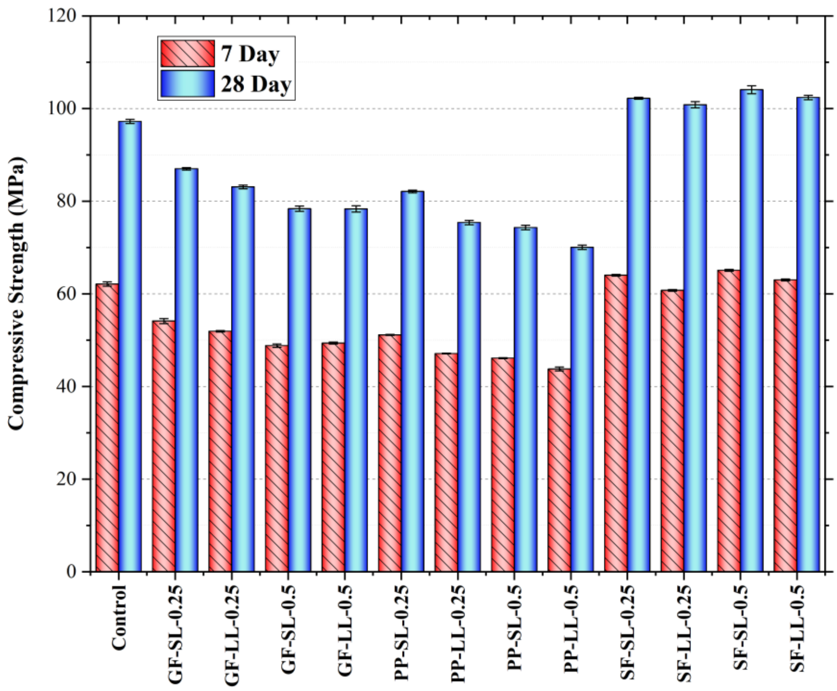


Fig. 8. Compressive strength test results of FRC and control mixtures.

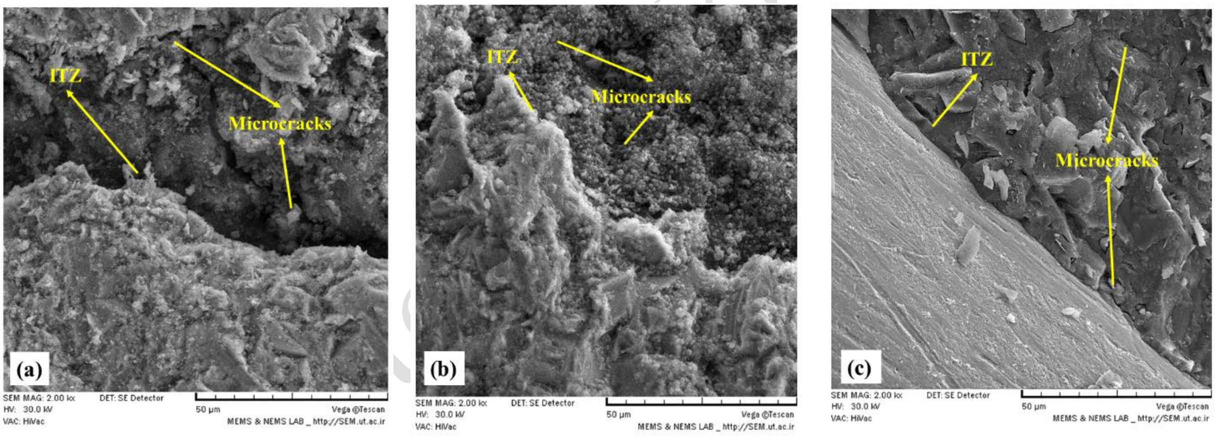


Fig. 9. Microstructural images of the ITZ between (a) PP, (b) glass, and (c) steel fibers and cementitious matrix.

To assess the impact of fiber length on the compressive resistance of mixtures, changes in compressive strength were analyzed for three types of fibers with varying lengths. Fig. 10 illustrates the variations in 28-day compressive strength concerning fiber amount for both long and short fiber lengths. Fig. 10 shows that the compressive strength decreases with increasing fiber length, according to a trend observed across all three types of FRC containing PP, glass, and steel fibers. For instance, at a constant volume of fibers (0.25%), the compressive strength of mixtures with short lengths of PP, glass, and steel fibers is 82.1, 87, and 102 MPa, respectively. However, with longer fibers, the compressive strength values decrease to 75.4, 83.1, and 100.8 MPa, respectively. In other words, the reduction in compressive strength for FRC containing PP, glass, and steel fibers with increased fiber length is 8%, 5%, and 1%, respectively. The decrease in compressive strength with longer fibers can be attributed to the creation of inhomogeneity among concrete particles and disturbing the packing density from the optimal state. Additionally, longer fibers increase the likelihood of overlapping fibers, creating weak gaps within the cement paste and reducing concrete compressive strength.

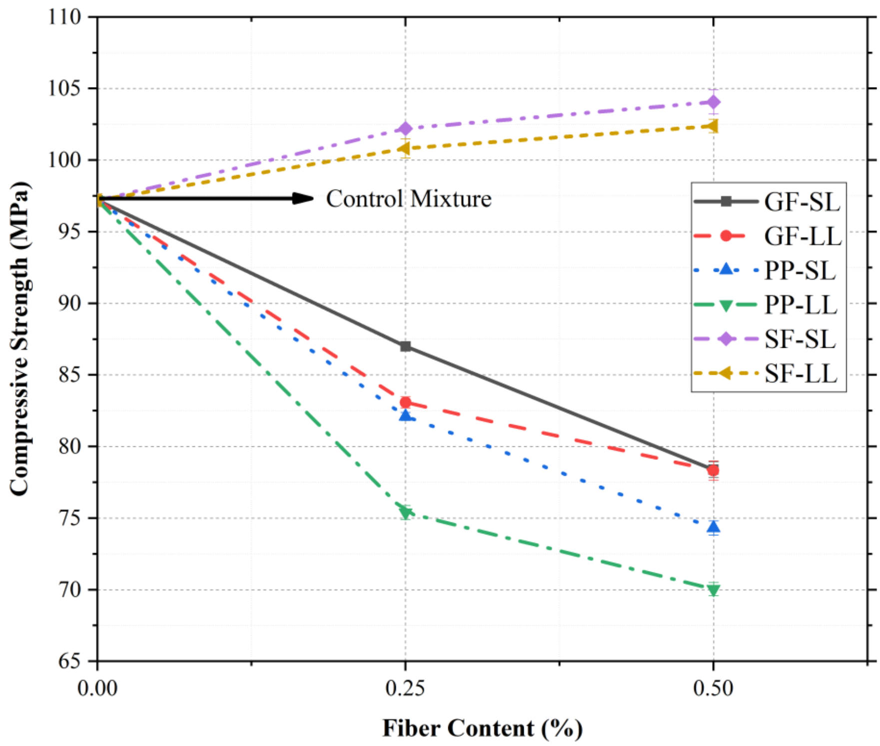


Fig. 10. Changes in 28-day compressive resistance of specimens with different fibers.

4.2. Splitting tensile strength (Brazilian test)

In general, the effect of different fibers is more visible in the state of tensile stresses than in compressive stresses (Tassew and Lubell 2014). Fig. 11 displays the splitting tensile strength results for the control and FRC mixtures. As depicted in Fig. 11, the tensile strength of FRC mixtures increases with the presence of fibers. The highest tensile resistance is observed in the mixture containing 0.5% long steel fibers at 13.6 MPa, while the lowest, after the control mixture, is in the mixture containing 0.5% long glass fibers at 11.3 MPa. On average, the increase in tensile strength of FRC compared to the control mixture is 9.7% for PP fibers, 6.7% for glass fibers, and 20.8% for steel fibers. The increase in tensile strength is attributed to the fibers' role in preventing the propagation of microcracks within the cementitious matrix. This is particularly notable due to the higher tensile resistance of steel fibers, which significantly influences the tensile strength of FRC.

The splitting tensile strength of FRC containing glass and PP fibers initially increases and then decreases as the fiber content increases. The low elastic modulus of PP and glass fibers, combined with the bonding slip characteristic ITZ between the fiber and cementitious matrix, affects the deformation behavior of the fiber post-cracking.

