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Parametric study for optimizing fiber-reinforced concrete properties

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Abstract

Concrete with fiber reinforcement is stronger and more ductile than concrete without reinforcement. Significant efforts have been made to demonstrate the properties and enhancements of concrete after reinforcement with various types and shapes of fibers. However, the issue of optimization in the reinforcement process is still unanswered. There is no academic study in the literature now available that can pinpoint the ideal fiber type, quantity, and shape and, more crucially, the overall technical viability of the reinforcement. The parametric analysis in this study determines the ideal shape, size, and proportion of fibers. The input and output parameters were separated from the optimization design variables. Input parameters included assessment of samples of fresh and mechanical concrete properties and the influence of type, length, and percentage of fiber on concrete performance. The aim was to establish the most efficient relationship between fiber dose and dimension to optimize the combined responses of workability and splitting tensile, flexural, and compressive strength. The mechanical and fresh properties of concrete reinforced with four different fibers, PFRC-1, PFRC-2, SFRC-1, and SFRC-2, were tested. The analysis showed that SFRC-2-20 mm-1%, with compressive, split tensile, flexural, and workability values of 44.7 MPa, 3.64 MPa, 5.3 MPa, and 6.5 cm respectively, was the most effective combination among the materials investigated. The optimization technique employed in this study offers new, important insights into how input and output parameters relate to one another.

KEYWORDS

fiber, mechanical properties, optimizing, reinforced concrete

Abbreviations: FRC, fiber-reinforced concrete; MOO, multi-objective optimization; PET, polyethylene terephthalate; PFRC-1, plastic fiber-reinforced concrete (macro/monofilament): Enduro® Mirage; PFRC-2, plastic fiber-reinforced concrete (crimped): Enduro®Fiber high-performance polymer (HPP); PP, polypropylene; SF, steel fiber; SFRC-1, steel fiber-reinforced concrete (straight): Novocon® XR-1050; SFRC-2, steel fiber-reinforced concrete (crimped): Novocon® FE-1050; WPF, waste plastic fibers.

1 | INTRODUCTION

Concrete is one of the most widely used construction materials because of its great compressive strength and environmental suitability. However, drawbacks include its brittleness, low resistance to crack propagation, and poor tensile strength.[1–3] Considerable efforts have been made to demonstrate the success of concrete reinforced with different kinds of fibers. Adding fibers considerably enhances the mechanical properties of concrete, as observed by the significant number of studies on fiber-reinforced concrete (FRC) available.[4–7] For example, several types of fiber (e.g., steel, glass, plastic, basalt, and waste material) were recently used as concrete reinforcement.[8,9] Researchers have also investigated the impact of steel fiber-reinforced lightweight pumice concrete on mechanical properties and found a significant improvement in compressive strength of about 42% in comparison to standard concrete. In the same studies the flexural strength in terms of post-crack behavior was reduced by adding SF to concrete.[10,11] In other work, the bending of steel fiber-reinforced concrete (SFRC) samples with fiber volumetric concentrations of 0.75% and 1.50% was estimated and compared with values measured in the laboratory. The results showed that, as predicted, the ultimate resistance increased proportionately to the volumetric SF content.[12,13] Li et al. showed that basalt fiber-reinforced polymer increased flexural strength capacity from 18.6% to 47.8% when compared to the control concrete. Researchers also indicated that ductility was improved by adding fibers and that tensile strength increased for two types of SF added to concrete.[10,14] Other studies indicated that ductility was improved by adding fibers and that tensile strength increased when two types of SF were added to concrete.[15–18] Various types of post-consumer plastics, such as polypropylene, glass-reinforced plastic and polycarbonate, have also been used to reinforce concrete.[19,20]

In addition to the mechanical properties of concrete, researchers have studied the fresh properties of this material, such as its workability, and test results were used to improve the existing building codes for structural materials.[21–23] The properties of fresh concrete are mainly influenced by the fibers used. According to GangaRao et al., the workability and resistance of concrete can be improved if a polymer is used with a fiber material of various mixtures.[24] The use of suitable fibers in an appropriate mixture can significantly increase the tensile strength of FRC. However, the final product may not always be suitable for construction applications due to the decreased workability of the concrete. Furthermore, this type of concrete will be hard to use due to the honeycomb phenomenon.[25] It is most often the case that a large amount of fiber can significantly decrease workability,[26] and researchers have observed that all types of fiber can potentially have this feature. This problem can still be overcome, however, by adding materials to enhance workability, such as a superplasticizer, or by employing tools for vibrating the concrete.

Research has also been conducted showing a high degree of performance for concrete that had been consolidated with plastic bottle fibers of various lengths, amounts, and shapes. This was attributed to tensile strength being reduced by an increased percentage of fiber.[27] The synergistic effect of fiber volume and length variables seems to affect the tensile strength of concrete.[28] In another study, the bond resistance of 20 mm fibers was lower than that of 16 mm waste plastic fibers (WPF) in all the samples studied.[29] Awolusi et al. tested various volume fractions to determine the optimal fiber content for reinforced concrete,[30] and Gao et al. studied the mechanical properties and failure mode of concrete with different quantities of steel fiber (0%, 0.5%, 1%, 1.5%, and 2%).[31] Other research investigated the effect of fiber-reinforced polymer on the mechanical properties of concrete in the presence of a high volume of rubber, in which rubber replaced 0%, 10%, 20%, 30%, and 40% of the sand content.[32] However, several reinforcement optimization issues are still unaddressed, such as the justification for a suitable fiber material, the percentage and shape of the fiber and the technical feasibility of the mixing method, and criteria to quantify the expected resultant properties, each of which requires extensive research.[33]

In the field of FRC research, there is a significant research gap regarding knowledge of the combined effects of the percentage, type, and shape of the fiber on the properties of concrete. This study aims to address this gap through parametric analysis to identify the optimal fibers in terms of shape, size, and percentage. The study categorizes design variables as input and output parameters, considering factors such as the influence of fiber type, length, and percentage on the properties of concrete. By optimizing the relationship between fiber dosage and dimensions, the study seeks to enhance concrete workability, its compressive, tensile and flexural strength. It also seeks to introduce an innovative optimization methodology that goes beyond single-parameter optimization to a comprehensive assessment of various properties. These findings emphasize the importance of considering multiple factors in FRC optimization, leading to improved performance in workability, durability, strength, and crack resistance.

2 | MATERIALS AND METHODOLOGY

2.1 | Materials

Portland EMC II composite cement and regular fine and coarse aggregates were used in this study. The sieve

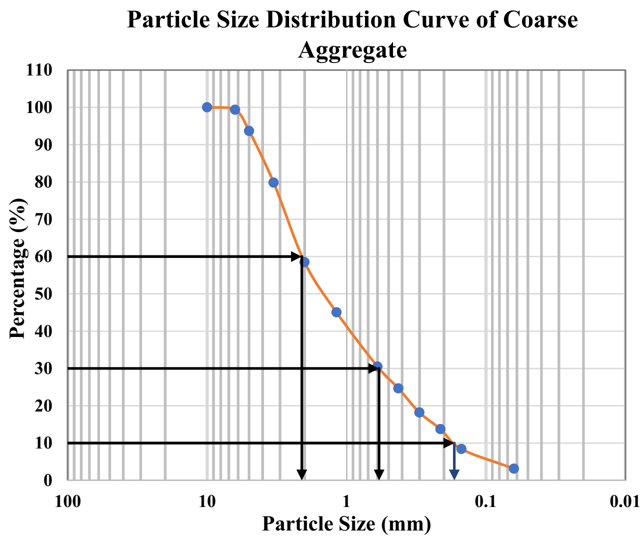

FIGURE 1 Particle size distribution of the coarse aggregate.

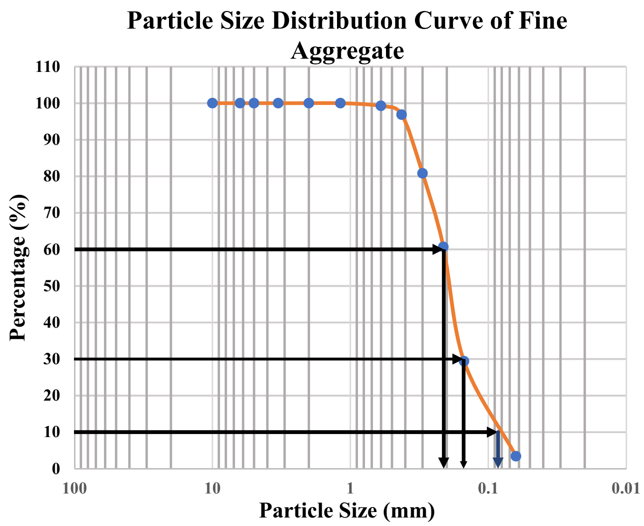

FIGURE 2 Particle size distribution of the silty sand sample 1.

analysis of the aggregates used shows that the aggregate is practical in terms of designing the concrete mixture. The particle size distribution of the coarse and fine aggregates is presented in Figures 1 and 2. Flow aid SCC superplasticizer was used to improve the workability of the concrete. Table 1 lists the requirements of the superplasticizer used in the study. With its outstanding cohesion, null segregation, and low bleed water, the concrete has very high levels of workability.[34]

Four types of fibers were used: Novocon® FE-1050 steel fibers; Novocon® XR-1050 steel fibers; Enduro®Fiber high-performance polymer (HPP); and Enduro® Mirage, which is 100% virgin copolymer fiber. The fibers were added to concrete in a range of percentages (0.5%, 1%, 1.5%, and 2%) of different lengths (20 mm, 30 mm, and 40 mm) for each type. Images of each type are presented in Figure 3. The properties of the different types of fiber and their suppliers are shown in Table 2.

TABLE 1 Specification for the superplasticizer.

Main action	Concrete superplasticizer
Dosage	0.5–1.25% of cement weight
Appearance	Yellow liquid
Specific gravity	1.10
Chloride content % w/w	Less than 0.1
pH value	4.0
Suitability of concrete	Suitable for all Portland cements

2.2 | Mixing, casting, and sample preparation

A slump target in the range from 3 to 6 cm and a specific strength of 30 N/mm^2 for 28 days was set, as shown in the mixing model (see Appendix A). The water–cement (w/c) ratio of the prepared concrete blend was 0.54. Table 3 provides the percentages for mixing 1 m^3 of the control concrete. A one-axis horizontal mixer was used to prepare the reinforced concrete mixes. This study performed 49 fiber mixes of reinforced concrete, including a control mix. For example, type-1 fiber (S1) was used to make 12 concrete mixtures using different lengths of fiber (20, 30, and 40 mm), each length making up a different percentage (0.5%, 1%, 1.5%, and 2%) of fibers as a replacement for the cement in the concrete mix. The test pieces were placed in water in a tank to be cured for 28 days at room temperature (20 ± 5°C). In accordance with the "Design of Normal Concrete Mixes" produced in 1975 by the British Department of Environment (DoE),[35] the process adhered to the standard 28-day hardening requirement for concrete.

