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Optimization of Tensile and Shear Properties of Concrete Reinforced with Polypropylene and Glass Fibers Using Taguchi Method

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Abstract

This study investigates the influence of fiber type (polypropylene and glass), length, and dosage on the mechanical properties of fiber-reinforced concrete, aiming to optimize these properties using the Taguchi method. An L18 orthogonal array was employed to produce 18 samples under varying conditions. The findings indicate that tensile behavior is significantly affected by these factors, with fiber dosage being the most influential. Polypropylene-fiber-reinforced concrete demonstrates superior tensile performance compared to glass fibers. Optimizing fiber length is crucial; an increase from 6 mm to 12 mm enhances tensile strength, but a further extension to 18 mm results in a decline, indicating an optimal fiber length. Regarding dosage, a moderate increase from 0.1% to 0.2% has a negligible effect on tensile strength, while a sharp decrease is observed at 0.3%, suggesting potential compromises in strength due to mixing and adhesion issues. Additionally, glass-fiber-reinforced concrete exhibits lower shear strength compared to polypropylene. Increasing fiber length and dosage contributes to a reduction in shear strength, with higher fiber length correlating to a decreased shear modulus.

1 INTRODUCTION

Reinforced concrete refers to conventional concrete augmented with added reinforcing elements to endure tensile strength. In its natural state, concrete exhibits strength in compression but weakness in tension. Therefore, the responsibility of withstanding tensile strength is allocated to the reinforcing elements integrated within the concrete. The conventional steel elements employed for concrete reinforcement may take the form of rods, bars, or mesh networks [1, 2]. Fibers are occasionally employed to reinforce concrete, primarily to mitigate crack formation. Cracking in concrete is often attributed to shrinkage caused by water evaporation from the surface or a decrease in concrete temperature. This shrinkage induces tensile strength within the concrete, resulting in cracks due to its low initial resistance. Urban structures are commonly constructed using steel-reinforced concrete, which is susceptible to damage from steel corrosion. Various methods exist to overcome this problem, one of which involves substituting steel bars with fibers to create fiber-reinforced concrete. This approach improves the mechanical properties of the inherently brittle cement matrix, which possesses minimal tensile strength relative to its compressive strength. The primary purpose of incorporating fibers into the cement matrix is to improve stiffness, and tensile strength, and enhance the crack resistance properties [3, 4].

Fiber-reinforced concrete (fiber concrete) is a composite material in which fibers are dispersed in multiple directions. Notably, fiber concrete exhibits exceptional energy absorption, flexibility, and impact resistance, reducing the risk of damage in areas prone to frequent seismic activity [5].

The mechanical properties of fiber concrete are influenced by several factors, including the type, percentage, and length-to-diameter ratio of the fibers, as well as the size, shape, and preparation method of the concrete and aggregates. In addition to the concrete paste, fibers play a crucial role in determining the overall strength of the concrete. Fibers impact the mechanical characteristics of concrete and mortar under various conditions, including direct tension, bending, compression, and shear.

Fiber reinforcement in concrete works by transferring tensile strength from the paste to the fibers. When the paste cracks, the tension is distributed between the fibers and the paste, and the entire strength is subsequently carried by the fibers [6, 7].

The U.S. Corps of Engineers was the first to use polypropylene fibers as concrete reinforcement in explosion-resistant constructions. They found that adding a small amount of polypropylene fibers (less than 0.5% by volume) significantly increased the concrete's flexibility and impact resistance. Since then, polypropylene fibers have been used

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not only as a primary reinforcement material but also as a supplement to enhance various properties of concrete [8-10].

Glass fibers are also used as reinforcing components in concrete, resulting in glass fiber-reinforced concrete (GFRC). GFRC has a wide range of applications, including enhancing roads, sidewalks, bridges, industrial hall floors, foundations for standard and vibrating machinery, and areas requiring improvements for heavy loads and impact resistance. It is also utilized in reinforcing existing floor coverings, military applications, dam overflows, sprayed concrete for rock and stone stabilization, tunnel linings, and more [11, 12].

In their research, Dave and Alice [9] conducted tests on concrete reinforced with monofilament fibers and filament tapes. They found that concrete reinforced with chopped polypropylene fibers could withstand greater loads from the onset of the first crack during flexural loading. Additionally, they discovered that increasing the fiber content in the concrete decreased the resistance at the first crack but improved the final flexural strength.