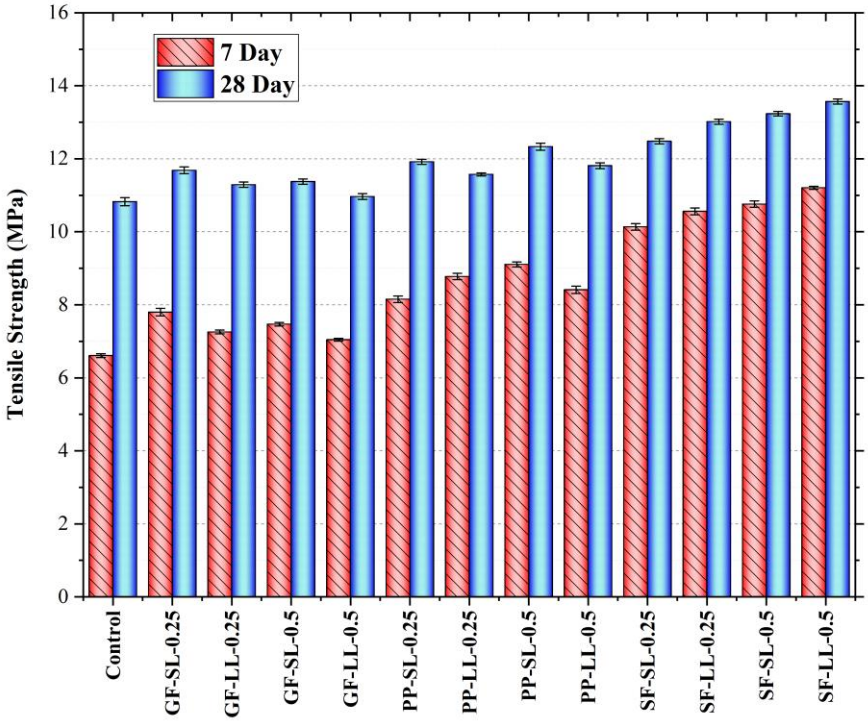


Fig. 11. Tensile strength test results of FRC and control mixtures.

To evaluate the influence of fiber length on 28-day tensile strength, changes in this parameter were analyzed for FRC mixtures containing PP, glass, and steel fibers in two different lengths, as shown in Fig. 12. Fig. 12 shows that tensile strength decreases with the increasing length of PP and glass fibers while it increases with the lengthening of steel fibers. This difference can be due to the superior engagement of steel fibers within the cementitious matrix and their improved bonding (as seen in Fig. 9). Specifically, the 28-day tensile strength of FRC mixtures containing PP and glass fiber decreased by approximately 4% as fiber length increased. In contrast, the tensile strength of FRC mixtures containing long-length steel fiber increased by 5% compared to short-length steel fiber. The significantly higher tensile resistance of steel fibers, approximately four times greater than PP and glass fibers, contributes to their superior performance in enhancing the tensile behavior of FRC. The unique hooked shape of the steel fibers used in this study suggests that increasing fiber length, or the restraining length within the cement matrix, improves the tensile behavior of FRC.

The mechanism by which longer fibers influence tensile strength and cracking behavior significantly differs from that of shorter fibers. Long fibers are more effective in bridging cracks, which helps to distribute stress and delay failure. When a crack initiates in the concrete, long fibers can span the crack and exert tensile forces, thereby resisting the propagation of brittle failure. This bridging behavior of fibers not only enhances the ductility of the concrete but also transforms the failure mode from a brittle to a more ductile response. In contrast, shorter fibers may not provide sufficient bridging capability across larger cracks, resulting in a more immediate and brittle failure. The lack of effective crack bridging with short fibers leads to rapid crack propagation and reduced energy absorption during loading; hence, lower tensile strength was observed when employing shorter fibers.

Furthermore, using longer fibers increases the likelihood of overlapping fiber and potential entanglement within the mixture, creating weak zones within the cement paste. These weak points may contribute to inhomogeneities and disturb the optimal packing density of concrete particles, further reducing the material's compressive strength. Therefore, given that the bonding of steel fibers to the cement matrix is better than that of PP and glass fibers, increasing the length of steel fibers has a better performance in increasing the tensile strength and ductile behavior of the concrete mixture.

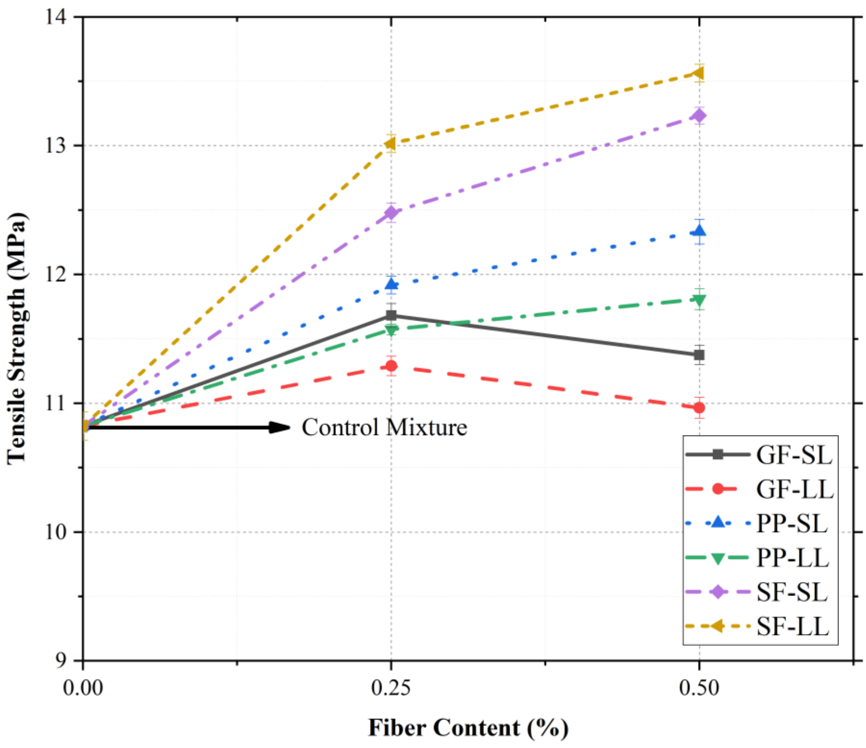


Fig. 12. Changes in 28-day tensile strength of mixtures with different fibers.

4.3. Modulus of elasticity

Fig. 13 illustrates the static elastic modulus of FRC mixtures for various fiber content fractions and fiber lengths. Generally, adding PP and glass fibers to FRC decreased the modulus of elasticity, while adding steel fibers led to an increase. According to the results, the lowest modulus of elasticity was recorded for the PP-LL-0.5 mixture at 38.7 GPa, while the highest was for the SF-SL-0.5 mixture at 62.4 GPa. In homogeneous materials, there is a direct correlation between density and modulus of elasticity. However, in heterogeneous and multiphase materials like concrete, the elastic modulus behavior of the composite is influenced by factors such as density, the modulus of elasticity of the principal constituents, and the characteristics of the ITZ (Afroughsabet et al. 2018). Steel fibers in FRC exhibit a higher static modulus than PP and glass fibers due to their higher strength and modulus of elasticity. Also, Aslani and Nejadi (2013) similarly observed that using steel fibers resulted in a higher modulus of elasticity compared to glass and PP fibers.