2.3 | Testing scheme

Fresh-state and mechanical property tests to observe the impact of FRC on workability and compressive, split tensile, and flexural strength were carried out in this study. The workability test was in accordance with BS EN 12350-2 (2009).[36] The compression test was performed in accordance with BS EN 12390-4 (2000),[37] using cube samples with each. The compressive test was conducted on day 7 and day 28. Cube samples of each mixture were produced of size 100 mm × 100 mm. A Universal Hydraulic Test Machine was used to perform the compressive test using load control by a displacement of approximately 5 mm. The split tensile test was performed in accordance

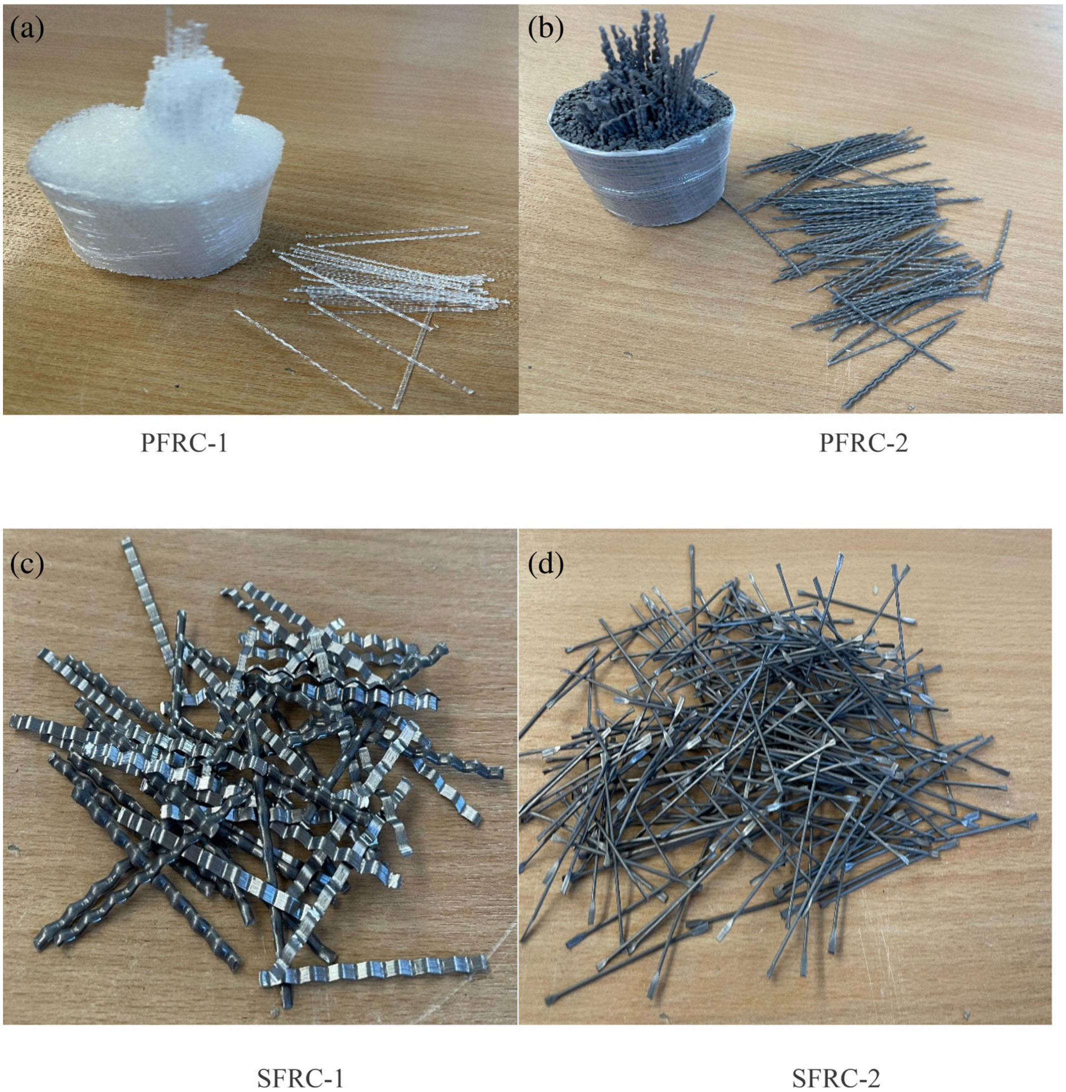

FIGURE 3 Different types of fibers used in the study.

TABLE 2 Properties of the fibers used in the study.

Type of fiber	Shape	Diameter (mm)	Length (mm)	Tensile strength (N/mm^2)	Supplier
SFRC-1	Straight	1.00	(20, 30, 40)	1150	Sika
SFRC-2	Crimped	1.45	(20, 30, 40)	690	Sika
PFRC-1	Macro/monofilament	0.95	(20, 30, 40)	465	Sika
PFRC-2	Crimped	0.92	(20, 30, 40)	552	Sika

with BS EN 12390-6 (2009),[38] using cylinder samples of each mixture produced of size 100 mm × 150 mm. The split tensile strength test was conducted on day 28 and performed using a displacement load control of approximately 5 mm. The flexural strength test was performed in line with BS EN 12390-6 (2009),[38] using three bending moments. Beam samples of each mixture were produced of size 100 mm*100 mm*400 mm. The flexural strength test was conducted on day 28 and performed using a displacement load control of approximately 5 mm. Figure 4 shows the machines used in the compressive, flexural, and split tensile strength tests.

3 | OPTIMIZATION METHODS

The earliest and most direct method found for addressing multi-objective problems was to convert them into single-

TABLE 3 Mixing percentages of the control concrete.

Quantity	Fiber percentage (%)	Cement (kg)	Water (kg)	Fine aggregate (kg)	Coarse aggregate (kg)
Per m^3		427	213	679	1061
Trial mix 0.017 m^3		7.26	3.62	11.54	18.037
SFRC-1-20 mm	0.5	7.22	3.62	11.54	18.037
SFRC-1-20 mm	1.0	7.187	3.62	11.54	18.037
SFRC-1-20 mm	1.5	7.151	3.62	11.54	18.037
SFRC-1-20 mm	2	7.115	3.62	11.54	18.037
SFRC-1-30 mm	0.5	7.22	3.62	11.54	18.037
SFRC-1-30 mm	1.0	7.187	3.62	11.54	18.037
SFRC-1-30 mm	1.5	7.151	3.62	11.54	18.037
SFRC-1-30 mm	2	7.115	3.62	11.54	18.037
SFRC-1-40 mm	0.5	7.22	3.62	11.54	18.037
SFRC-1-40 mm	1.0	7.187	3.62	11.54	18.037
SFRC-1-40 mm	1.5	7.151	3.62	11.54	18.037
SFRC-1-40 mm	2	7.115	3.62	11.54	18.037
SFRC-2-20 mm	0.5	7.22	3.62	11.54	18.037
SFRC-2-20 mm	1.0	7.187	3.62	11.54	18.037
SFRC-2-20 mm	1.5	7.151	3.62	11.54	18.037
SFRC-2-20 mm	2	7.115	3.62	11.54	18.037
SFRC-2-30 mm	0.5	7.22	3.62	11.54	18.037
SFRC-2-30 mm	1.0	7.187	3.62	11.54	18.037
SFRC-2-30 mm	1.5	7.151	3.62	11.54	18.037
SFRC-2-30 mm	2	7.115	3.62	11.54	18.037
SFRC-2-40 mm	0.5	7.22	3.62	11.54	18.037
SFRC-2-40 mm	1.0	7.187	3.62	11.54	18.037
SFRC-2-40 mm	1.5	7.151	3.62	11.54	18.037
SFRC-2-40 mm	2	7.115	3.62	11.54	18.037
PFRC-1-20 mm	0.5	7.22	3.62	11.54	18.037
PFRC-1-20 mm	1.0	7.187	3.62	11.54	18.037
PFRC-1-20 mm	1.5	7.151	3.62	11.54	18.037
PFRC-1-20 mm	2	7.115	3.62	11.54	18.037
PFRC-1-30 mm	0.5	7.22	3.62	11.54	18.037
PFRC-1-30 mm	1.0	7.187	3.62	11.54	18.037
PFRC-1-30 mm	1.5	7.151	3.62	11.54	18.037
PFRC-1-30 mm	2	7.115	3.62	11.54	18.037
PFRC-1-40 mm	0.5	7.22	3.62	11.54	18.037
PFRC-1-40 mm	1.0	7.187	3.62	11.54	18.037
PFRC-1-40 mm	1.5	7.151	3.62	11.54	18.037
PFRC-1-40 mm	2	7.115	3.62	11.54	18.037
PFRC-2-20 mm	0.5	7.22	3.62	11.54	18.037
PFRC-2-20 mm	1.0	7.187	3.62	11.54	18.037
PFRC-2-20 mm	1.5	7.151	3.62	11.54	18.037
PFRC-2-20 mm	2	7.115	3.62	11.54	18.037

(Continues)

TABLE 3 (Continued)

Quantity	Fiber percentage (%)	Cement (kg)	Water (kg)	Fine aggregate (kg)	Coarse aggregate (kg)
PFRC-2-30 mm	0.5	7.22	3.62	11.54	18.037
PFRC-2-30 mm	1.0	7.187	3.62	11.54	18.037
PFRC-2-30 mm	1.5	7.151	3.62	11.54	18.037
PFRC-2-30 mm	2	7.115	3.62	11.54	18.037
PFRC-2-40 mm	0.5	7.22	3.62	11.54	18.037
PFRC-2-40 mm	1.0	7.187	3.62	11.54	18.037
PFRC-2-40 mm	1.5	7.151	3.62	11.54	18.037
PFRC-2-40 mm	2	7.115	3.62	11.54	18.037
Superplasticizer (0.5% form cement)	0.0363 kg for trial mix				
Notes	Coarse aggregate size is 10 mm.				