Kizilkanat et al. [13] investigated the mechanical properties of concrete reinforced with basalt and glass fibers. The results showed that adding fibers increased both the compressive strength and the elastic modulus of the concrete. For basalt fiber-reinforced concrete (BFRC), tensile strength increased as the fiber dosage was raised. However, for glass fiber-reinforced concrete (GFRC), no increase in strength was observed when the fiber dosage exceeded 0.5%. Similarly, the tensile and flexural strength of BFRC gradually increased with the fiber content, while GFRC did not show such changes beyond 0.5% fiber content. The fracture resistance significantly improved for both basalt and glass-reinforced concrete after a 0.5% fiber dosage.

Bagherzadeh et al. [14] studied the impact of different proportions and aspect ratios of polypropylene fibers on the physical and mechanical properties of fiber-reinforced concrete. Fibers of various lengths and proportions were used in the concrete mixture. The hardened concrete properties, including 7- and 28-day compressive strength, splitting tensile strength, flexural strength, water and air absorption, and restrained shrinkage cracking, were evaluated. The results indicated that polypropylene fibers had no statistically significant effect on the compressive strength of concrete. However, toughness indexes, splitting tensile strength, flexural strength, and durability parameters showed an increase in the presence of polypropylene fibers.

Imran Khan et al. [15] utilized waste synthetic fibers (glass, polyester, and polypropylene) in three different weight percentages (2%, 4%, and 6%) to reinforce concrete. They investigated the compressive strength, impact strength, and three-point bending strength of the samples. The study concluded that adding waste synthetic fibers improved the mechanical properties of the concrete.

Some researchers have demonstrated that hybridizing two or more different types of fibers can produce cementitious composites with enhanced ultimate strength, strain capacity, and strain-hardening behavior. Generally, the hybridization of fibers in cementitious composites is used to achieve higher strain capacity, enhanced durability, and cost-effective products compared to individual fiber reinforcement. Different methods of hybridization include combining fibers of varying lengths, diameters, moduli, and tensile strengths. Another purpose of using hybrid fibers is to control cracks at different size levels, in various zones of concrete, at multiple curing ages, and during different loading stages. Large and strong fibers control large cracks, while small and soft fibers help to control the initiation and propagation of small cracks [16-19].

However, a review of the literature reveals that much of the research has focused on using flexible and ductile fibers, such as polypropylene, or on brittle fibers like glass. To the best of the authors' knowledge, a comprehensive study comparing concrete reinforced with these two types of fibers under identical conditions has not yet been conducted. Additionally, most research has centered on examining the tensile, compressive, and bending properties of fiber-reinforced concrete. In contrast, the shear properties, which significantly affect crack resistance, have received less attention.

Therefore, the current research aims to investigate the effects of adding polypropylene and glass fibers in varying dosages and lengths on both the shear and tensile properties of concrete, which are crucial for fiber-reinforced concrete's overall performance. Furthermore, this study seeks to optimize these parameters using the Taguchi method to achieve the best possible properties.

2 MATERIALS AND METHODS

In this research, polypropylene fibers and glass fibers have been utilized to reinforce concrete. The specifications of the fibers used are presented in Table 1.

Table 1 Specification of the fibers

Fiber type	Tensile strength (MPa)	Density (g/cm^3)	Diameter (μ)
E-GLASS	3400	2.6	23
PP	30	0.90	17

The gravimetric method was employed to fabricate the concrete samples, which consisted of cement (14%), sand (49%), gravel (31%), and water (6%). Glass and polypropylene fibers, with varying lengths and dosages, were individually added to the mortar. To ensure uniform distribution and random orientation of fibers within the mortar, the fiber-matrix mixture was thoroughly hand-mixed before casting.

The mortar was then poured into silicone molds designed for tensile and shear specimens. After one day, the concrete samples were de-molded and immersed in water for seven days. Following this curing period, the concrete underwent a complete drying process for three days, making it ready for mechanical testing.

This study aimed to investigate the effects of three variables—fiber type, fiber length, and dosage—on the tensile and shear properties of concrete. Two levels of fiber type and three levels each of fiber length and dosage percentage were examined. Given the number of factors and interactions under consideration, the L18 orthogonal array was chosen for its suitability. Table 2 presents the analyzed factors and their respective levels, while Table 3 outlines the details of the production samples.

The selection of variable levels of length and fiber dosage is based on practical values that are most commonly used in the literature as well as in commercial applications. It should be noted that values higher than the specified levels for both variables lead to disruption in the proper fiber and mortar mix, and lower values also do not result in a significant strengthening effect based on previous research findings.