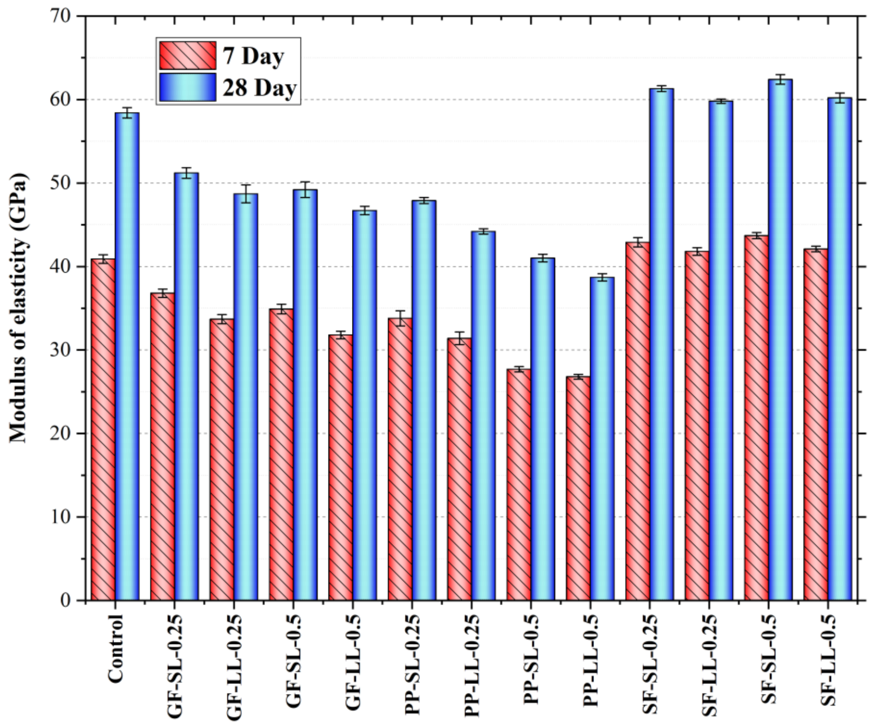


Fig. 13. Elastic modulus test results of FRC and control mixtures.

As depicted in Fig. 14, as the fiber content increased, the elastic modulus values of FRC containing PP and glass fibers decreased, while using steel fibers, this value increased. This reduction under the use of PP and glass fibers can be attributed to the increased heterogeneity in the concrete mass, leading to weak areas in the cementitious matrix. Additionally, an increase in fiber length leads to a decrease in the modulus of elasticity, a trend observed across all three types of FRC containing PP, glass, and steel fiber (Fig. 14). For instance, at a constant volume of fibers (0.5%), the modulus of elasticity for FRC containing PP, glass, and steel fibers with short lengths averaged at 41, 49.2, and 62.4 GPa, respectively. However, with longer fibers, the modulus of elasticity decreased to 38.7, 46.2, and 60.2 GPa, respectively. In other words, the reduction in modulus of elasticity for FRC containing PP, glass, and steel fibers with increased fiber length was 6%, 5%, and 4%, respectively.

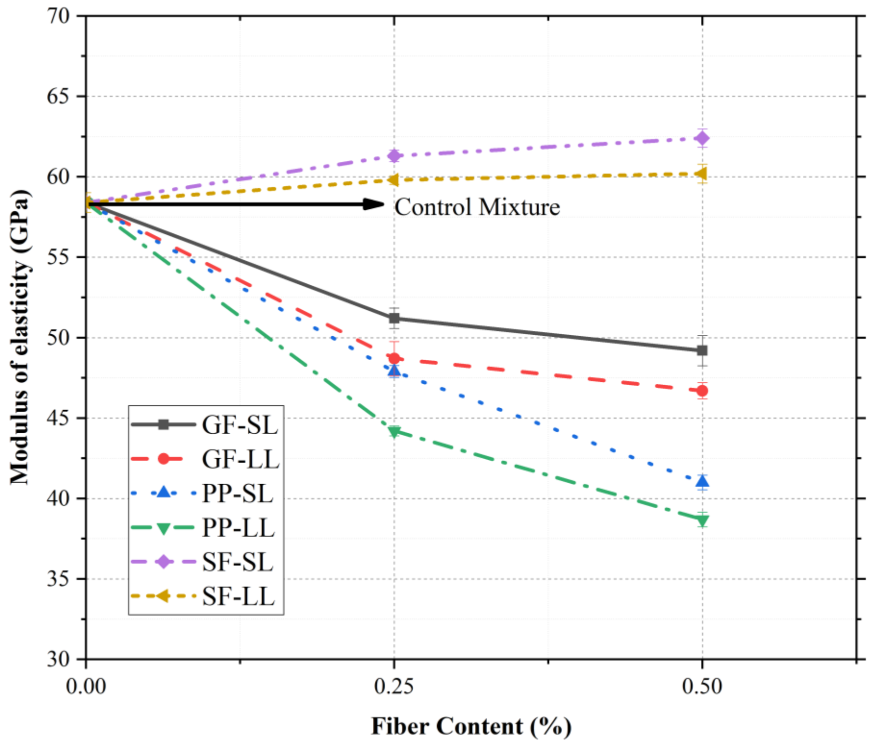


Fig. 14. Changes in 28-day modulus of elasticity of mixtures with different fiber lengths.

Understanding FRC and its possible uses necessitates an examination of the relationship between compressive strength and the modulus of elasticity. The incorporation of PP, glass, or steel fibers can improve the ductility, toughness, and crack resistance of FRC (Masoud and Yenny Nurchasanah 2015). This study's experimental results demonstrate that the modulus of elasticity values obtained from different fiber combinations are correlated with compressive strength. Fig. 15 illustrates a comparative examination of the experimental data and the statistical correlation between compressive strength and modulus of elasticity for fiber-reinforced concrete containing various fibers at 28 days of curing. It is clear that although a general trend exists, the diverse array of fiber kinds, lengths, and volumes employed in this work leads to a broader variability in elasticity values than is usually documented in the literature.

The variation in material specifications indicates that although the modulus of elasticity can typically be inferred from compressive strength, variations may arise due to the properties of the fibers. The coefficient of determination (R^2) of roughly 0.97 signifies a robust association; however, it also highlights that the breadth of this relationship differs from other studies due to the distinctive combinations of fibers utilized in this context. Consequently, prospective research could be gained by investigating the impact of particular fiber types and quantities on the modulus of elasticity to reconcile these discrepancies with established theoretical models and literature.

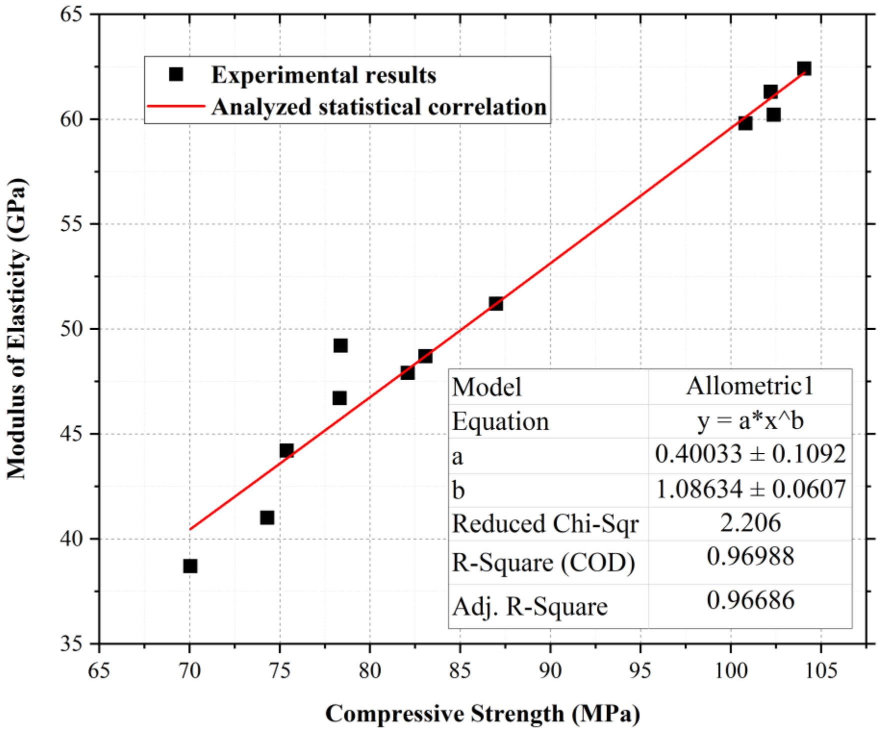


Fig. 15. The analyzed statistical correlation between the experimental results of compressive strength and modulus of elasticity of FRC.