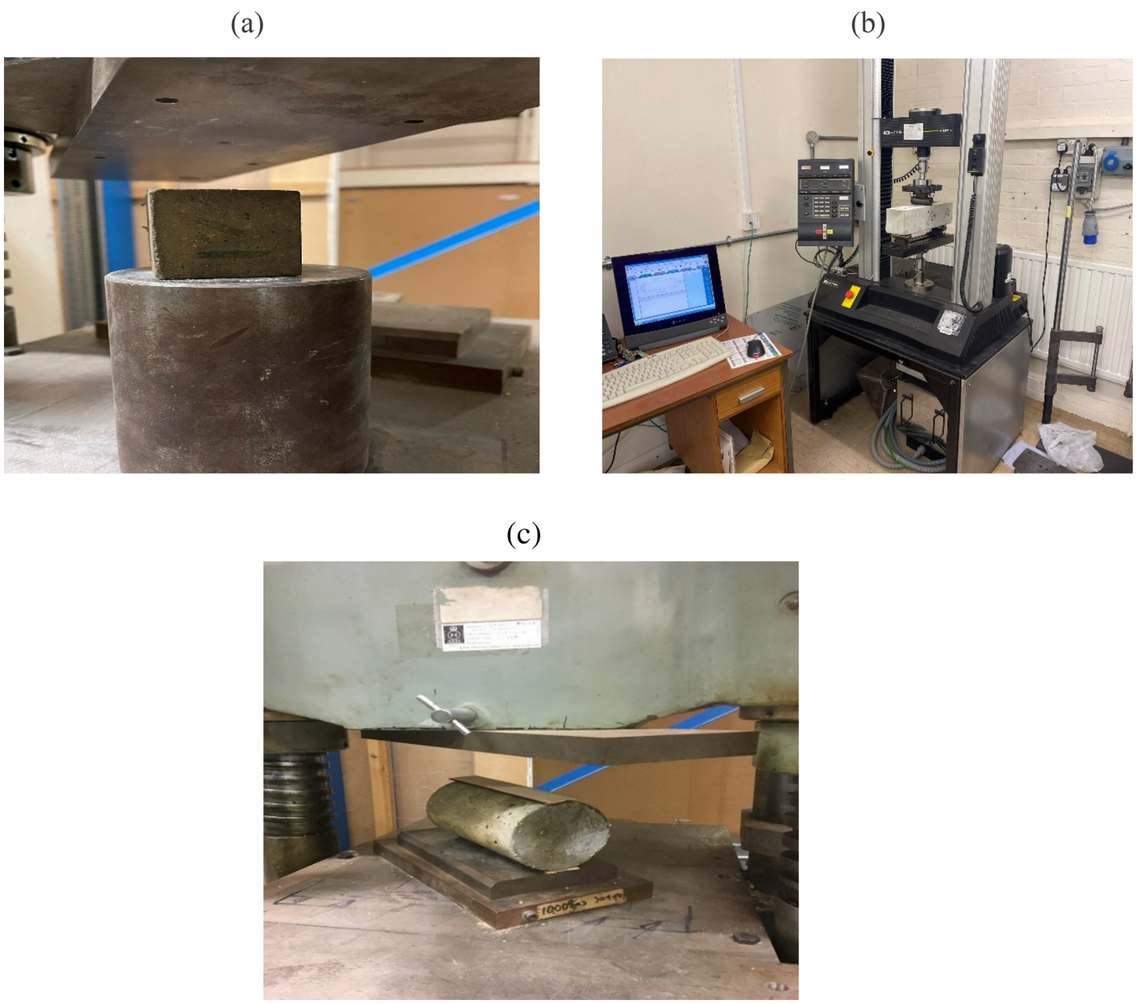

FIGURE 4 Mechanical tests of (a) compressive, (b) flexural, and (c) split tensile strength.

objective issues and then solve them using traditional optimization algorithms. In order to use this method, we must determine the degree of importance of each objective, which is either determined beforehand using an a priori method (such as the weighted sum method) or during the research process using an interactive method (such as the

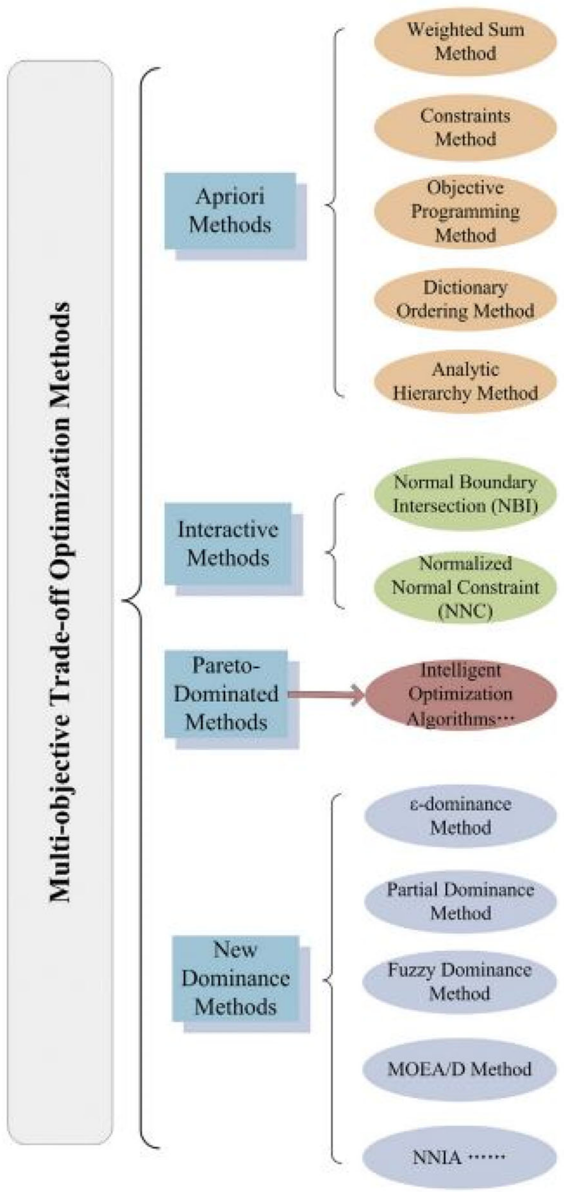

FIGURE 5 Classification of multi-objective optimization trade-off method.[47]

boundary intersection method).[39] To reach a trade-off solution for multiple, conflicting, and non-similar objectives, research is increasingly being conducted using various approaches, from classical optimization techniques to intelligent optimization algorithms. To simplify a problem, there are two methods of multi-objective optimization (MOO) that do not require complicated mathematical equations: the Pareto method and scalarization.[39–45] Researchers have proposed a model using the weighted sum method (WSM), which is used to weight multiple objective functions for solving a joint optimization model based on the input–output matrix of signal objective optimization modes.[46] Figure 5 is a summarized demonstration of trade-off methods for solving MOO problems.[47]

According to previous studies, the different sample parameters are used as objective functions to find the optimal value. MOO is used when different functions need to be minimized and maximized, whereby the optimal is the trade-off between these objectives. The target of the design is to maximize all the objectives, so weighted sum MOO is used. The WSM combines the various objectives into a single objective function, which is a common strategy in MOO. Each objective is given a weight, which will then be added. The single objective function that results can then be improved using conventional optimization methods. The weights assigned to each objective reflect their relative importance, and the WSM assumes that all objectives are equally important. This strategy may be helpful when there is no obvious hierarchy among the objectives and the decision-maker wants to consider them equally.

The WSM effectively fuses multiple objectives into a single objective function.

3.1 | Weighted sum method

To meet the optimization objectives $f_i(x), i=(1,2,\ldots,m)$, we use the weighted sum method to combine multiple objectives into one.

$$f(x) = min\sum_{i=1}^{m}[w_i \times f_i(x)] \quad (1)$$

wherein, $w_i \geq 0, \mathrm{i}=(1,2,\ldots,m)$ is a set of weighted coefficients, $\sum_{i=1}^{m} w_i = 1$. Therefore, the multi-objective problem is transferred into a single objective problem, which can be solved using a classical optimization algorithm.

The structure of the WSM makes it simple to understand and apply. However, in this method, decision-makers need to decide the weighted coefficients beforehand according to real-world problems or technical experience. A variant of the WSM is the weighted product method, which is represented as follows:

$$f(x) = min\prod_{i=1}^{m}[f_i(x)]^{w_i} \quad (2)$$

Xia et al. proposed a hybrid optimization algorithm based on sequential quadratic programming and chaos particle swarm optimization (SQP-CPSO) to realize the optimal modeling of an ethylene cracking system. The optimized objectives were transformed into one single objective using the WSM, according to previous experience. They used SQP-CPSO to optimize the single objective. The proposed method improved the accuracy of the Kumar model with a certain extendable performance.[48] Other researchers employed the WSM to calculate the weight coefficients of the objectives so that multiple objectives were weighted into a single objective and that single objective was then optimized using GAMS software.[46,49]

3.2 | Design optimization procedure

The test outcomes and the cost of FRC were used in the study to create an optimization method in order to choose the most appropriate fibers to add to concrete in terms of assessing its mechanical properties, how they influence hardness, the impacts of the fiber properties (percentage, length, and type), and from an economic point of view. An optimization method is mainly served by determining a performance criterion for the decision, whereby dependent and independent variables influence the final decision and parameter formulation. Figure 6 shows the input parameters (types, lengths, and percentages of fibers) that influence ease of mixing and the cost of the fibers. Concrete has a considerable compression force, so to make it stronger, engineers add fiber to the internal concrete structures. Fiber enhances the tensile strength of the structure of the concrete, developing its robust use in construction. Figure 6 shows the weighted scale-based parametric analysis developed for the design optimization of reinforced concrete in this study. Design variables for the optimization were divided into two groups: input and output parameters. The input parameters were the influence of the type, length, and percentage of fibers on the performance of concrete, including the mechanical and fresh-state concrete property samples. In order to search for the best relation of fiber dose and dimension to optimize the combined responses of workability, split tensile strength, flexural strength, and compressive strength, the input parameters in this study were according to the type, length, and percentage of the fibers used. Cost was also used as an influencing input parameter as it can vary for the different types of fiber. Fiber length and percentage were influenced by ease of mixing the fiber, especially in terms of the workability of the concrete.

The empirical analysis was undertaken using the input and output parameters referred to above and the following explanation combines the parameters in this study.

3.3 | Input parameter optimization

The input parameters are the type, length, and percentage of the fibers added to the concrete. The scale of the fiber type $F(\text{type})i$ according to the scale of cost if cost: expensive = 5; cheaper = 10. The scale of fiber length F(length) according to scale of easy to mix 20 mm = 10; 30 mm = 7.5; 40 mm = 5. The scale of fiber percentage $F(\text{amount})i$ according to scale of quantity of fiber 0.5% = 10; 1% = 7.5; 1.5% = 5; 2% = 2.5. After obtained the scale infancies number will combine the scales for input parameters to calculate the optimization number of input parameters as shown in Equation (3).

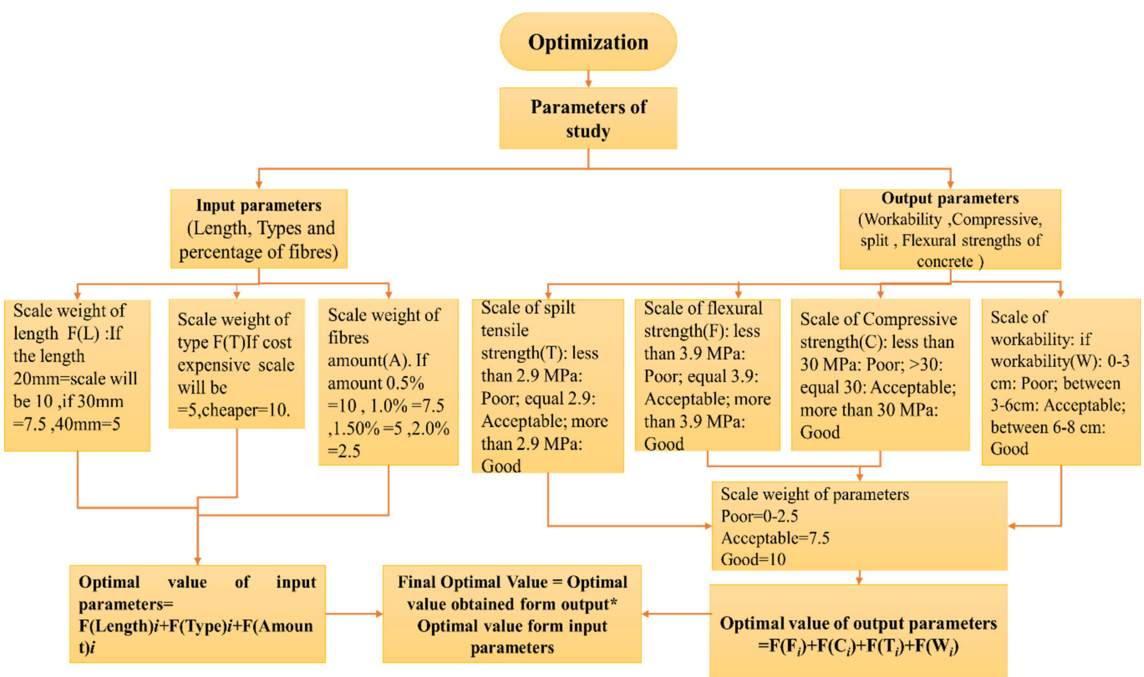

FIGURE 6 Optimization procedure.

$$\text{Optimization number of input parameters}(i) = (\text{type scale} + \text{length scale} + \text{percentage scale}) \quad (3)$$

3.4 | Output parameter optimization

The output parameters are workability, compressive strength, split tensile strength, and flexural strength. The scales used to measure the parameters are explained below.