Table 2 Factors and levels of the selected factors

Factors	Level 1	Level 2	Level 3
Fibers type	Polypropylene	Glass	-
Fibers length (mm)	6	12	18
Fiber weight percentages (dosage) (%)	0.1	0.2	0.3

Table 3 Orthogonal table l_{18} design for selected factors

Experimental trials	Factors		
	A	B	C
Run 1	PP	6	0.1
Run 2	PP	12	0.1
Run 3	PP	18	0.1
Run 4	PP	6	0.2
Run 5	PP	12	0.2
Run 6	PP	18	0.2
Run 7	PP	6	0.3
Run 8	PP	12	0.3
Run 9	PP	18	0.3
Run 10	Glass	6	0.1
Run 11	Glass	12	0.1
Run 12	Glass	18	0.1
Run 13	Glass	6	0.2
Run 14	Glass	12	0.2
Run 15	Glass	18	0.2
Run 16	Glass	6	0.3
Run 17	Glass	12	0.3
Run 18	Glass	18	0.3

The tensile test was conducted in accordance with the ASTM C307 standard using concrete specimens molded into a silicon dog-bone shape. During the test, the lower jaw remained fixed while the upper jaw moved upward at a constant elongation rate of 6 mm/min. Figure 1 shows a specimen after undergoing the tensile test on the Kardoteck universal testing machine. To ensure the reliability and consistency of the results, three specimens from each sample were tested.

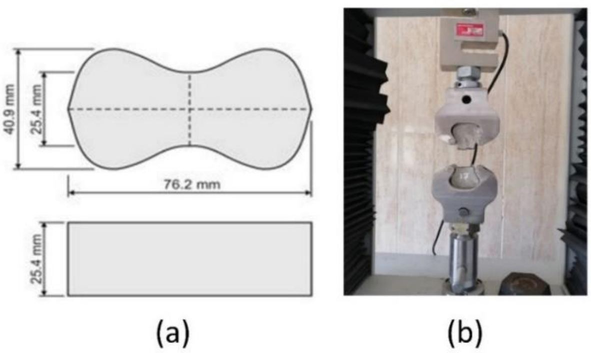


Fig. 1 Tensile test specimen dimensions (a) and a specimen after the tensile test (b).

The shear test was performed in accordance with the ASTM D5379 standard, employing a specialized grip set as illustrated in Fig. 2a attached to the Kardoteck universal testing machine. The specimens, shaped in silicon molds with dimensions specified in Fig. 2b, were securely positioned in the grips at precise locations and held firmly by tightening the adjustable jaws. The left grip remained stationary, while the right grip descended at a rate of 2 mm/min, applying shear force to the central narrow segment of the specimen with an area of 180 mm². The shear test was also conducted on three specimens from each sample to account for variability and enhance the robustness of the findings.

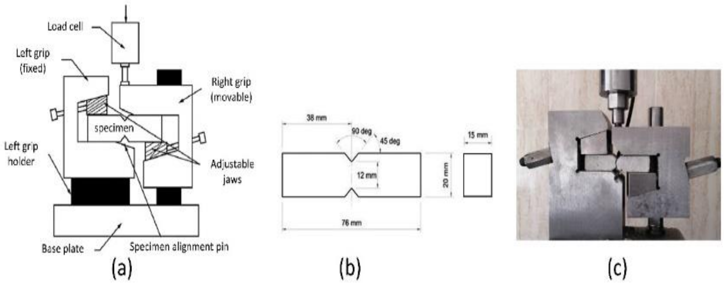


Fig. 2 Schematic view of the shear test set-up (a), the specimen dimensions (b), and a specimen after the shear test (c).

3 RESULTS AND DISCUSSIONS

In this study, the effects of a 2-level factor (fiber type) and two 3-level factors (fiber length and dosage) on the tensile and shear properties of fiber-reinforced concrete were examined using the L18 orthogonal array and the Taguchi method. The Taguchi experimental design employs orthogonal arrays to systematically organize the parameters influencing the process and the levels at which they vary. The Taguchi method's advantage lies in its ability to optimize multiple factors simultaneously while extracting extensive quantitative information from a minimal number of experimental trials. As a result, this method is widely applied in various industries [20].

After preparing the samples according to the L18 orthogonal array (refer to Table 2) and performing the required tests, the results were analyzed using Qualitek software. In the Taguchi method, the standard deviation function, as represented by Eq. (1), is used to evaluate the response dispersion:

$$S/N = -10 \, \text{Log}\,(MSD) \tag{1}$$

The negative sign in Eq. (1) is due to the fact that maximizing the S/N causes minimizing the quality loss, the mean square deviations (MSD), or a decline in data spread. The number 10 is considered contractually. The Log is also used to apply a wide range of numbers. Based on the use of the S/N ratio in engineering and statistical sciences, the larger this value, the better it is, and as a result, the MSD value should be small. Thus MSD for the following three quality features have different definitions [20-22].