4.4. Flexural strength

Fig. 16 illustrates the results of the flexural strength (modulus of rupture) of FRC and control mixtures. These results align with other studies on the enhancement of flexural resistance in FRCs through the use of fibers (Wang et al. 2006). As depicted in Fig. 16, including fibers in FRC has significantly increased its flexural strength. This improvement is shown across all three types of fibers. The flexural strength of the control mixture after 28 days of curing was 3.8 MPa. Adding 0.25% of PP, glass, and steel fibers increased the 28-day flexural strength by 40%, 8%, and 55%, respectively, in the case of short length and by 47%, 26%, and 66% in the case of long length, respectively. Furthermore, according to Fig. 16, increasing fiber length generally enhances the flexural strength of all three types of FRC. The FRC mixture containing 0.5% long steel fibers demonstrated the most significant increase in flexural strength, with a 79% increase over the control mixture. The lowest increase in FRC flexural strength was achieved by mixing 0.25% short glass fibers with the control mixture, which increased by almost 8%.

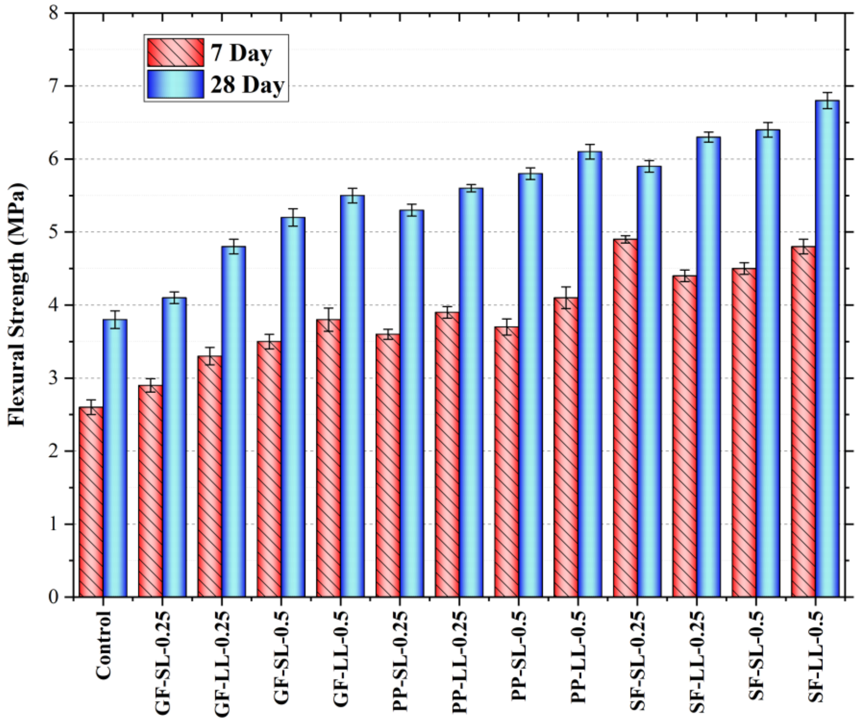


Fig. 16. Flexural strength test results of FRC and control mixtures.

During flexural loading, the fibers in the specimen experience tension, effectively preventing crack propagation by creating strong bonds between cementitious matrices (as seen in Fig. 9). This mechanism is evident in Fig. 17. Fibers play a critical role in averting premature tensile cracks in concrete due to their crack-arresting behavior and high tensile strength (Afroughsabet et al. 2017). The enhancement in flexural strength is particularly significant with steel fibers compared to PP and glass fibers, owing to their higher tensile strength and superior bonding with the cementitious matrix. Hooks at both ends of steel fibers strengthen this bond, preventing fiber slippage and enhancing fiber performance against tensile cracks. In contrast, plain fibers like PP and glass may experience slippage, leading to inefficient use of their full strength in resisting tensile cracking (Hussain et al. 2020). Furthermore, the microstructure images in Fig. 9 indicate that steel fibers have a stronger chemical bond with cementitious matrix than glass and PP fibers.

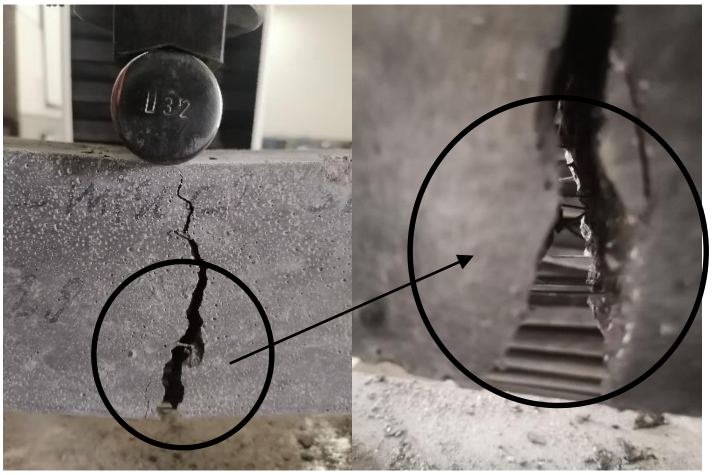


Fig. 17. Performance of steel fibers in FRC under flexural loading.

Variations in this parameter were analyzed for three different fibers to assess the impact of fiber length on the flexural strength of FRC. Fig. 18 illustrates the changes in the flexural strength of mixtures containing varying PP, glass, and steel fiber lengths. It is evident from Fig. 18 that the flexural strength of FRC increases with the lengthening of PP, glass, and steel fibers. The most substantial enhancement in flexural resistance due to fiber length is observed in the FRC mixture containing steel fibers. The use of steel fibers, characterized by their hooked end and superior tensile strength compared to the other fibers, significantly improved the flexural behavior of FRC.

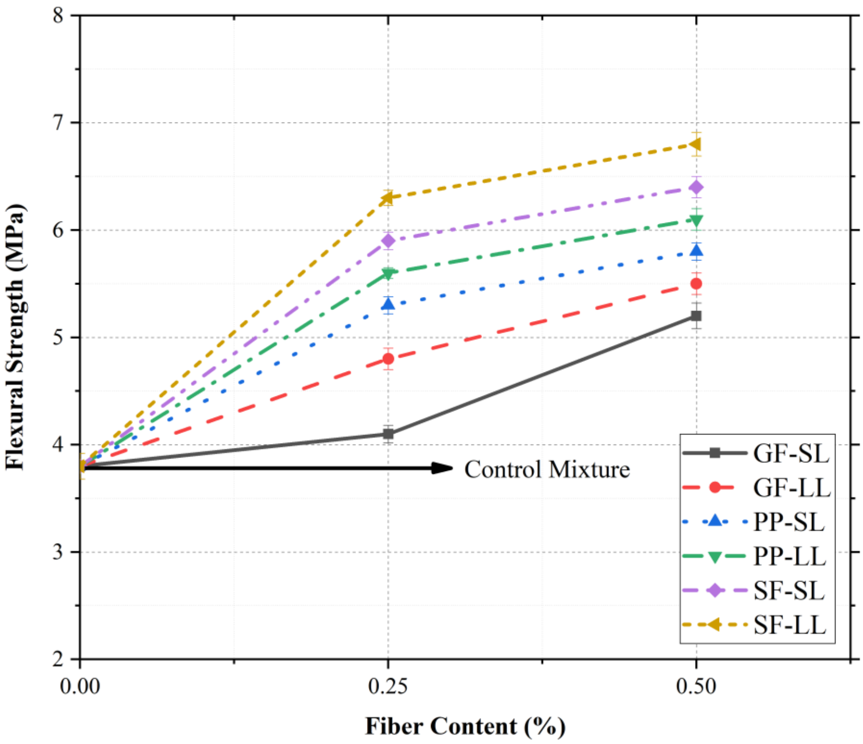


Fig. 18. Changes in 28-day flexural strength of mixtures with different fiber lengths.

4.5. Load-displacement curves & flexural toughness

Investigating the load-displacement behavior of FRC and control mixtures, load-displacement curves were plotted, as shown in Figs. 19, 20, and 21. These figures depict the load-displacement curves for the control mixture and FRC reinforced with PP, glass, and steel fibers, respectively. The curves demonstrate the increased peak load resistance due to fiber addition. Specifically, as evident from the figures, the inclusion of fibers enhances the peak load capacity, which correlates with the improved performance of the fibers in resisting external loads. Furthermore, fiber type and length significantly influence cracking behavior in FRC mixtures.