- The workability scale has three different values depending on the slump test result: 0–3 cm = poor; 3–6 cm = acceptable; 6–8 cm = good. The weight scale of workability is as follows: 2.5 = poor; 7.5 = acceptable; and 10 = good. Equation (4) shows the workability scale value:

$$F(\mathrm{W}_i) = \text{weight scale of workability} \times \text{workability value obtained from test} \quad (4)$$

- The compressive strength scale has three different values depending on the results of the compressive test: <30 MPa = poor; 30 MPa = acceptable; >30 MPa = good. The weighted scale for compressive strength is as follows: 2.5 = poor; 7.5 = acceptable; and 10 = good. Equation (5) shows the compressive strength scale:

$$F(C_i) = \text{weight of requirement} \times \text{compressive strength value obtained from test} \quad (5)$$

- The spilt tensile strength scale has three different values depending on the results of the tensile strength test: <2.8 MPa = poor; 2.8 MPa = acceptable; >2.8 MPa = good. The weighted scale for split tensile strength is as follows: 2.5 = poor; 7.5 = acceptable; and 10 = good. Equation (6) presents the tensile strength scale. Note: the standard for the tensile strength values is in accordance with Table 2 of BS EN 1992-1-1.

$$F(T_i) = \text{weight of requirement} \times \text{tensile strength value obtained from test} \quad (6)$$

- The flexural strength scale has three different values depending on the results of the flexural strength test: <3.8 MPa = poor; 3.8 = acceptable; >3.8 MPa = good. The weighted scale of split tensile strength is as follows: 2.5 = poor; 7.5 = acceptable; and 10 = good. Equation (7) presents the flexural strength scale. Note: the standard for the flexural strength values is in accordance with Table 2 of BS EN 1992-1-1.

$$F(F_i) = \text{weight of requirement} \times \text{flexural strength value obtained from test} \quad (7)$$

- After calculating the scale influences for each parameter will be combined these equations to calculate the optimization number of output parameters, as illustrated in Equation (8). The higher the number, the more highly optimized the concrete.

$$\text{Optimization number of output parameters} = F(W_i) + F(C_i) + F(T_i) + F(F_i) \quad (8)$$

$$\text{Final optimization number} = \text{number of effects of input parameters on optimization} \times \text{output optimization number} \quad (9)$$

4 | RESULTS AND DISCUSSION

4.1 | Fresh test

4.1.1 | Results of fresh concrete test

Figure 7 shows the results of the slump test, which was conducted on 48 reinforced-fiber mixtures and the control. The results show that there was a gradual decrease in the workability of the concrete. It can clearly be seen that the slump in all the mixture samples containing different types of fiber was lower than that for the control concrete. The results show that the highest slump was 8 cm for the control mixture without fiber.

The lowest value in the slump test was 4 cm, which included 2% of fibers of all types (S_1, S_2, P_1, and P_2).

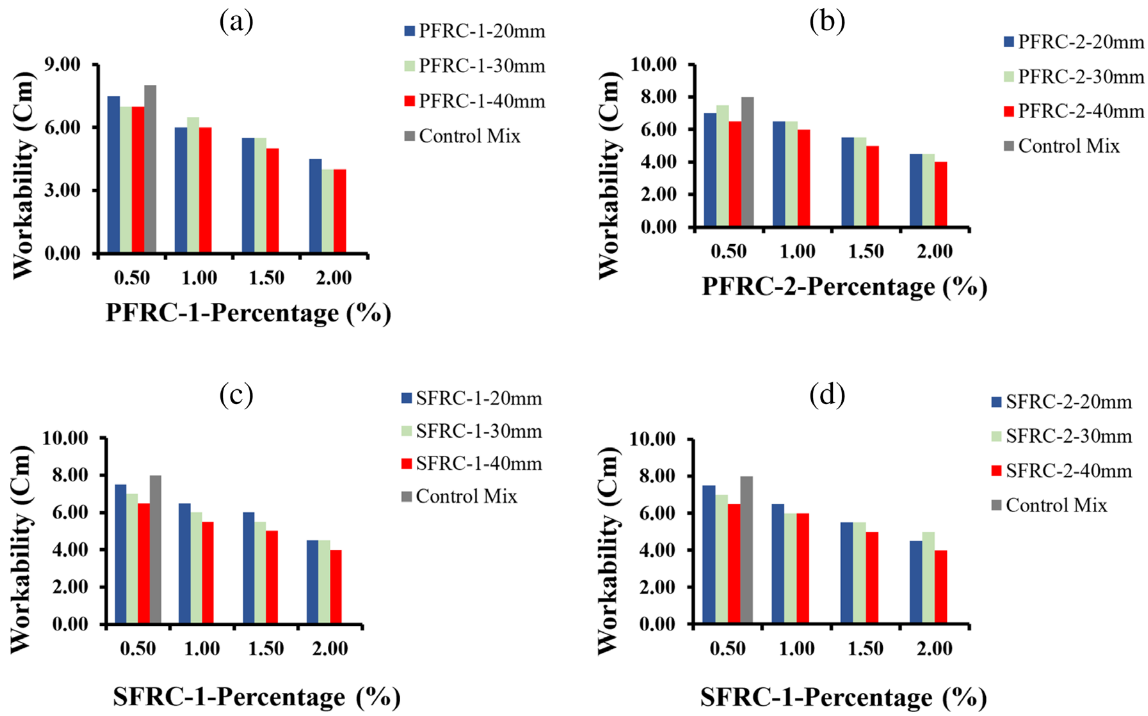

FIGURE 7 Impact of different types of fiber on concrete workability.

Figure 7 demonstrates the variation in slump according to the type, length, and percentage of fiber. It can be observed that there was a drop in the workability of both types but the impact of SF (S_1, S_2) on workability was less than that of plastic fiber (P_1, P_2). The length of the fiber was considered one of the reasons for the reduced workability. The results of this test show that a 20 mm-length fiber has a lower influence than lengths of 30 mm and 40 mm for steel (S_1, S_2) and plastic (P_1, P_2) fiber on fresh concrete. Thus, it is evident from the results that workability is reduced when the amount of fiber increases.

Reinforced concrete made with steel and plastic fiber shows low workability. An increase in fiber fractions led to a linear downward trend in the workability diameter. However, this low workability was still within the range of the target slump (3–6 cm).

4.2 | Mechanical properties tests

4.2.1 | Compressive strength

Figures 8 and 9 demonstrate the results of the impact of fiber type, shape, and percentage on the compressive strength of FRC at 7 and 28 days. There is little improvement in the compression of samples regardless of the different fibers, shapes, and percentages. An increase can be observed in the compressive strength of concrete when adding 30 mm plastic-1 fibers. However, no compressive influence was observed for lengths of 40 or 20 mm, as demonstrated in Figures 12 and 13. There was a 10% increase in compressive resistance when the length and percentage of plastic-1 fibers were 30 mm and 1.5%, respectively. The results indicate that compressive strength at 28 days had decreased by approximately 9% when the plastic-1 fiber proportion increased.

The results demonstrate that for two lengths (20 and 30 mm) of plastic-2 fiber in the concrete mix, the compression strength increased slightly. However, no compression effects were seen for a length of 40 mm, as shown in Figures 8 and 9. When the percentage of steel-1 fiber was increased by adding fibers of 20, 30, and 40 mm to the concrete mix, the compressive strength at 7 and 28 days decreased slightly. In contrast, this low compression was still higher than the compression target of the concrete mixture (30 MPa), as indicated in Figures 8 and 9. As the percentage of 40 mm steel-2 fibers increased in the concrete mixture, the compressive strength at 7 and 28 days also increased slightly. However, no compressive influence was observed for lengths of 20 and 30 mm.

The results of the tests show that the FRC and the control concrete generally had similar compressive properties. The compressive strength of the FRC decreased with an increase in the volume fraction of fiber for all types of fiber used in the study. For example, in comparison to the control, the compressive strength of the plastic-1 fiber specimen increased slightly by adding fiber

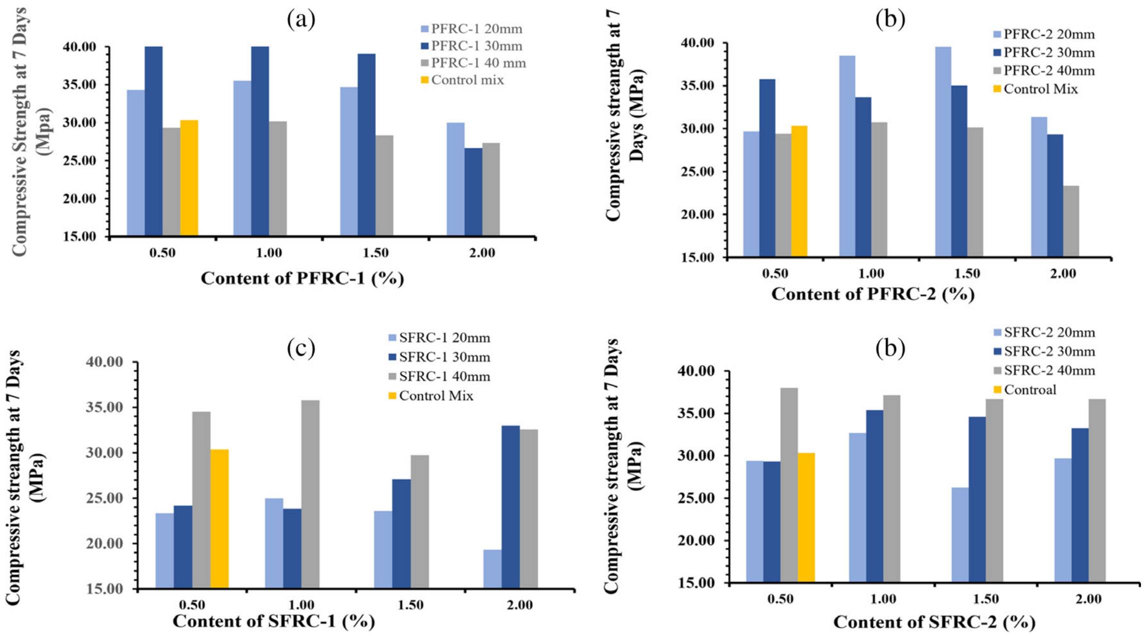

FIGURE 8 Influence of different type of fibers on compressive strength of concrete at 7 and 28 days.