Table 4 S/N results of tensile and shear properties of the samples

Sample number	Tensile strength	Tensile strain	Tensile modulus	Shear strength	Shear strain	Shear modulus
1	5.455	30.700	25.322	8.416	17.296	31.251
2	9.366	31.960	13.976	4.923	17.564	26.954
3	4.151	31.984	24.869	-0.491	22.529	25.596
4	6.399	28.008	24.752	5.795	21.336	32.712
5	9.054	31.958	-0.955	4.690	22.175	32.692
6	2.665	29.180	20.230	3.827	22.670	27.469
7	11.991-	15.648	9.984	2.271	20.260	33.494
8	4.136	25.424	17.680	2.098	21.164	33.519
9	1.804	28.639	14.566	2.304	21.267	31.597
10	2.665	22.639	20.160	2.215	22.256	30.814
11	4.413	27.419	6.353	2.975	22.219	21.992
12	3.843	28.273	10.567	-0.653	25.033	17.868
13	1.777	26.191	15.780	-1.065	22.133	25.565
14	4.011	26.217	4.154	-1.191	22.581	24.257
15	2.954	26.847	2.890	-7.121	25.463	17.644
16	13.237-	12.989	6.822	-2.997	21.643	23.279
17	1.532-	23.913	3.628	-2.963	32.537	27.535
18	8.914-	14.933	2.384	-12.670	25.673	22.657

For the qualitative characteristic of "the smaller, the better"

$$MSD = [(y_1)^2+(y_2)^2+(y_3)^2+\ldots] / n \quad (2)$$

For the qualitative property of "the closer to the nominal value, the better"

$$MSD = [(y_1-m)2+(y_2-m)2+(y_3-m)2+\ldots] / n \quad (3)$$

For the qualitative property of "the larger, the better"

$$MSD = [(1/y_1)^2+(1/y_2)^2+(1/y_3)^2+\ldots] / n \quad (4)$$

Where y1, y2, … are the results of the experiments, m is the characteristic or target value, and n is the number of repetitions (y_i). The S/N results of tensile and shear tests correlated to fiber-reinforced samples are illustrated in Table 4.

3-1 Analysis of tensile properties

The analysis of the variance of the tensile results by the S/N method is displayed in Table 5. In this table, the impacts of fiber type, fiber length, and dosage on the S/N ratio obtained from the tensile test are presented. In the S/N analysis, the degree of freedom of fiber type is equal to 1, the degree of freedom of fiber length and dosage is 2, and the degree of freedom of other items and errors is 12. Considering Table F, $F_{0.05,2,12}$ is equal to 3.89, and $F_{0.05,1,12}$ is 4.75. The Fisher coefficient column in Table 5 indicates values exceeding the corresponding thresholds, signifying the significance of all factors at the 95% confidence level. The analysis of results highlights the prominent influence of fiber dosage on tensile strength, followed by the impact of fiber length and fiber type. Moreover, as per Table 5, it is indicated that the predominant impact on tensile strain is attributed to the fiber dosage, succeeded by fiber type and subsequently by fiber length. Furthermore, Table 5 presents the ANOVA results for tensile modulus. The outcomes indicate an unsatisfactory error variance, rendering the results unreliable and precluding meaningful conclusions.

Table 5 Variance analysis of s/n tensile test result

Output	Factors	DOF	Sum of square	Variance	F value	Pure sum of square	Contribution percentage (%)
Tensile Strength	Fiber Type	1	68.289	68.289	5.608	53.113	7.850
	Fiber Length	2	124.317	62.158	5.105	99.965	13.986
	Dosage	2	376.028	188.014	15.441	351.676	49.203
	Other/Error	12	146.108	12.175	-	-	28.961
	Total	17	714.743	-	-	-	100
Output	**Factors**	**DOF**	**Sum of square**	**Variance**	**F value**	**Pure sum of square**	**Contribution percentage (%)**
Tensile Strain	Fiber Type	1	107.942	107.942	12.088	99.013	17.325
	Fiber Length	2	86.324	43.162	4.833	68.465	11.980
	Dosage	2	270.076	135.038	15.122	252.218	44.132
	Other/Error	12	107.152	8.929	-	-	26.563
	Total	17	571.496	-	-	-	100
Output	**Factors**	**DOF**	**Sum of square**	**Variance**	**F value**	**Pure sum of square**	**Contribution percentage (%)**
Tensile Modulus	Fiber Type	1	335.288	335.288	9.439	299.767	24.292
	Fiber Length	2	191.949	95.974	2.701	120.907	9.798
	Dosage	2	280.491	140.245	3.948	209.448	16.973
	Other/Error	12	426.252	35.521	-	-	48.937
	Total	17	1233.982	-	-	-	100

Fig. 3 shows the influence of the three factors on the tensile strength of samples.