For flexural toughness evaluation, the focus was primarily on the area under the load-displacement curve, which represents the energy absorption capacity of the concrete up to a specified displacement (commonly referred to as toughness). The area under the curve illustrates how fibers contribute to residual strength after the initial crack formation and delay crack propagation due to their bridging effect. Without fibers, the control mixture shows no residual load resistance beyond the modulus of rupture, whereas FRC mixtures retain considerable post-cracking strength due to fiber reinforcement.

According to Figs. 19, 20, and 21, fibers that assist in bridging cracks improve the load capacity, energy absorption, and overall toughness of the concrete. This improved ductility is evident from the softening behavior in the post-cracking region of the curves, which reflects the energy absorbed during crack progression. The enhanced ductility fibers provide is particularly effective in mitigating the brittle failure behavior observed in conventional concrete.

Variations in fiber type, content, and length significantly impact the post-peak response compared to the pre-peak phase. Higher fiber volumes notably increase peak strength, attributed to the bridging mechanism facilitated by the fibers (Yan et al. 2021). Furthermore, increasing both the quantity and length of fibers leads to an overall rise in the peak strength of FRC. Generally, the FRC mixture with long-length steel fibers shows the highest peak strength increase at 80%, while the mixture with short-length glass fibers shows the lowest increase at 7% compared to the control mixture. During the linear elastic phase, the role of fibers in load transfer is relatively minor, resulting in performance nearly similar to FRC without fibers. However, in post-cracking conditions, fibers continue to bear loads through mechanical interlocking and friction at the fiber-matrix interface. The pattern of crack generation and propagation observed aligns with findings in the literature (Yu et al. 2016). Additionally, PP fibers had less impact on post-cracking behavior than glass and steel fibers. This issue may be due to their lower chemical adhesion and weaker ITZ than other fibers. Steel and glass fibers, by controlling the cracks, caused changes in the peak and the slope of the descending portion of the curves.

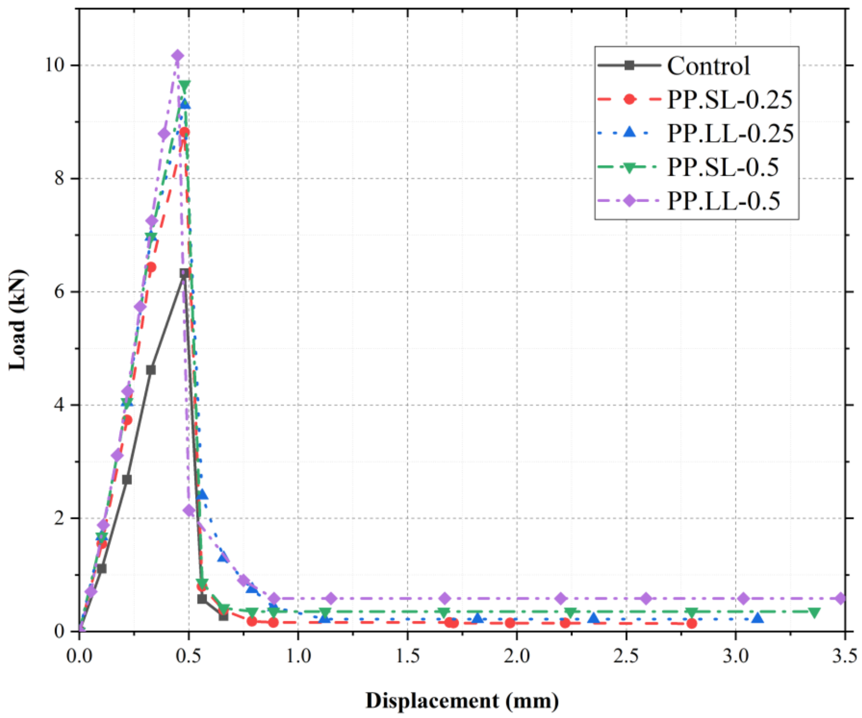


Fig. 19. Impact of PP fiber content and length on the load-displacement curve of FRC.

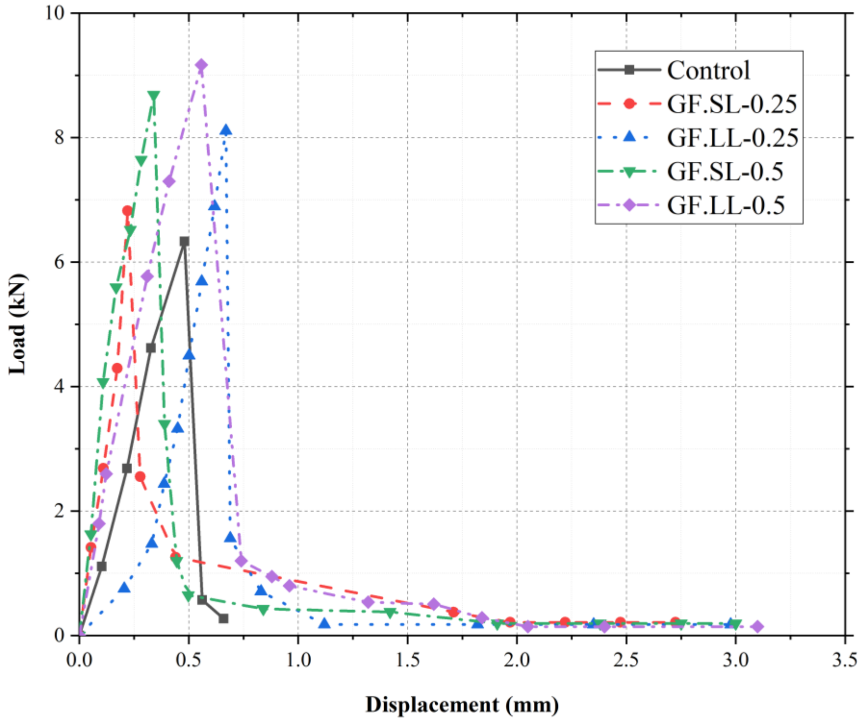


Fig. 20. Impact of glass fiber content and length on the load-displacement curve of FRC.

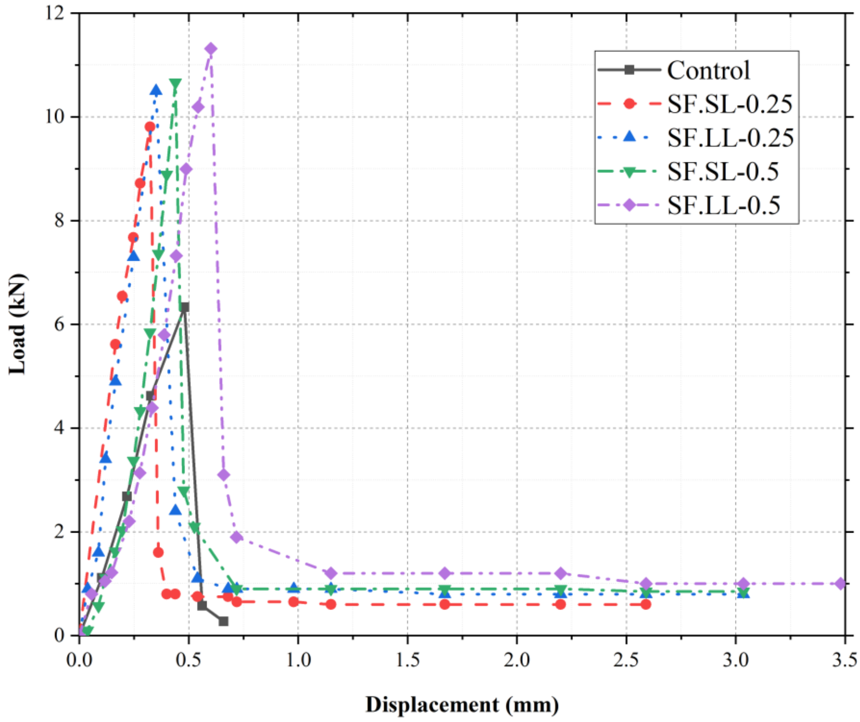


Fig. 21. Impact of steel fiber content and length on the load-displacement curve of FRC.