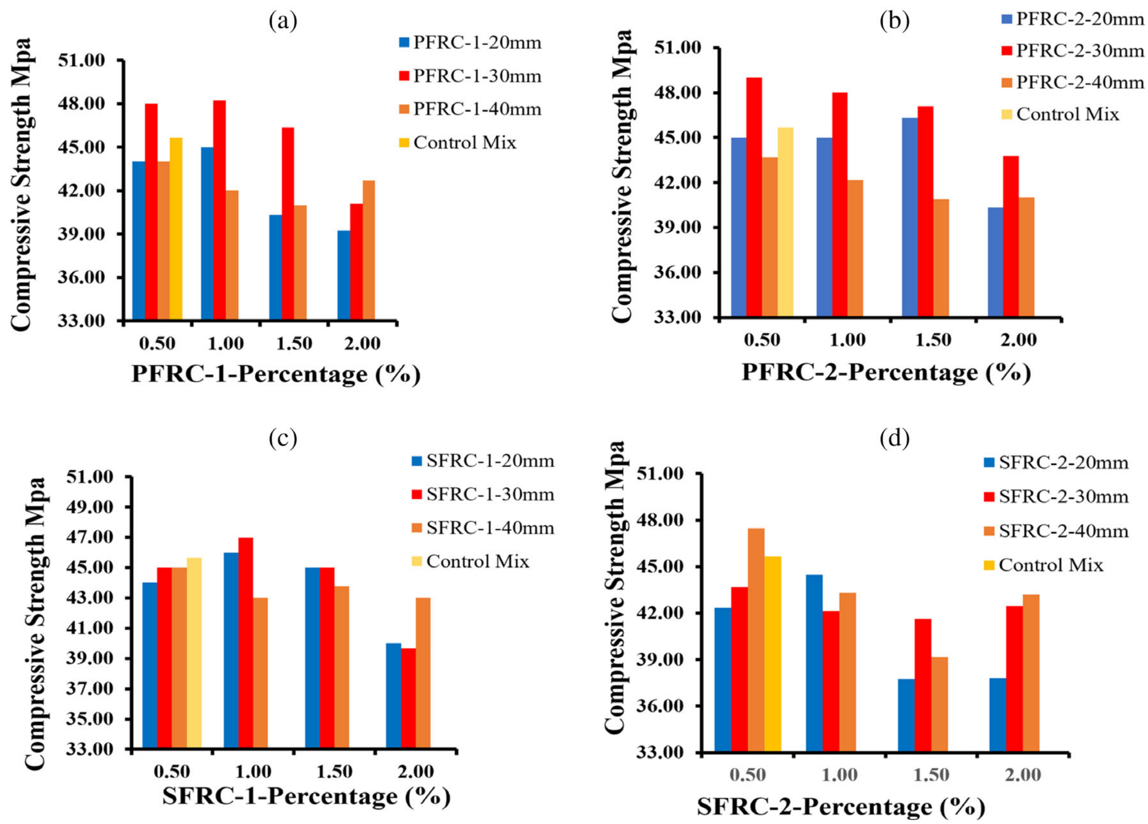

FIGURE 9 Impact of different type of fibers on compressive strength of concrete at 7 and 28 days.

(0%, 5%) (20 mm, 30 mm) but there was a decrease in compressive strength at 40 mm of about 4%. It is clear that the enhancement in compressive strength is the same as the compressive strength of normal concrete.

It is also clear that the decrease in workability of FRC increased significantly compared to the workability of normal concrete. In addition, in respect of the effect of the fiber volume fraction on tensile properties, fiber length

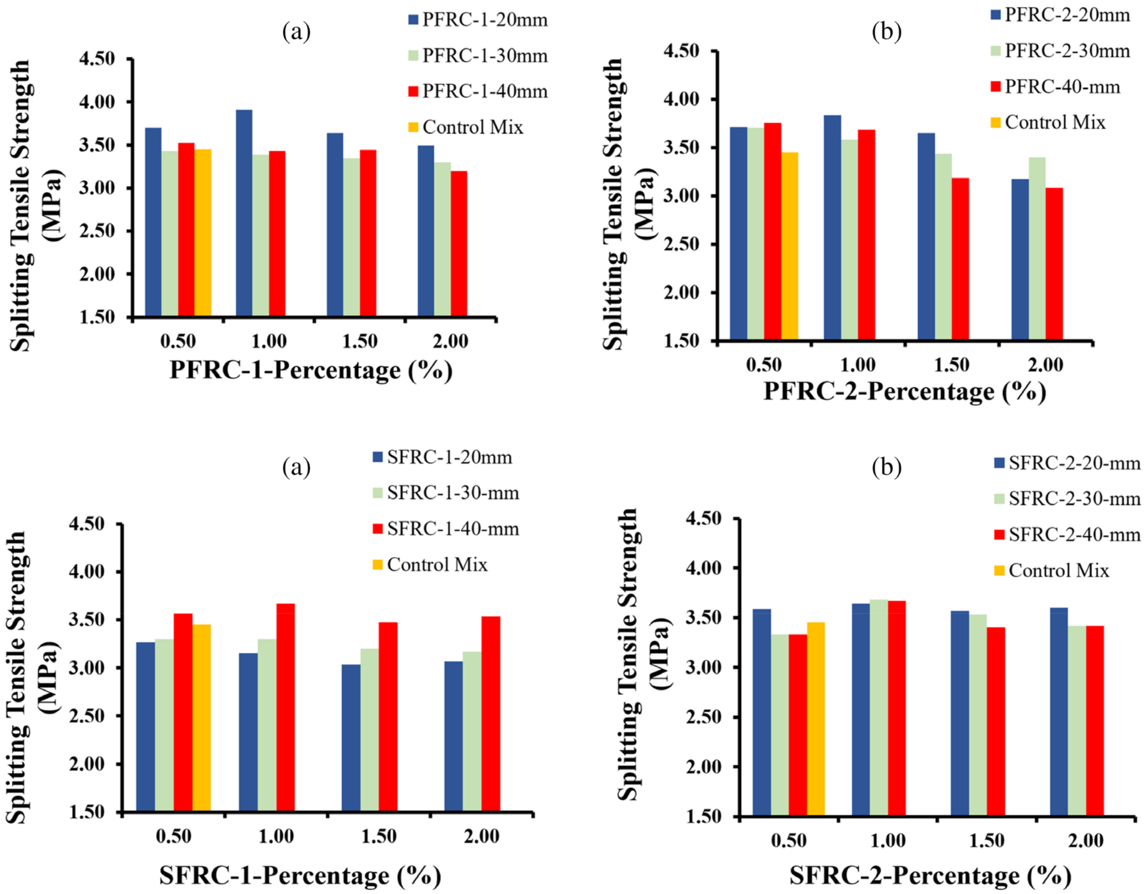

FIGURE 10 Impact of different type fiber on splitting tensile strength of concrete.

also had a negative impact, particularly when increasing the length, as the results show a decrease in workability.

4.2.2 | Split tensile strength

A total of 147 cylinders of FRC samples of different lengths, shapes, and percentages were tested under uniaxial stress in this study. Figure 10 shows the influence of fiber type, shape, and percentage on the 28-day tensile strength of different fiber types. A mixed result was observed when we added fibers of different lengths and percentages against tensile strength. A slight increase was observed in tensile strength for 20 mm plastic-1 fibers in the concrete mix. However, no tensile influences were seen for lengths of 30 or 40 mm. For plastic-2 fibers, the results demonstrate that at lengths of 20, 30, and 40 mm in the concrete mix, the tensile strength increased slightly for 0.5% and 1.0% fiber. However, tensile strength dropped for all lengths when the amount of fiber increased to 1.5% and 2%. For SFRC-2, the results show that at lengths of 40 mm, as the proportion of fiber in the concrete mixture increased, the tensile strength increased slightly. However, for lengths of 20 and 30 mm, as the proportion of fiber increased, the strength of the concrete decreased.

The results of the tests show that the FRC and the control concrete generally had similar split tensile and flexural strength properties. For instance, the tensile strength of the FRC increased with an increase in the volume fraction of all types of fiber used in this study. In comparison to the control specimen, the tensile strength when using three different lengths (20, 30, and 40 mm) of each of the fibers (PFRC-1, PFRC-2, SFRC-1, and SFRC-2) increased when adding a different percentage (11%, 3%, 0%), (11%, 4%, 7%), (3%, 5%, 5%), and (5.5%, 6%, 7%), respectively. It is clear that the enhancement in tensile strength of FRC increased significantly when compared to the tensile strength of normal concrete. In addition, in respect of the effect of the fiber volume fraction on tensile properties, fiber length also had a positive impact, particularly when increasing the length, as the results show increases in tensile strength.

4.2.3 | Flexural strength

Ninety-eight prisms of FRC samples of different lengths, shapes, and percentages of fibers were tested under bending force. Figure 11 shows the results of the impact of fiber type, shape, and percentage on flexural strength at

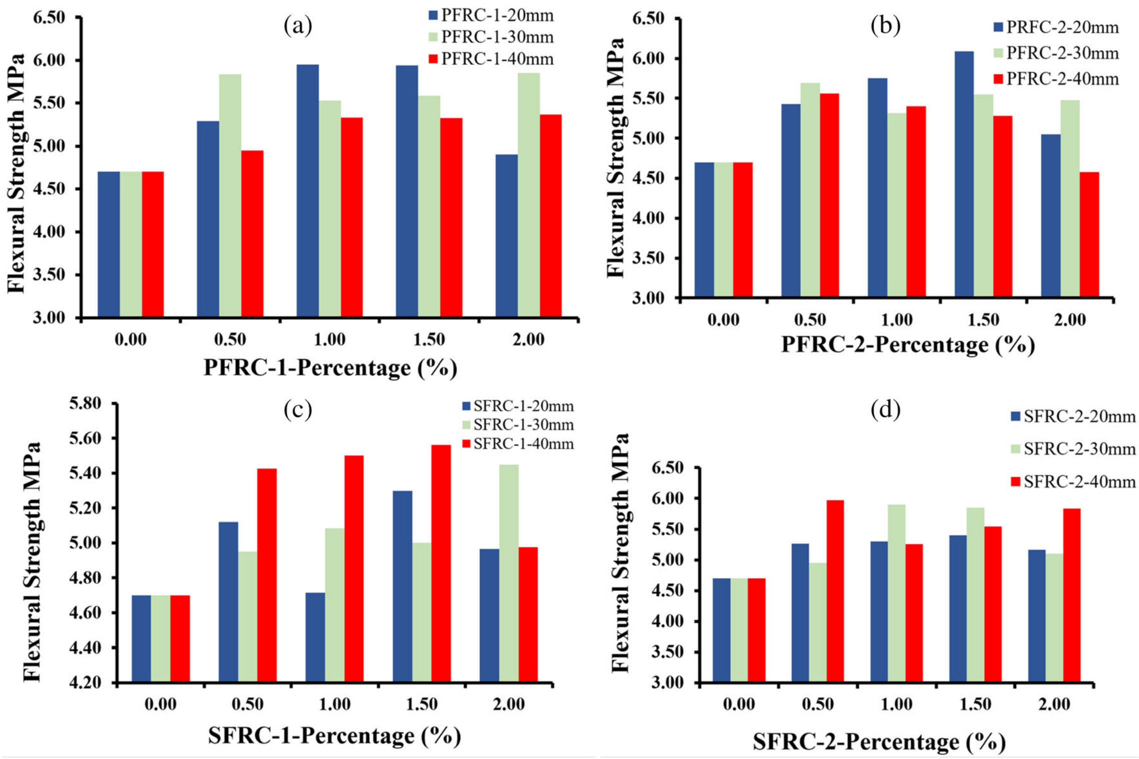

FIGURE 11 Influence of different type fibers on the flexural strength of concrete.