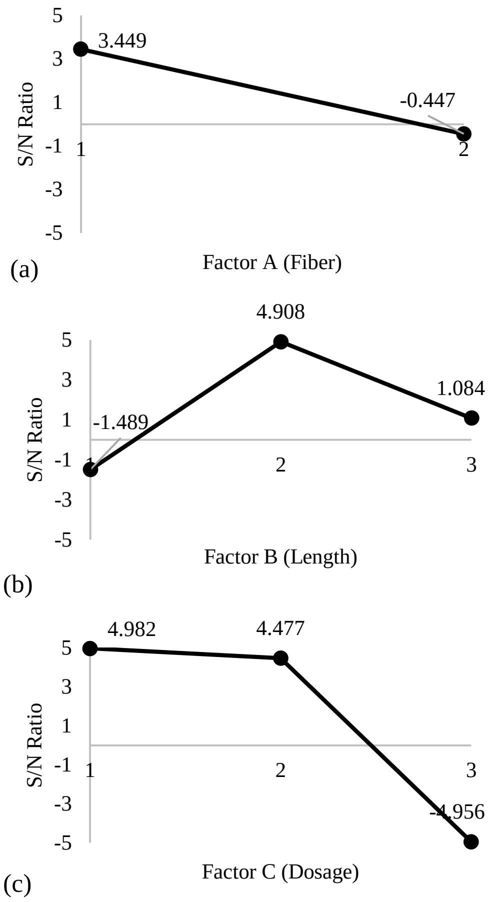


Fig. 3 Effect of fiber type, fiber length, and dosage of fiber on tensile strength of reinforced concrete

As shown in Fig. 3a, the tensile strength varies with the change in the fiber types utilized in concrete reinforcement. According to the results, the concrete samples containing polypropylene fibers have a better tensile strength than samples comprising glass fibers.

Figure 3b illustrates the effect of fiber length on the signal-to-noise (S/N) ratio obtained from the tensile strength test. The graph shows that tensile strength increases as the fiber length extends from 6 mm to 12 mm, but begins to decline when the fiber length is further increased from 12 mm to 18 mm. This trend indicates that fiber length plays a reinforcing role in the composite up to a certain point. The tensile strength improves with increased fiber length up to 12 mm due to the greater surface area for interaction between the fibers and the mortar. However, extending the fiber length beyond 12 mm can lead to a decrease in tensile strength. This reduction occurs because excessively long fibers may not mix properly with the mortar and are more likely to bend or fold, which can diminish their reinforcing effectiveness.

Fig. 3c illustrates the influence of the fiber dosage on the S/N ratio obtained from the tensile strength test. As can be noticed, the tensile strength did not change significantly with the increase in the dosage from 0.1 to 0.2, but with its increase to 0.3, there was an astute drop in the tensile strength. This issue reveals that high percentages of fibers lessen the tensile strength of fiber-reinforced mortar due to disruption in proper mixing and adhesion.

The effect of the factors on the tensile strain of samples is depicted in Fig. 4. According to Fig. 4a, a change in the type of fibers used in concrete reinforcement causes the tensile strain of concrete to change so that the concrete samples containing polypropylene fibers have more tensile strain than the ones containing glass fibers.

Figure 4b shows that increasing the fiber length from 6 mm to 12 mm initially results in higher tensile strain, but this strain decreases when the fiber length is extended further to 18 mm. This pattern parallels the observed changes in tensile strength. When fiber length exceeds a certain threshold, the effectiveness of fiber mixing with the concrete diminishes. This results in reduced adhesion between the fibers and the concrete matrix. As a consequence, both the tensile strength and strain of the fiber-reinforced concrete decrease as the fiber length increases from 12 mm to 18 mm. This decline indicates that the concrete is experiencing failure at lower stress and strain levels, highlighting the limitations of using excessively long fibers in concrete reinforcement.

The impact of fiber dosage on tensile strain is illustrated in Fig. 4c. A pattern akin to the variations in tensile strength is discernible with changes in fiber dosage. This graph indicates that augmenting the weight percentage of fibers from 0.1 to 0.2 does not markedly alter the tensile strain. Nevertheless, an increase from 0.2 to 0.3 induces a decline in tensile strain, mirroring the decrease in tensile strength attributed to the disturbance in the adhesion between fibers and the matrix.