Fig. 22 presents the flexural toughness comparison between the control mixture and FRC mixtures containing PP, glass, and steel fibers. Fibers enhance energy absorption and crack resistance, as noted by Bayraktar et al. (2023). This improvement is attributed to the fibers' ability to impede the propagation of microcracks within the cementitious matrix. The rise in flexural toughness is notably evident with increased fiber length and content. For instance, the mixture with long-length steel fibers exhibits the highest flexural toughness at approximately 7 J, while the control mixture shows a flexural toughness of 1.8 J. Compared to the control mixture, in the amounts of 0.25% and 0.5% different fibers, the curve of flexural toughness changes is shown in Fig. 23. Based on Fig. 23, due to the better performance of long-length steel fibers in crack bridging, more energy absorption capacity was obtained for the SF-LL-0.5 mixture. In mixtures containing steel fibers, there is a notable increase in energy absorption post-cracking, showcasing the concrete's enhanced ability to withstand significant energy before failure. The mechanism of fiber pull-out plays a crucial role in crack bridging during micro and macro fractures in the matrix, as highlighted by Shi et al. (2022). This mechanism elevates the energy threshold needed for crack propagation, a concept supported by studies like those of Yoo et al. (2016) and Uygunolu (2011). Thus, enhancing the energy absorption capacity of FRC occurs by impeding microcrack and macrocrack propagation. Consequently, this leads to a substantial increase in ductility and toughness of FRC, as observed in research by Yu et al. (Yu et al. 2015) and Zeyad (2020).

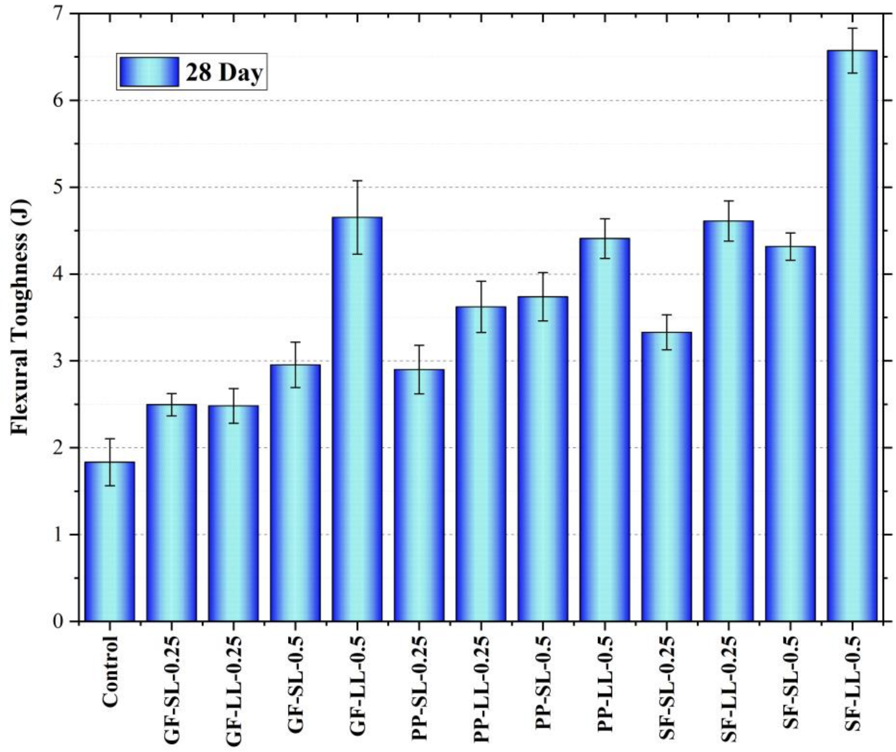


Fig. 22. Impact of PP, Glass, and Steel fibers on the flexural toughness of mixtures.

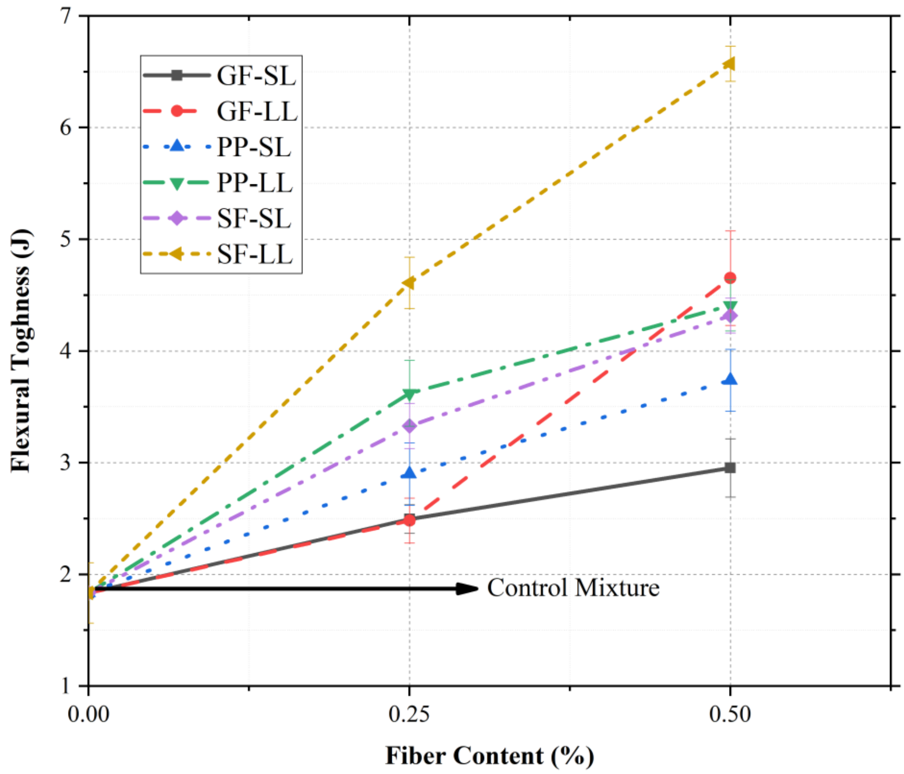


Fig. 23. Changes in 28-day flexural toughness of mixtures with different fiber lengths

5. Economic evaluation

Economic comparison aids in making informed decisions for construction applications by evaluating the cost-effectiveness of FRC mixtures in relation to fiber type, content, length, and mechanical properties. This section presents a comprehensive economic evaluation focusing on changes in mechanical performance (i.e., compressive strength, tensile strength, flexural strength, and flexural toughness) associated with the price increase from adding different fiber types (i.e., steel, PP, and glass fibers). Fiber prices were selected based on (Ali et al. 2020), with steel, PP, and glass fibers priced at 0.8, 0.9, and 0.75 USD/kg, respectively.

It should be noted that, in this study, the workability of concrete (slump) was assumed to remain nearly constant across all mixtures due to controlled superplasticizer dosage. Consequently, additional costs related to the impact of workability on the cost of placement, pumping, installation, etc., were not considered due to the comparison between the effects of fibers. The scope of this analysis is limited to comparing the performance improvements and price implications of the selected fibers.