28 days for the different types of fiber. When increasing the percentage of lengths of 20, 30, and 40 mm of plastic-1 fiber in the concrete mix, the flexural strength increased slightly with the increased fiber amount. Plastic-2 FRC showed good bending strength compared to standard concrete for all lengths and percentages of fiber used. With an increase in the proportion of SF in the steel-1 fiber in the concrete mixture, there was a significant increase in flexural strength. It can be seen that the flexural strength of all mixture samples with different types of fiber was greater than that of the control concrete. The test results show that the FRC and the control concrete generally had similar effects in terms of split tensile and bending properties. The flexural strength of the FRC increased with a higher fiber volume fraction for all types of fiber used in this study. For example, in comparison to the control specimen, the flexural strength of PFRC-1, PFRC-2, SFRC-1, and SFRC-2 increased when adding fibers by about (11%, 3%, 0%), (11%, 4%, 7%), (3%, 5%, 5%), and (5.5%, 6%, 7%), respectively. The results show that the highest bending force was 6.09 MPa in the concrete that contained 1.5% plastic-2 fibers. The lowest slump value was 4.70 cm for the control mixture without fiber.

The test results reveal that the FRC and the control concrete generally had similar effects on split tensile strength and bending properties. The flexural strength of the FRC increased with a rise in volume fraction and length in both types of SF used in this study. For example, in comparison to the control specimen, the flexural strength of PFRC-1, PFRC-2, SFRC-1, and SFRC-2 was increased when adding fibers by (13%, 14%, 18%), (15%, 26%, 27%), (0%, 0%, 5%), and (20, 30, 40 mm), respectively. The flexural strength of the FRC decreased with an increased volume fraction and length for both types of plastic fiber used in this study. For example, compared to the control specimen, the flexural strength of PFRC-1 and PFRC-2 was increased when adding fibers by about 26% and 30% at 20 mm. However, the flexural strength decreased when the volume at length 30, 40 mm around (24%, 0%, 14%) and (21%, 18%), respectively.

5 | DISCUSSION

5.1 | Workability of fiber-reinforced concrete

Workability is an essential factor in the approval of any mixture design and can be used in the development of the construction industry in accordance with BS EN 12350-2.[50] In comparing the effects of the fresh concrete properties for all mixtures, it has been possible to ensure that the addition of fibers to the concrete has an impact on the workability of the concrete. Hence, the use of fiber requires the addition of a superplasticizer to mixes, which leads to improved concrete workability. Recent research investigated the production possibilities by assessing the workability of FRC. Samples of concrete reinforced with plastic and steel fibers performed poorly. In addition, the flow of concrete decreased with an increase in fiber length and aspect ratios. The lengths of all types in this study at (40 mm) of FRC mixes showed slightly lower workability performance than smaller steel fiber at length (20 mm) reinforced concrete. However, the measured flow values were consistently within the range of the specified flow values. Several researchers have used workability tests because they seem to be reliable and straightforward in their application. In Ref. [51], the researchers report reductions in workability with an increased fiber amount of the concrete specimen. Another study observed decreased fresh concrete workability when either of two kinds of SF was combined.[18] Other researchers observed that slump values were enhanced at plastic levels below 20%, with slump loss reductions of as much as 30%.[52] Workability was also found to decrease when polyethylene terephthalate (PET) was added, which was attributed to the sharpness of PET increasing the water requirements of the concrete.[53] The study found that all types of fiber reduced workability but that this issue could be avoided by adding materials, such as a superplasticizer, or using equipment to vibrate the concrete. In the present study, the shape and ratio of the fibers had a considerable impact on concrete flow and the level of skill required by workers to produce high-quality concrete constructions. In a review of higher levels of cement, fine aggregate or fiber additions may be useful in this area, as the reinforcement provided by fiber additions can improve sample responses and lead to improvement in which the shape of the fibers is reduced to focus on workability.

5.2 | Mechanical properties

To meet the objectives of this study, 49 FRC mixtures were created in the laboratory, including a control concrete mixture. The tests carried out in the study were on the fresh state and mechanical properties of the concrete (i.e., compressive strength, tensile strength, and flexural strength).

5.2.1 | Compressive strength

The compressive strength of the control concrete was found to be higher than that of the concrete that contained fibers. The result points to the addition of too much steel and plastic fiber leading to a weak mix, which decreases compressive strength. The results indicate that an increase in SF can raise the load capacity, as the addition of fibers to the concrete had a significant impact on the maximum load capacity. The relationship between the SF fiber and replacing the fiber with cement without transverse reinforcement.

A more quantitative examination revealed a 20% increase in maximum load capacity with an addition of 30 kg/m^3 SF. Moreover, there was no significant effect on the behavior of the compression force. SF was found to be more effective with recycled aggregates compared to natural aggregates and, therefore, could be used to replace the mix design.[54] Li et al. note that SFRC obtained an acceptable plastic deformation, but this deformation was low compared to that of conventional concrete.[55] Other results suggest that the compressive strength of concrete using recycled SF and recycled steel cords exceeded that of SFRC.[56] Other researchers found that the compressive strength of recycled aggregate concrete was approximately 72.26% of natural aggregate concrete, but, after adding silica fume, the compressive strength of concrete with recycled PET increased slightly (by 3.6%–9%). The impact of steel and plastics has been studied by previous researchers. Steel fiber was found to increase compressive strength, but not by much and, in the case of plastic fiber, no impact was observed on mechanical properties. In a more quantitative investigation, it was determined that the inclusion of 30 kg/m^3 of SF led to a notable 20% increase in the maximum load capacity. Conversely, no significant impact was observed in terms of compressive strength behavior. It was also noted that SF exhibited greater effectiveness when used in conjunction with recycled aggregate as opposed to natural aggregate, suggesting the potential for SF to substitute the mixed design.[54] Studies have also demonstrated that elevating the proportion of polyester polymer results in increased elasticity, compressive strength, and bending resistance of concrete (Figure 12).[57]

The results of the tests in this study show that the FRC and the control concrete generally had similar effects in terms of compressive properties. The maximum compressive strength of the PFRC-2 samples tested also increased with the volume fraction of the fiber, by about 6% compared to the control sample (1%) at 30 mm, and the strength of the concrete matrix. For example, in comparison to the reference specimen, the compressive strength of the PFRC-1 specimen increased by 6%. As concrete strength, especially compressive strength, is a fundamental characteristic related to the widespread use of this material, incorporating fiber into concrete requires an evaluation of the strength of the concrete-fiber composite. Incorporation can lead to several technical advantages. However, it is essential to produce a composite that is durable. Nevertheless, if the resistance of the concrete-fiber composite is significantly lower than that of the reference concrete, the realistic possibilities for its being used in various concrete applications could be minimal.

5.2.2 | Split tensile strength

This study conducted an assessment of the different types of FRC resistance in order to analyze the relationships between tensile strength and other mechanical concrete properties. Compared to standard concrete, the addition of PFRC-1, PFRC-2, SFRC-1, and SFRC-2 fibers to the concrete mix significantly increased the tensile strength ratio. Similar to the aforementioned results found in the literature, the split tensile strength measured in this study for 1% volume PFRC-1 was about 3.9 MPa. According to one study, the tensile strength of concrete with fibers compared to the reference concrete was strongly influenced.[28] Other researchers suggested that a decrease in tensile strength with the addition of e-plastic was caused by the replacement of the aggregate with e-plastic. However, an increase in tensile properties with a higher percentage of e-plastic waste was attributed to the increased ratio of resin, resulting in better moistening and encasement of the gaps in the materials.[58] Ameri et al. demonstrated that tensile strength increased with the addition of SF content. However, one configuration exhibited a lower w/c ratio and reduced tensile strength.[59,60] In a similar vein, an increase in the WPF content was found to lead to higher tensile strength and greater ductility in the material. This effect was attributed to the higher ultimate applied load and reduced internal stresses.[28,61–66] Leone et al. reported in their study that the use of SF did not result in significant effects on tensile strength. They observed only minor alterations in tensile strength when SF was added to both types.[67,68] In contrast, Pereira et al. found that the inclusion of fibers had a substantial impact on the tensile strength of concrete when compared to the reference concrete.[28,69]

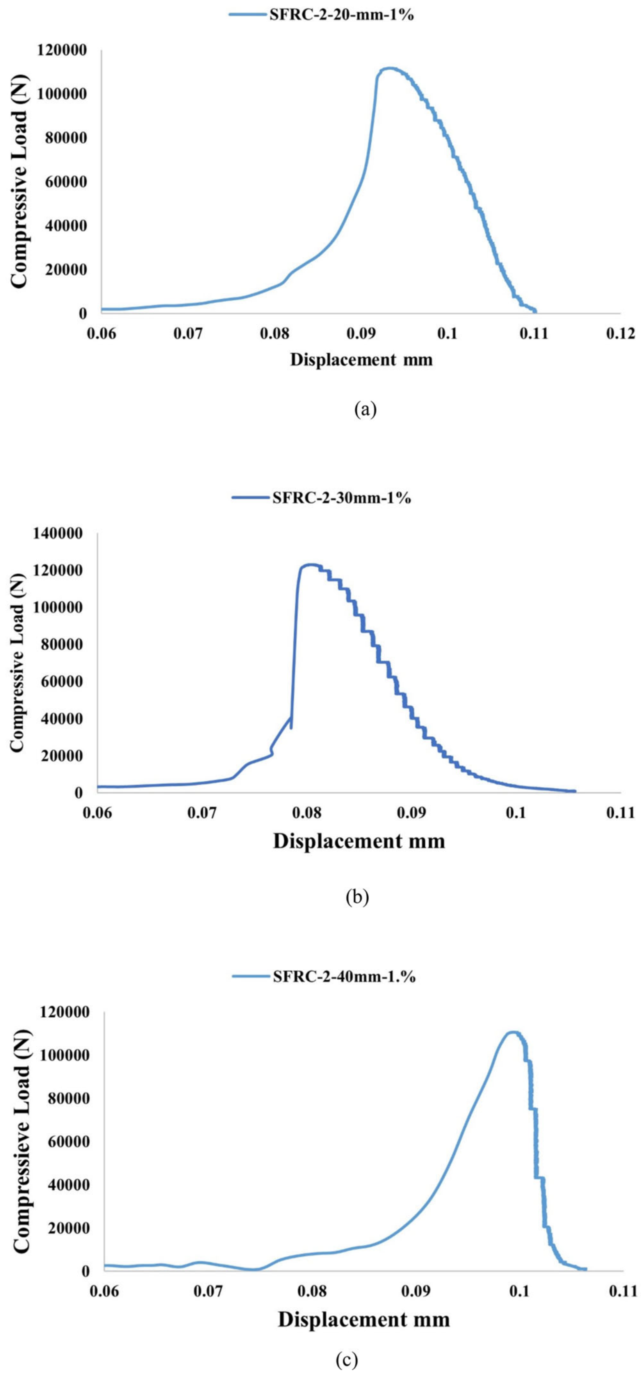

FIGURE 12 Compressive load vs. displacement behavior of steel fiber reinforced concrete samples.