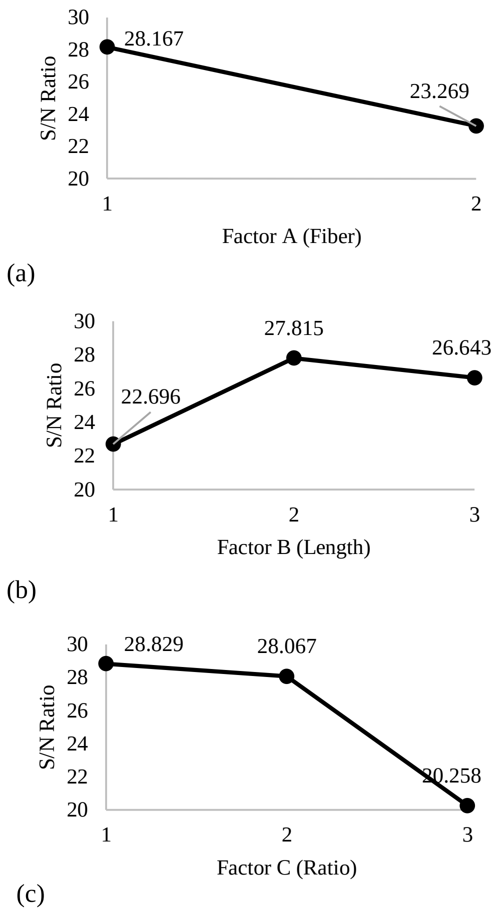


Fig. 4 The effect of fiber type, length, and dosage on the tensile strain of reinforced concrete

Table 6 shows the optimal conditions for S/N analysis of the results of tensile strength and tensile strain. As can be seen in Table 6, the maximum tensile strength and tensile strain are obtained by the fiber type factor in level 1 (polypropylene fibers), the fiber length factor in level 2 (12 mm), and the fiber dosage factor in level 1 (0.1%) are chosen. As shown in Table 3, the optimal conditions are the same as the conditions in which concrete sample No. 2 was produced.

Table 6 Optimal conditions of S/N analysis of tensile strength and strain

Response Variables	Optimum Condition	Factor A	Factor B	Factor C
Tensile strength	Level	1	2	1
	Value	Polypropylene	12 mm	0.1%
Tensile strain	Level	1	2	1
	Value	Polypropylene	12 mm	0.1%

A verification experiment is the final phase of the experiment. Its purpose is to predict and validate the improvement of the statistical model performance using the optimal level. The verification experiment is performed by conducting a test with optimal settings of the factors and levels previously evaluated. The predicted value of S/N ratios at its optimum factor level is calculated by Eq. (5) [20].

$$S/N = T + \sum_{i=1}^{k} (F_i - T) \quad (5)$$

Where, k is the number of factors, T is the mean of S/N ratio, and F_i is the S/N ratio of the significant factor level.

The anticipated tensile strength and strain of fiber-reinforced concrete, determined using the S/N ratio from Equation (5) under optimal conditions, are presented in Table 7 alongside their corresponding experimental values. Notably, a close proximity is observed between the experimental S/N ratio and the predicted value.

Table 7 Results of s/n ratio validation for tensile strength and strain of fiber-reinforced concrete

Fiber reinforced concrete property	Validation (S/N)	Predicted (S/N)	Relative error (%)
Tensile Strength	9.366	10.335	10.34
Tensile Strain	31.960	33.374	4.42

3-2 Analysis of shear properties

The ANOVA outcomes resulting from the analysis of shear test results through the S/N method are presented in Table 8, illustrating the influence of fiber percentage, fiber length, and fiber dosage on the S/N ratio. By comparing the numbers in the Fisher coefficient column of Table 8 with the corresponding numbers in the F tables ($F_{0.05,2,12}$ = 3.89 and $F_{0.05,1,12}$ = 4.75), one can conclude that the effect of all of the investigated factors on the shear behavior of reinforced concrete with one type of fiber is significant at the 95% confidence level, except for the effect of the fiber dosage on the shear strain and shear modulus. As can be seen in Table 8, the type of fibers has the greatest effect on the shear behavior of reinforced concrete.