This economic evaluation directly compares the mechanical property enhancements achieved with different types of fibers in relation to their respective costs, simplifying decision-making for applications where variations in workability or installation methodologies are minimal or can be controlled through proper mix design. For the economic evaluation, changes in parameters (strength and price) are initially calculated using Eq. (4). P_{FRC} represents the parameter value for the fiber-reinforced concrete mixtures, while $P_{Control}$ denotes the parameter value for the control mixture (without fibers).

$$Change\ in\ Parameter\ = \frac{(P_{FRC} - P_{Control})}{(P_{Control})} \quad (4)$$

Then, a modified normalization approach (MNA) is applied according to Eq. (5) to scale the values between -1 and 1, where negative results indicate a decrease in that indicator. This method represents the increase and decrease of the value relative to a reference point. In Eq (5), "Max Absolute Change" refers to the maximum absolute value of the percentage changes across all mixtures. This ensures that the normalization is relative to the most significant change observed.

$$Normalized\ Parameter\ = \frac{Change\ in\ Parameter}{Max\ Absolute\ Change\ in\ Parameter} \quad (5)$$

Finally, the economic efficiency index (EEI) for each mechanical parameter is obtained using Eq (6). A negative EEI indicates that the addition of fibers decreases the mechanical parameter relative to the cost increase, suggesting that the mixture may not be economically viable for that mechanical parameter (CS: compressive strength, TS: tensile strength, FS: flexural strength, FT: flexural toughness). The final value obtained from the MNA is normalized for clearer analysis, as shown in Fig. 24, which illustrates the economic comparison of FRC mixtures in different situations.

$$Economic\ Efficiency\ Index\ (EEI)\ = \frac{Normalized\ Mechanical\ Performance}{Normalized\ Price} \tag{6}$$

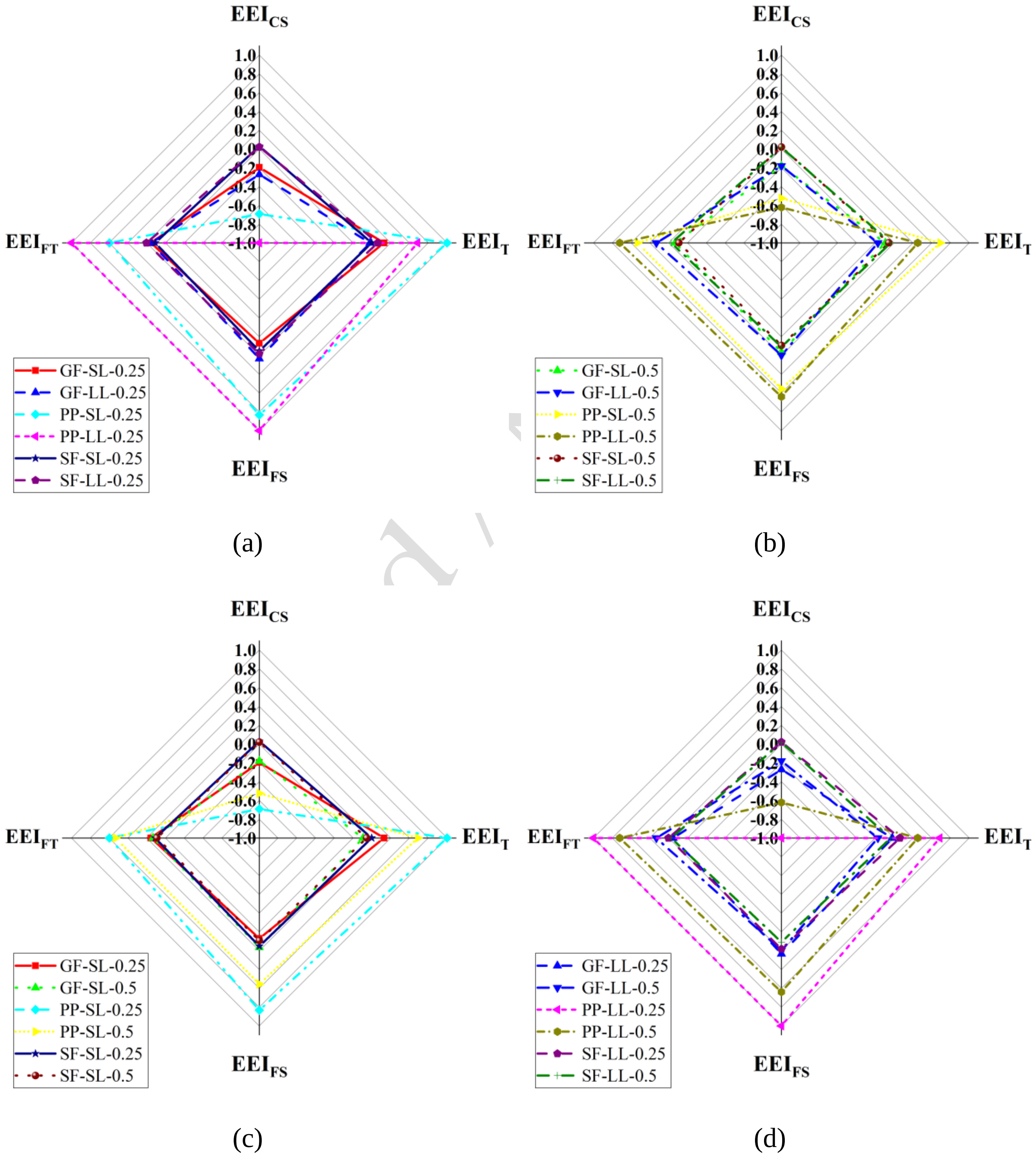


Fig. 24. Economic comparison of different EEI parameters of FRC mixtures in terms of (a) constant value of 0.25, (b) constant value of 0.5, (c) short length, and (d) long length

Economic analysis of the mixtures shows that mixtures containing PP fibers perform the worst in the compressive EEI parameter due to a reduction in compressive strength compared to the control mixture. However, given the lower cost of mixtures containing PP fibers and their mechanical performance in tensile strength, flexural strength, and flexural toughness, the EEI of these mixtures far exceeds that of others. Notably, using PP fibers at a 0.25% content (in short and long fiber lengths) demonstrates improved EEI outcomes. This indicates that despite the increased cost associated with adding PP fibers, significant improvements in tensile strength, flexural strength, and flexural toughness can still be achieved. Additionally, increasing fiber length enhances the EEI performance of mixtures, a trend observed for both PP and steel fibers. Glass fibers, however, exhibited different behavior due to challenges such as improper dispersion.

From a practical standpoint, PP fibers are most suitable for applications where cost-effectiveness and improved flexural and tensile properties are prioritized, such as thin concrete panels, sidewalks, and other secondary structural elements requiring crack control without high compressive strength. While PP fibers effectively improve ductility and crack resistance at a lower cost, they are less suited for applications that demand extremely high mechanical performance.

On the other hand, steel fibers, which incur higher costs, show superior performance in flexural toughness and overall mechanical strength. Mixtures containing steel fibers are ideal for structural applications requiring significant energy absorption, impact resistance, or high flexural performance, such as industrial floors, bridge decks, tunneling segments, and pavements subjected to heavy loads.

Glass fibers demonstrate an intermediate position between steel and PP fibers in terms of both cost and mechanical performance, with varied results in the EEI. GFRC shows promise in applications requiring lightweight materials, aesthetic finishes, and moderate mechanical performance, such as architectural and decorative elements and non-load-bearing facade panels. However, their performance strongly depends on proper fiber dispersion and mixing techniques.

6. Sustainability analysis

To conduct a more comprehensive analysis and align with the principles of the circular economy, economic evaluations must integrate environmental impacts into decision-making frameworks. This is essential because traditional economic assessments, which focus solely on costs and mechanical performance, often overlook broader repercussions such as resource use, energy consumption, carbon emissions, and pollution. These factors play a significant role in meeting global sustainability goals (Hristova et al. 2024; Ma et al. 2024; Svazas et al. 2023). In this study, where steel, PP, and glass fibers are used in FRC mixtures, it is critical to assess mechanical performance, financial costs, and CO_2 emissions. Such an analysis offers a holistic perspective on the sustainability and feasibility of using these materials, supporting economic and environmental objectives.

The addition of steel, PP, and glass fibers significantly modifies the mechanical properties of concrete and has the potential to alter the CO_2 emissions of the mixture. Based on previous studies (Joshi et al. 2004; Habert et al. 2013), the CO_2 emissions associated with producing one kilogram of raw fibers are as follows: steel fibers emit 2.68 kg of CO_2, PP fibers emit 1.85 kg of CO_2, and glass fibers emit 2.04 kg of CO_2. To compare the CO_2 emissions of FRC mixtures, normalized parameters (calculated according to Eq. (4) and Eq. (5)) and the Sustainability Efficiency Index (SEI) (evaluated using Eq. (7)) were analyzed.

$$Sustainability\ Efficiency\ Index\ (SEI) = \frac{Normalized\ Mechanical\ Performance}{Normalized\ CO_2\ emissions} \quad (7)$$

The results of the sustainability comparison across mixtures are depicted in Fig. 25. Although steel fibers have the highest CO_2 emissions, they significantly enhance compressive, tensile, and flexural performance, which reduces the total material consumption and extends the lifespan of concrete structures. This increased lifespan compensates for some environmental costs associated with steel production. In contrast, FRC mixtures with glass fibers exhibit lower direct CO_2 emissions compared to steel fibers while providing Lower mechanical properties. PP fibers have the lowest carbon emissions among all fiber types examined in this study. However, since they are petrochemical-based products, their lifecycle contributes to greenhouse gas emissions, particularly within the upstream processes tied to the petrochemical industry. Despite this, their ability to enhance tensile and flexural strength at low dosages makes them an economically and environmentally attractive option for non-load-bearing and medium-load applications.