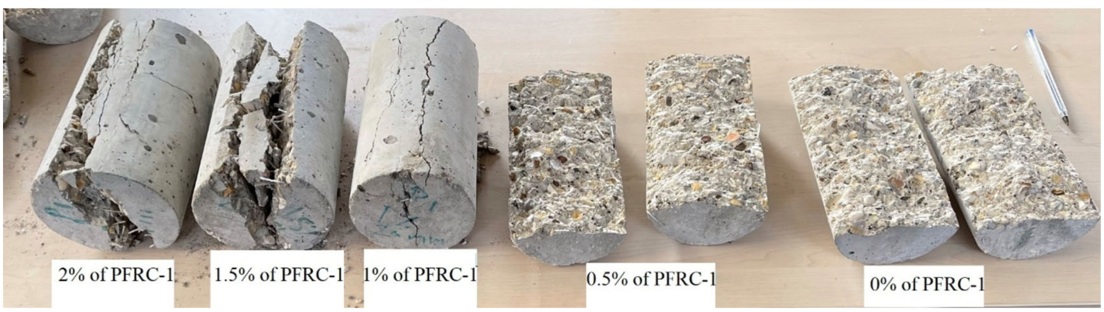

FIGURE 13 Impact of PFRC-1 (20 mm) on split tensile strength.

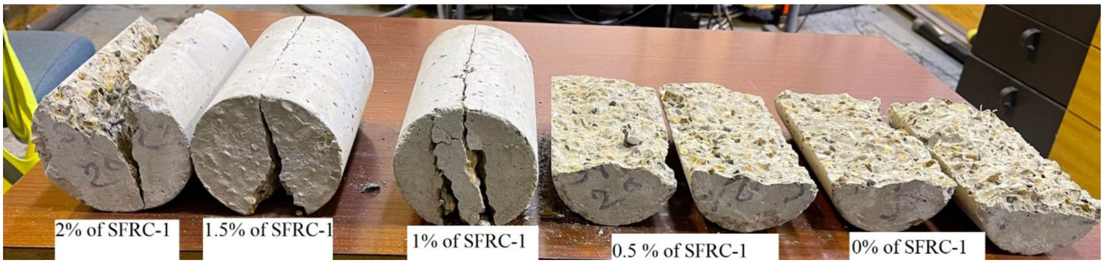

FIGURE 14 Impact of SFRC-1 (20 mm) on split tensile strength.

All fiber lengths tested in this study assisted direct tension by forming and connecting multiple microcracks. Fibers maintained both sides of the cracks, and the steel and plastic fibers did not allow the crack width or macrocracks to grow. The PFRC-1 sample did not break in half due to the plastic fiber connection, thus maintaining good integrity. There was a noticeable drop section of the side load-deformation curve for the samples of FRC. The results indicate that the mixture of plastic fibers altered the tensile fracture mode of normal concrete from the brittle fracture of the plastic fracture. After the maximum tensile fracture load was reached, the crack width continued to expand, as shown in Figures 13 and 14.

The addition of SFRC-1, SFRC-2, SFRC-1, and SFRC-2 helped to increase the crack resistance of the concrete. The samples with fibers at a volume fraction of 1%, 1.5%, and 2% did not split into two because the PFRC-1 connected the two parts of the concrete matrix when the sample was subjected to the maximum tensile break load. This process revealed that PFRC-1 was more efficient than PFRC-2 at restraining crack-width expansion. SFRC-1 is longer and has a more significant aspect ratio than SFRC-1, SFRC-2, and PFRC-2, so its bond force with the concrete mix is also more significant. It is clear that the enhancement in tensile strength is much greater than that for compression strength. Therefore, the fiber volume fraction was also shown to have a good impact on tensile properties, especially when increasing the length of the fiber, as the results show increases in tensile strength.

5.2.3 | Flexural strength

There were significant improvements in bending resistance, maximum stress deformation, toughness, and residual strength. Compared to the impact of fiber percentage on flexural strength, the impact on the resistance of the FRC mix was greater than that of the control concrete.

It should be noted here that the flexural strength of PFRC-1, PFRC-2, SFRC-1, and SFRC-2 increased sufficiently. Compared to the control specimen, the bending force was increased by the addition of fiber. For example, the bending restraints improved by approximately 12%, 15%, and 18% for the SFRC containing an amount of 1.5% and 20 mm, 30 mm, and 40 mm with different lengths of corrugated steel fiber, respectively. However, the results indicate that the addition of too much steel or plastic fiber leads to low mixing, which reduces bending. The fibers are distributed randomly in the concrete, indicating that the directions of most of the fibers vary from those of the axial load.

The addition of fibers to a concrete mix can reduce crack initiation and propagation. Fibers also provide greater flexibility in structures against crack propagation and, therefore, lengthen the catastrophic failure time and improve the mechanical properties of concrete.[70] The presence of fibers was shown to affect the cracking resistance of concrete and improve other properties.[43] The addition of SF has also been shown to improve mechanical properties, including crack resistance and toughness.[71] The addition of SF was also found to improve mechanical properties, including crack resistance and toughness, and Sengul showed that SF was more effective at increasing crack-growth resistance due to its geometric and material properties.[72] This study demonstrated that the bending strength of PFRC and SFRC was significantly greater than that of standard concrete. In one study, the addition of waste fibers resulted in an impressive (approximately 43%) enhancement in the flexural strength of reinforced recycled aggregate concrete.[73] Yap et al. discovered that the inclusion of silica fume led to notable improvements in the mechanical properties of concrete, such as increased resistance to cracking and enhanced toughness.[74] In addition, Monteiro et al. demonstrated that hooked-end SF was particularly effective in enhancing resistance to crack growth, which they attributed to its geometric properties and material characteristics.[75] In another investigation, by Iqbal et al., there was a substantial increase in both flexural strength (around 110%) and tensile strength (approximately 37%).[18]

Furthermore, in this study, along with the impact of fiber volume fraction on flexural properties, fiber length also had an effect, particularly with an increased length.

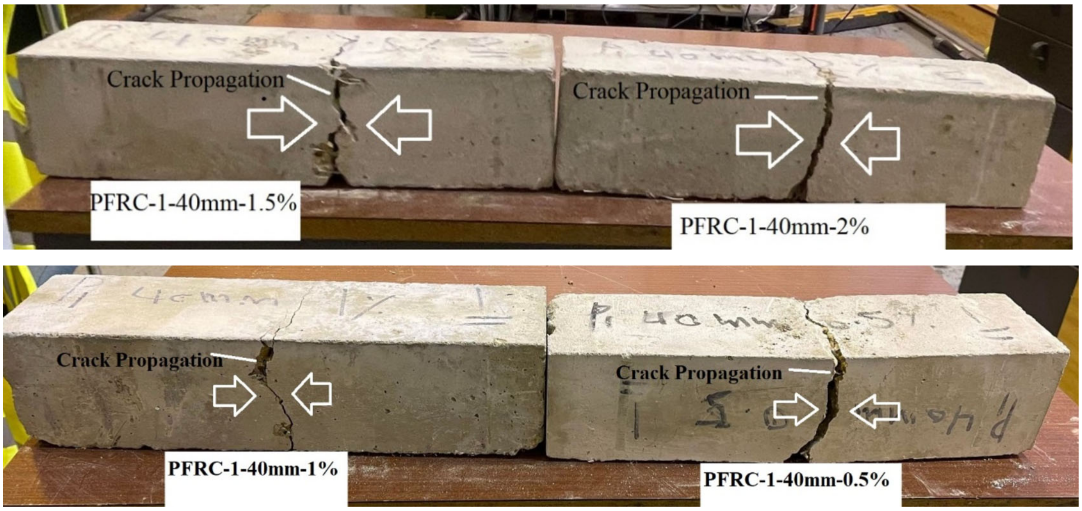

FIGURE 15 Impact of PFRC-1 (40 mm) on flexural strength.

The results showed increases in bending force. SF of both types improved the bending strength and reduced cracking when increasing the length of the fiber. However, flexural strength was reduced when the length of both types of plastic fiber was increased. Figures 15 and 16 show the significant impact of fiber length on cracking propagation.

This result was expected because the code demonstrates that bending resistance directly relates to the tensile strength properties of concrete. Since the tensile failure rose with an increase in the length of the steel and plastic fibers, it was expected that the bending force would also rise. However, the reduced bending resistance can be attributed to the length and amount of plastic fibers.

6 | PARAMETRIC ANALYSES FOR THE OPTIMIZATION OF FRC

This optimization study demonstrates a correlation between the mechanical and fresh-state properties of concrete, using fiber parameters (i.e., the length, type, and amount of fiber) to obtain the optimal values for additional fiber. The input parameters were the way in which the volume, type, and length of fiber affected the reinforced concrete mix. As mentioned in the results section, the length and type of the fiber had a significant impact on the optimal value. An increase in plastic fiber length from 20 to 40 mm had a negative impact, decreasing the mechanical properties. However, increases in the length of SF increased the strength of the concrete in terms of bending and tensile strength. In addition, increases in the amount of steel and plastic fiber reduced the fresh-state and mechanical properties. Other researchers have reported reductions in the workability of concrete specimens with an increase in fiber amount and length. Different studies observed decreased fresh concrete workability when either of two kinds of SF was combined.[10,13–31] Researchers have also suggested that a decrease in tensile, compressive, and flexural strength with the addition of e-plastic was caused by the replacement of the aggregate with e-plastic.[39]

A significant influence of parameter on type is cost because the price of plastic, according to Fibre Concrete Solutions Limited, is double that of the SF price. Concrete is considered a cost-effective long-term solution for concrete design. Prices of steel and plastic fibers will vary considerably, depending on their physical properties and whether they are used for their structural advantages in concrete or for non-structural advantages in terms of plastic (microfiber). Thus far, the evidence supports the idea that fiber length and percentage are influenced by ease of mixing the fiber, especially in the workability of concrete. Statistical experimental design approaches are stringent techniques for achieving the chosen properties and determining an optimized mix for a given set of limitations.[76] They are widely utilized in industry to optimize products and procedures and have been used in investigations into enhancing high-performance concrete. Concretes with 1% of SF indicated the optimal value, after combining all input and output parameters by using the equations we explained. The mechanical and fresh concrete test results were considered the output parameters, and included compressive, split tensile, and flexural strength, as well as workability (44.47 MPa, 3.64 MPa, 5.30 MPa, and 6.5 cm), as shown in Figure 17. For the input parameters, we considered steel fiber to be cheaper than plastic, according to the price information we obtained from the LTD suppliers. The other two input

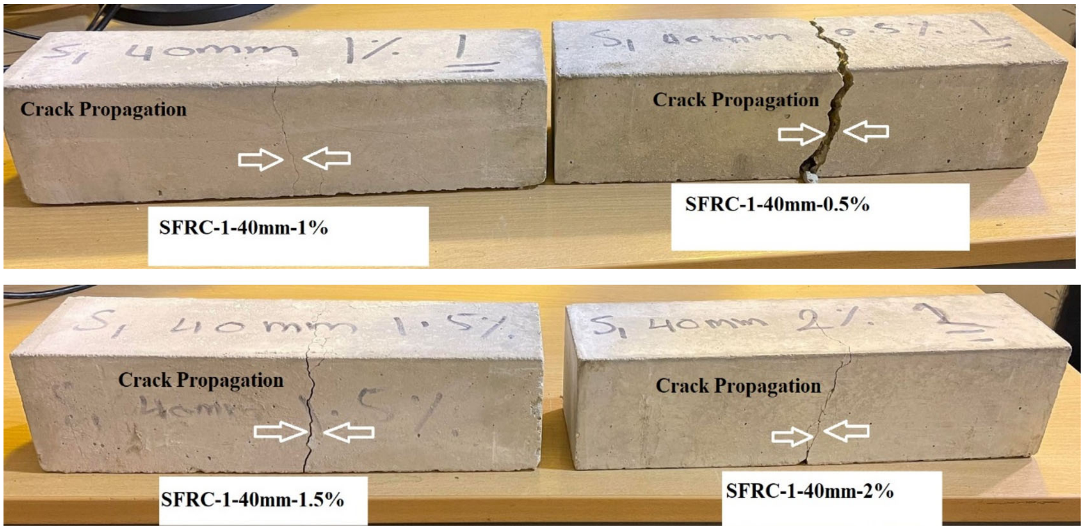

FIGURE 16 Impact of SFRC-1 (40 mm) on flexural strength.