Table 8 Variance analysis of S/N results of shear test

Output	Factors	DOF	Sum of squares	Variance	F value	Pure sum of square	Contribution percentage (%)
Shear strength	Fiber Type	1	182.464	182.464	27.127	174.738	41.818
	Fiber Length	2	84.760	42.380	6.300	71.308	16.968
	FWP	2	72.299	36.149	5.374	58.847	14.003
	Other/Error	12	80.712	6.726	-	-	27.211
	Total	17	420.237	-	-	-	100
Output	Factors	DOF	Sum of squares	Variance	F value	Pure sum of square	Contribution percentage (%)
Shear Strain	Fiber Type	1	32.654	32.654	24.786	31.337	36.965
	Fiber Length	2	28.458	14.229	10.800	25.823	30.461
	FWP	2	7.853	3.926	2.98	5.219	6.156
	Other/Error	12	15.808	1.317	-	-	26.418
	Total	17	84.775	-	-	-	100
Output	Factors	DOF	Sum of squares	Variance	F value	Pure sum of square	Contribution percentage (%)
Shear Modulus	Fiber Type	1	225.245	225.245	30.439	217.845	49.044
	Fiber Length	2	103.348	51.674	6.983	88.548	19.935
	FWP	2	26.789	13.394	1.810	11.989	2.699
	Other/Error	12	88.796	7.399	-	-	28.322
	Total	17	444.179	-	-	-	100

Fig. 5 shows the effect of the three factors on the shear strength of the samples. Fig. 5a shows that the shear strength of reinforced concrete with glass fibers is lower than that of polypropylene fibers. Fig. 5b and Fig. 5c show that as the increase in the length and dosage of fibers with concrete happens, the shear strength of reinforced concrete decreases. In this context, akin to the findings discussed in the section on tensile properties, it is evident that an augmentation in both fiber dosage and length, within the studied range, results in a diminished shear resistance. Regarding the percentage increase, as elucidated earlier, the rationale behind this phenomenon may stem from a disruption in fiber-concrete adhesion, impeding the formation of structural cohesiveness due to a reduction in the bonding element, i.e., concrete. Moreover, the observed decrease with extended fiber length can be attributed to a higher likelihood of fiber bending and folding.

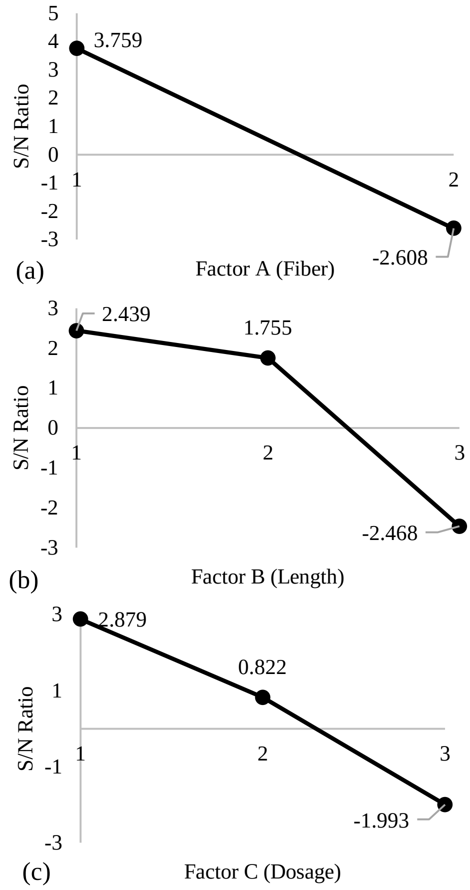
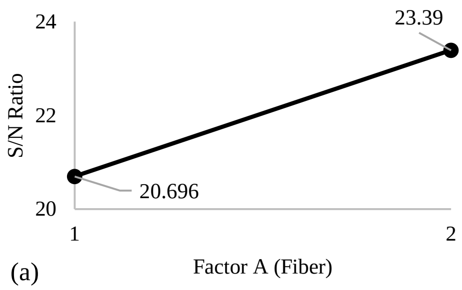


Fig. 5 The effect of fiber type, fiber length, and fiber dosage with concrete on the shear strength of reinforced concrete

Fig. 6 and Fig. 7 show the effect of fiber type and length on the shear strain and the shear modulus of reinforced concrete.