Sustainability analysis indicates that increasing fiber length in FRC mixtures can improve the SEI because longer fibers enhance mechanical properties more effectively relative to their CO_2 cost. However, increasing the fiber content decreases the SEI, as higher quantities of fibers lead to incremental CO_2 emissions without proportionally improving mechanical performance. This suggests that increasing fiber content introduces diminishing returns regarding sustainability and structural efficiency. Therefore, optimizing the fiber content and length is crucial for balancing environmental and mechanical performance objectives.

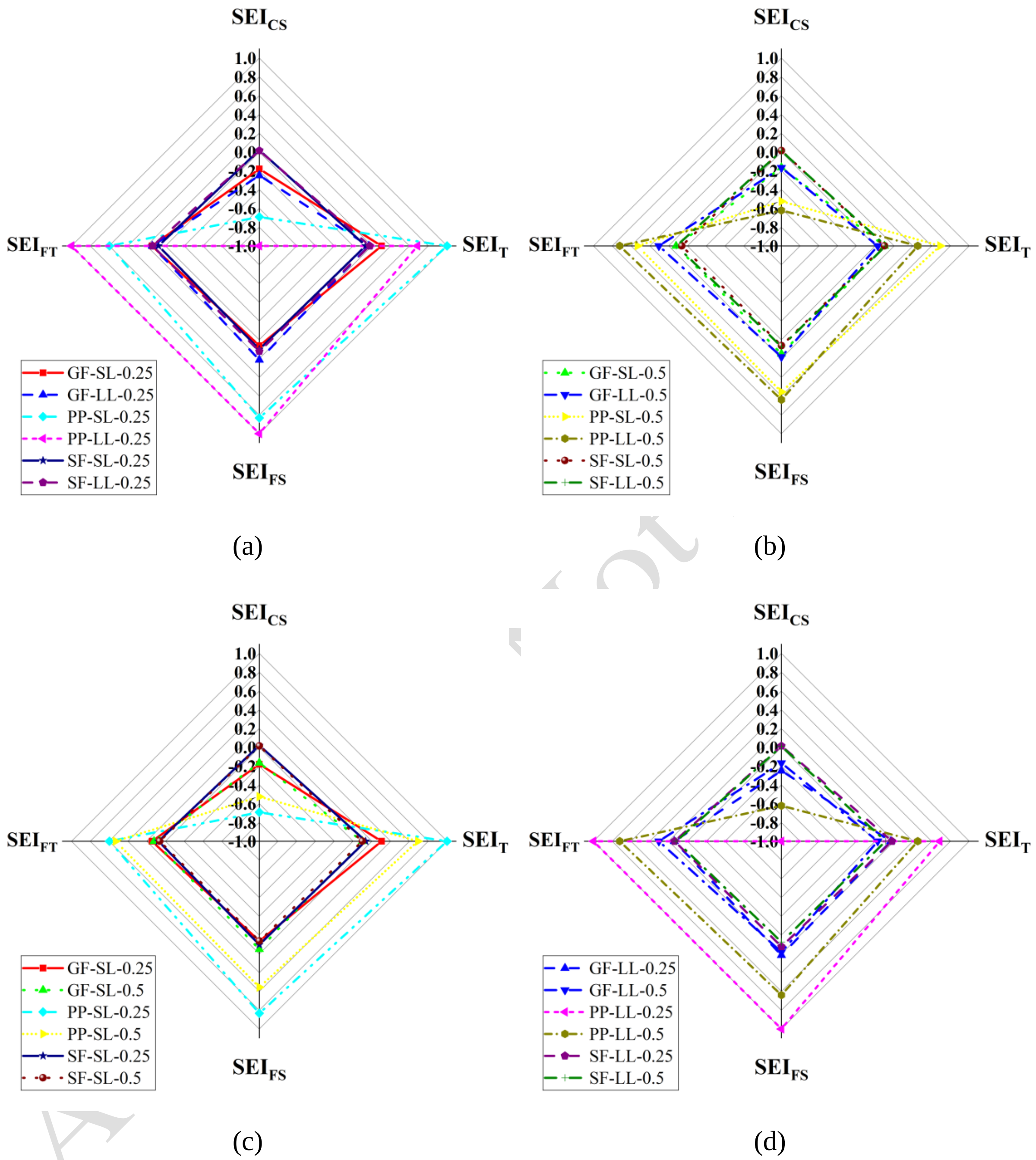


Fig. 25. Sustainability comparison of different SEI parameters of FRC mixtures in terms of (a) constant value of 0.25, (b) constant value of 0.5, (c) short length, and (d) long length

Based on the results shown in Fig. 25, FRC mixtures containing PP fibers exhibit the best SEI performance in tensile strength, flexural strength, and toughness, particularly when used at low contents (e.g., 0.25% by volume). Although FRC mixtures containing steel fibers demonstrate superior mechanical properties, glass and PP fibers provide compelling environmental and economic advantages under specific conditions. By balancing performance, cost, and CO_2

emissions, FRC can make meaningful contributions to sustainable construction practices and the circular economy. This study underscores the importance of designing FRC mixtures that optimize fiber content and type to align mechanical efficiency with environmental responsibility, ultimately supporting the broader goals of low-carbon and resource-efficient construction methods.

7. Conclusion

In this study, three types of FRC were reinforced with steel, PP, and glass fibers of varying lengths and contents. With nearly constant slump conditions across all mixtures, a comprehensive technical and economic performance comparison was conducted to determine the most efficient combination of fiber amount and length for each type of FRC. Finally, an overall comparison of the mixtures was made for the industrial application of three types of FRC. The findings from these experiments provide the following main conclusions:

- The inclusion of glass fibers in FRC reduced the compressive strength and modulus of elasticity of the mixture. Moreover, increasing the content and length of glass fibers led to a further decline in these parameters. However, the tensile strength of FRC mixtures containing glass fibers improved by around 7%. Additionally, increasing the length and content of glass fibers enhanced tensile strength, flexural strength, and flexural toughness. Despite these positive outcomes, the increased cost did not result in an appropriate EEI for the FRC mixture containing glass fibers.
- The performance trend of FRC with PP fibers in mechanical specifications is nearly identical to that of FRC with glass fibers. However, the proportion of improvement in tensile and flexural performance relative to PP fibers' increased cost and CO_2 emissions has resulted in the best EEI and SEI in these mixtures. Generally, In FRC mixtures containing PP fibers, tensile and flexural performance is enhanced at a lower cost and lower CO_2 emissions.
- FRC with steel fibers demonstrated superior performance in all mechanical specifications compared to other mixtures. Increasing the length of steel fibers reduced compressive strength and modulus of elasticity compared to FRC mixtures with short-length steel fibers but improved tensile and flexural strength. Additionally, steel fibers enhanced flexural toughness by approximately 258%. However, the EEI and SEI were lower than FRC with PP fibers due to the relatively higher cost.

FRC mixtures with steel fibers are crucial for applications requiring high flexural toughness and mechanical performance, while PP fibers offer a cost-effective alternative for moderate-performance needs. Long-length fibers at 0.25% and 0.5% content show potential for improved mechanical behavior when flowability and alignment are well-controlled. Future research should focus on long-term durability tests, including environmental exposure and freeze-thaw cycles, and evaluations of fundamental structural elements such as beams and slabs. Additionally, exploring hybrid fiber combinations remains a promising direction to optimize EEI and meet diverse design requirements, paving the way for broader adoption of FRC in practical applications.

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Not applicable.

Data availability statement

Data will be made available on request.

Conflict of interest

The authors declare no competing interests.

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