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Mechanical, Durability and Electrical Properties of Steel Fibers Reinforced Concrete

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ABSTRACT

Concrete is a constantly evolving building material whose demand is increasing due to population growth and urban development. This calls for more research on this composite material to improve its performance. However, concrete has some disadvantages, including that it is a brittle material and cannot withstand tensile stress. Therefore, rebars and fibers are incorporated into concrete to improve this property. Although previous works investigated the properties of concrete containing steel fibers, most of them were concerned with mechanical properties, while the durability properties still require further investigation to understand them. Thus, the purpose of this study is to ascertain how adding steel fibers to concrete in varying proportions (0.5, 1.0 and 1.5%) affects its mechanical and durability properties, including compressive strength, flexural strength, tensile strength, bulk density, water absorption, mode of failure, ultrasonic pulse velocity, dynamic modulus of elasticity and electrical resistance. Statistical relationships between the compressive strength and other characteristics were also established. The results indicated that all mechanical and durability characteristics significantly improved after adding steel fibers for all addition ratios, except for electrical resistivity, which showed lower values than the reference mixture for the 0.5 and 1% steel fiber proportions. Moreover, it was found that the best addition rate of steel fibers was 1.5%. At this percentage, the recorded increasing rates over the control sample were 29.3% in compressive strength, 83.7% in tensile strength, 27.9% in flexural strength, 50.1 in water absorption resistance, and 11.2% in electrical resistivity.

Keywords: steel fibers, electrical resistivity, compressive strength, ultrasonic pulse velocity, water absorption.

INTRODUCTION

The good mechanical and durability properties of concrete have made it one of the most widespread and used materials in the construction industry [1]. However, ordinary concrete has some significant drawbacks, such as low cracking resistance, poor tensile strength, and limited ductility, which restrict its use in construction [2–4]. Structures made of concrete could be made more ductile by using steel fibers [5]. Hence, concrete is strengthened with fibers and rebars to address this issue [6]. Fibers can greatly enhance certain concrete and mortar properties, such as flexural strength, crack resistance, ductility and toughness, based on the type of fiber used [7]. Numerous studies have demonstrated that using fibers greatly enhanced the different concrete properties, whether mechanical or durable [8, 9]. The incorporation of fibers into concrete improved its energy absorption capacity and post-cracking behavior [10]. To enhance the performance of concrete, a range of fiber types (such as steel, nylon, sisal, glass, synthetic, and natural fibers) have been added [7, 11–16].

Concrete was combined with steel fibers to enhance the ductile fracture, inhibiting the initial crack formation, stopping or limiting the expansion of existing cracks, and effectively enhancing ductility, strength, and durability [17]. The enhancement of the crack propagation, ductility, and toughness of concrete provided by steel fibers finally leads to improving its mechanical characteristics [18, 19]. Steel fibers can also decrease the overall environmental impact of construction by extending the service life of structures made from steel fiber-reinforced concrete [18, 20]. Numerous earlier studies have examined how adding steel fibers to concrete affects its behavior. For instance, the content and lengths of steel fibers on various concrete parameters were investigated by Abbas et al. 2015 [21]. The percentages of fiber addition were (1, 3 and 6%). It was found that by increasing the content of steel fibers, the durability relatively improved, while the improvement was more evident in the mechanical properties.

Moreover, a study was undertaken by Abbass et al. 2018 [22] to examine the impact of incorporating steel fibers of varying diameters and lengths on the mechanical properties of concrete. Three addition rates (0.5%, 1.0%, and 1.5%) of steel fibers were adopted. It was found that the concrete mechanical properties revealed improvement by 10–25% in compressive strength and 31–47% in direct tensile strength. Additionally, compared to the concrete without fibers, the flexural strength showed a noteworthy increase of 124% or 140%, depending on the aspect ratio of the fibers.

Furthermore, Young et al. 2021 [23] studied the modulus of elasticity and compressive strength of UHPFRC (ultra-high-performance fiber reinforced concrete) with different levels and aspect ratios of steel fibers. According to the results, increasing the steel fiber proportion or aspect ratio of stiffened UHPFRC enhanced its compressive strength and elastic modulus. However, this increase continued until 2% content and then slowed down. Furthermore, the occurrence and development of cracks of UHPFRC had been prevented by the inclusion of steel fibers but also reduced the workability of fresh UHPFRC, which hurts the strengthening effect. Additionally, the effect of using steel fibers on water absorption and mechanical performance of recycled aggregate-based concrete was searched by Kaplan et al. 2021 [18]. The findings indicated that incorporating steel fibers at a rate of 1% to concrete containing 50% recycled aggregate or 2% steel fibers to 100% recycled aggregate concrete performed similarly to plain concrete (free of steel fibers or recycled aggregate).