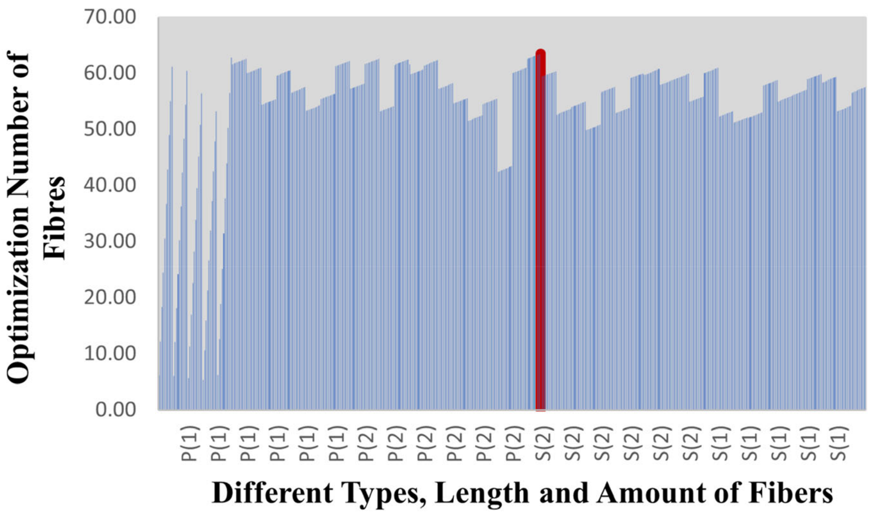

FIGURE 17 Parametric analyses for the optimization of FRC.

parameters will combine as explained at the beginning of the optimization study. After completing the calculation, the highest number means highly optimized concrete was 42.44.

These results should be taken into account when considering how to optimize any FRC because this method considers the properties of all the parameters that have an impact on mixed concrete, such as the influence on workability, durability, strength, and the crack resistance of the concrete, in terms of the type, cost, and amount of fibers required.

7 | CONCLUSION

This study presented a comprehensive exploration of the optimization of FRC with a specific focus on its mechanical properties. Through extensive experimentation and a parametric analysis-based optimization approach, we contribute valuable insights that hold substantial relevance for the field of concrete technology. Key conclusions drawn from our research are as follows:

- *Workability and fiber content*: The study revealed that an increase in fiber content leads to reduced workability. The length of the fibers is identified as a significant factor contributing to this reduction.
- *Compressive strength*: Although the enhancement in compressive strength aligns with that of conventional concrete, the standout finding is in the realm of tensile strength.
- *Tensile strength enhancement*: The addition of fibers, especially steel and plastic fibers, significantly enhances tensile strength by bridging and containing cracks effectively. The impact of fiber volume fraction on tensile properties is particularly noteworthy, especially with an increase in fiber length.

- *Flexural strength*: Both plastic fiber-reinforced concrete (PFRC) and steel fiber-reinforced concrete (SFRC) exhibit significantly improved bending strength compared to standard concrete. The influence of fiber volume fraction is further amplified by longer fiber lengths, resulting in increased bending strength and reduced initial crack formation.
- *Optimal parameters*: Our study pinpoints the optimal configuration as SFRC-2-20 mm-1%, which exhibits superior values in relation to compressive, tensile, and flexural strength while maintaining reasonable workability.
- *Innovative optimization method*: A noteworthy innovation of this work lies in the optimization methodology used. The proposed method provides a deeper understanding of the intricate relationship between input and output parameters, encompassing properties such as workability, durability, strength, and crack resistance. This comprehensive approach transcends individual parameter optimizations to consider the holistic impact on mixed concrete. These findings underscore the importance of considering various factors in FRC optimization. As we explore the properties of all influencing parameters, we pave the way for a more robust understanding of FRC behavior, opening doors to improved workability, durability, strength, and crack resistance in concrete.

Our research not only enriches our understanding of FRC, but also contributes valuable insights into the optimization of this material. It is our hope that this study will serve as a reference point for future endeavors in optimizing FRC for diverse applications.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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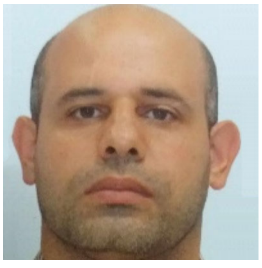

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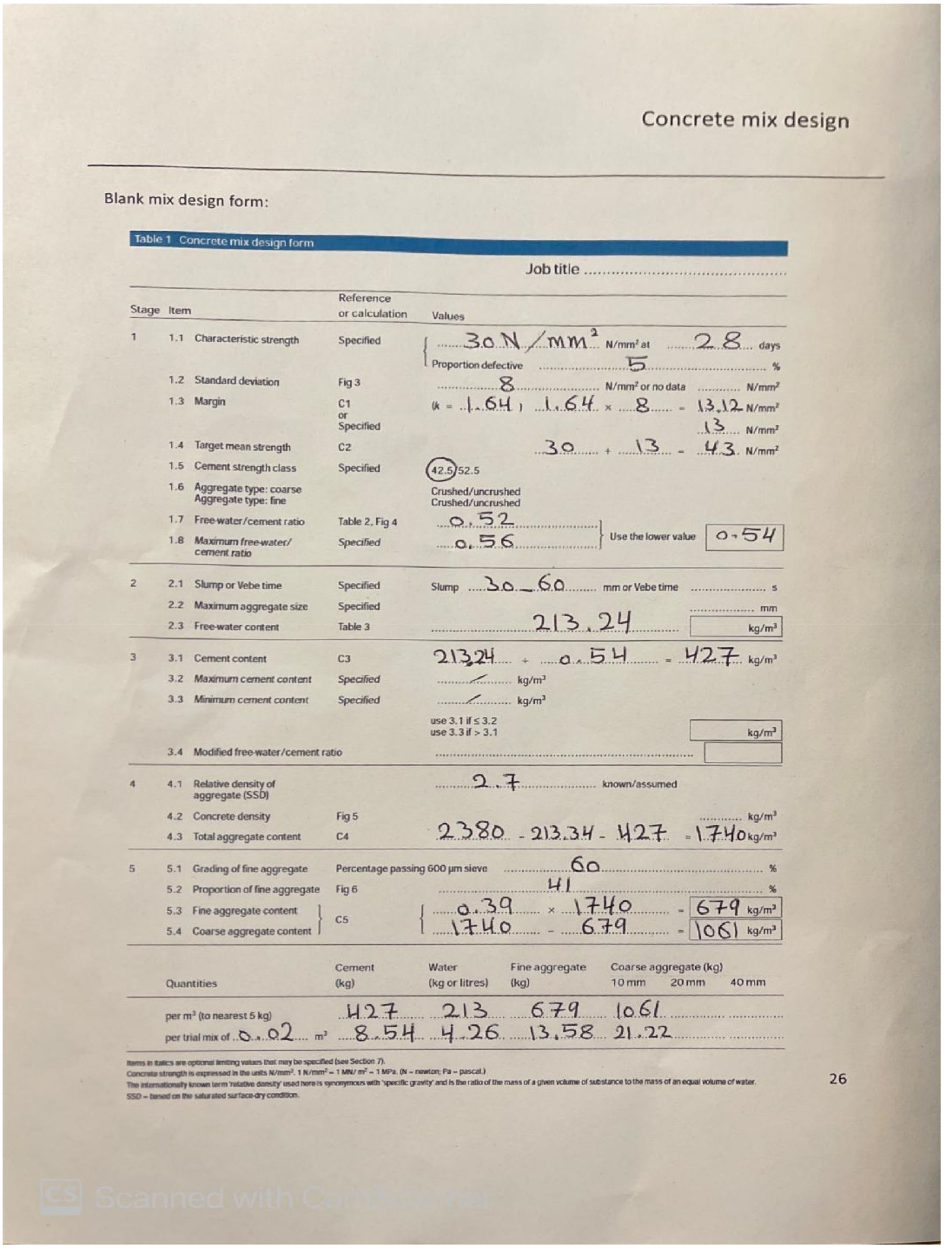
APPENDIX A: Mixing model



Concrete mix design

Blank mix design form:

Table 1 Concrete mix design form

Job title ....

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	30 N/mm² N/mm² at 28 days; Proportion defective 5 %
	1.2	Standard deviation	Fig 3	8 N/mm² or no data .... N/mm²
	1.3	Margin	C1 or Specified	(k = 1.64) 1.64 × 8 = 13.12 N/mm²; 13 N/mm²
	1.4	Target mean strength	C2	30 + 13 = 43 N/mm²
	1.5	Cement strength class	Specified	(42.5) / 52.5
	1.6	Aggregate type: coarse; Aggregate type: fine		Crushed/uncrushed; Crushed/uncrushed
	1.7	Free-water/cement ratio	Table 2, Fig 4	0.52 } Use the lower value 0.54
	1.8	*Maximum free-water/cement ratio*	*Specified*	0.56
2	2.1	Slump or Vebe time	Specified	Slump 30_60 mm or Vebe time .... s
	2.2	Maximum aggregate size	Specified	.... mm
	2.3	Free-water content	Table 3	213.24 kg/m³
3	3.1	Cement content	C3	213.24 ÷ 0.54 = 427 kg/m³
	3.2	*Maximum cement content*	*Specified*	/ kg/m³
	3.3	*Minimum cement content*	*Specified*	/ kg/m³
				use 3.1 if ≤ 3.2; use 3.3 if > 3.1 .... kg/m³
	3.4	Modified free-water/cement ratio		....
4	4.1	Relative density of aggregate (SSD)		2.7 known/assumed
	4.2	Concrete density	Fig 5	.... kg/m³
	4.3	Total aggregate content	C4	2380 - 213.34 - 427 = 1740 kg/m³
5	5.1	Grading of fine aggregate	Percentage passing 600 μm sieve	60 %
	5.2	Proportion of fine aggregate	Fig 6	41 %
	5.3	Fine aggregate content	C5	0.39 × 1740 = 679 kg/m³
	5.4	Coarse aggregate content	C5	1740 - 679 = 1061 kg/m³

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	427	213	679	1061		
per trial mix of 0.02 m³	8.54	4.26	13.58	21.22		

Items in italics are optional limiting values that may be specified (see Section 7).
Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface-dry condition.

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Parametric study for optimizing fiber-reinforced concrete properties

Khalel, Hamad Hasan Zedan

Wiley