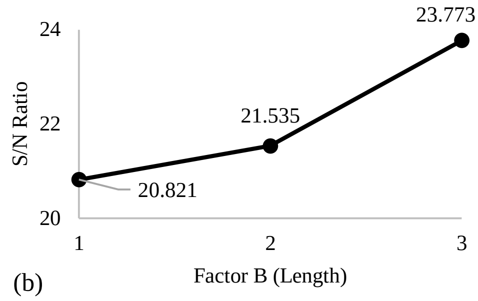


Fig. 6 The effect of fiber type and fiber length on the shear strain of reinforced concrete

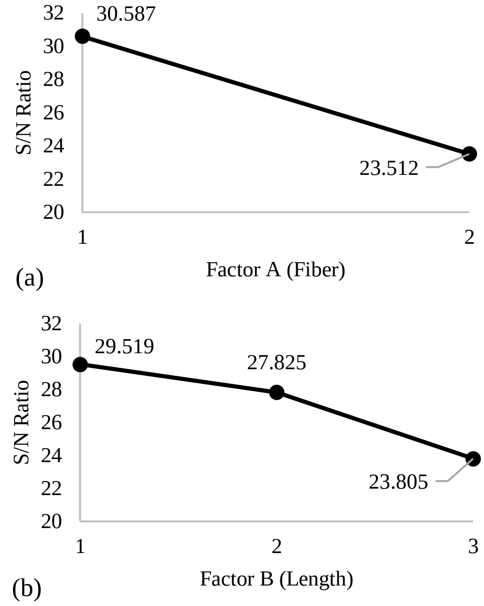


Fig. 7 The effect of fiber type and fiber length on the shear modulus of reinforced concrete

In Fig. 6a, it is evident that the shear strain exhibited by reinforced concrete containing glass fibers surpasses that of polypropylene fibers. Fig. 6b further illustrates that an augmentation in fiber length correlates with an increase in the shear strain of the reinforced concrete. Examining Fig. 7a, the shear modulus of reinforced concrete incorporating polypropylene fibers is observed to exceed that of concrete with glass fibers. Additionally, Fig. 7b indicates a decrement in the shear modulus as fiber length extends from 6 mm to 18 mm.

Table 9 shows the optimal conditions for S/N analysis of shear strength, shear strain, and shear modulus results. As can be seen, the maximum shear strength is obtained when the fiber type factor (polypropylene fibers), the fiber length factor (6 mm), and the fiber mixing ratio factor with concrete (0.1%) are chosen all in level 1. As depicted in Table 3, these optimal conditions are the same as the conditions in which concrete sample No. 1 was produced. The maximum shear strain is obtained when the type of fibers used in the concrete reinforcement is glass fibers and the length of the fibers is 6 mm. Given the fact that the fiber dosage has no significant effect on the tensile strain, the dosage of 0.1% is suggested as the optimal condition considering the production cost. Using polypropylene fibers with a length of 6 mm maximizes the shear modulus of reinforced concrete.

Table 9 Optimal conditions of s/n analysis of shear strength, strain, and modulus

Response Variables	Optimum Condition	Factor A	Factor B	Factor C
Shear strength	Level	1	1	1
	Value	Polypropylene	6 mm	0.1%
Shear strain	Level	2	1	1
	Value	Glass	6 mm	0.1%
Shear modulus	Level	1	1	1
	Value	Polypropylene	6 mm	0.1%

The predicted shear strength, shear strain, and shear modulus of fiber-reinforced concrete, based on the S/N ratio from Equation (5), are prepared under optimum conditions. Their experimental values are shown in Table 10. It can be seen that the experimental S/N ratio was found to be very close with the predicted value.

Table 10 Results of s/n ratio validation for shear strength, strain, and modulus of fiber reinforced concrete

Fiber reinforced concrete property	Validation (S/N)	Predicted (S/N)	Relative error (%)
Shear Strength	8.416	7.942	5.63
Shear Strain	22.256	25.801	15.92
Shear Modulus	31.251	34.686	10.99

4 CONCLUSIONS

The type of fibers, the length of fibers, and fiber dosage significantly influenced the tensile and shear behavior of fiber-reinforced concrete. Among these factors, fiber dosage proved the most impactful on tensile behavior. Concrete samples containing polypropylene fibers exhibited superior tensile performance compared to those with glass fibers.

As fiber length increased from 6 mm to 12 mm, tensile strength enhanced. However, extending the length further to 18 mm led to a decline, suggesting an optimal fiber length exists beyond which benefits diminish. A similar trend occurred with fiber dosage - while increasing from 0.1% to 0.2% did not significantly alter tensile strength, a sharp drop manifested at 0.3% dosage. This indicates high fiber percentages disrupt proper mixing and adhesion, reducing the tensile capacity of the fiber-reinforced mortar.

For shear behavior when using a single fiber type, fiber type, length and dosage exhibited statistically significant effects at the 95% confidence level, except for fiber dosage on shear strain and modulus. Polypropylene fibers outperformed glass fibers, providing higher shear strength. However, increasing fiber length and dosage decreased shear strength, with longer fibers also lowering the shear modulus. This phenomenon likely arises from greater fiber bending and folding probabilities during mixing with excessive lengths present.

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