Besides, Liu et al. 2022 [24] explored the impact of adding steel fibers with varying amounts of graphene oxide on concrete properties. The findings showed that when these two materials were combined, compressive, tensile, and flexural strengths were significantly increased by 20.1%, 26.2%, and 29.5%, respectively, compared to the reference sample (without any additives). Furthermore, the properties of freeze-thaw resistance and chloride penetration depth were also enhanced. Additionally, a study by Naser et al. 2024 [25] looked into how concrete's structural and mechanical qualities were affected by adding of macro and micro steel fibers, including waste and synthetic fibers. The added percentage of steel fiber was 0.75% by volume. The mechanical test findings indicated improved compressive, flexural, and tensile strength over the reference specimen. In addition, Rashidi et al. 2024 [26] carried out a study that utilized both laboratory tests and numerical simulations. According to the findings, increasing the proportion of steel fibers in concrete specimens resulted in a considerable improvement in both the tensile strength and the energy absorption ability of the concrete. This improvement resulted from the steel fibers acting as a barrier that restricted the propagation of cracks, thereby enhancing the concrete's strength. However, this positive effect was only observed up to a certain fiber ratio (about 4%). Beyond that, the concrete specimens prematurely failed due to the weakening of the link between the steel fibers and the cement mortar, which inhibited the increase in energy absorption.

Furthermore, in their study, Zhou et al. 2024 [27] examined the effects of adding steel fibers in varying proportions (ranging from 0.5% to 1.5% in increments of 0.5%) to concrete. Their research focused on investigating the fracture properties, microstructure and macroscopic mechanical properties of the concrete. The results demonstrated that higher steel fiber content (1.5% or more) significantly reduced in tensile strength, fracture toughness, and fracture energy in the interfacial transition zone.

According to the above, the properties of steel fibers-based concrete were addressed previously in a significant amount. However, most were concerned with mechanical properties, while the durability properties still require further investigation. Furthermore, in previous studies, there have been different findings regarding the optimal percentage of steel fiber addition for achieving the best performance in various properties of concrete. This variation may be attributed to differences in the shape, dimensions, and type of fibers used, as well as variations in the concrete's strength and its bonding with the fibers. Additionally, the literature has contradictory results about how fibers affect particular concrete durability properties. In addition, a recent review by Zheng et al. 2024 [17] noted that the mixing, vibrating, and shaping process of steel fiber-reinforced concrete may lead to instability in its mechanical characteristics. They also mentioned that there are limited studies on the durability of this type of concrete. As a result, Zheng et al. 2024 [17] emphasized the urgent need for further comprehensive research to cover the properties of steel fiber-reinforced concrete, mainly focusing on its durability. Due to these reasons, more research is required to fully comprehend the steel fibers and concrete interaction, how it affects its properties. Thus, this study aims to examine how steel fibers affect the different characteristics of concrete, including compressive, flexural and tensile strengths, water absorption, mode of failure, bulk density, ultrasonic pulse velocity, dynamic modulus of elasticity and electrical resistance.

EXPERIMENTAL PROGRAM

Materials

The following materials were used in the manufacturing of concrete specimens:

Cement

Locally produced limestone cement (CEM I-42.5R-SR) was used. The cement properties are conformed to the Iraqi standard No. 5 [28]. The cement chemical analysis is displayed in Table 1.

Fine aggregate

As a fine aggregate, natural sand meeting Iraqi standard No. 45 [29] was used. Table 2 displays the findings of the grading analysis for the sand.

Coarse aggregate

The coarse aggregate utilized was locally available natural gravel. Table 3 shows the aggregate sieve analysis, which is in accordance with Iraqi specification No. 45 [29].

Steel fibers

Micro steel fibers (type WSF0213, made in China) were utilized to reinforce the concrete specimens. The steel fiber's length, diameter and aspect ratio and other details are displayed in Table 4.

Table 1. The chemical compounds of the cement

Oxide	Content, %
SiO_2	19.56
CaO	61.21
Fe_2O_3	5.51
Al_2O_3	4.72
MgO	2.5
SO_3	1.87
Free lime	1.11
Insoluble residue	0.97
Loss on ignition (L.O.I.)	1.73

Table 2. The sand sieve analysis's findings

Sieve size (mm)	Accumulative passing %	Iraqi specification limits (zone one)
10	100	100
4.75	96	90–100
2.36	83	60–95
1.18	53	30–70
0.6	33	15–34
0.3	6.2	5–20
0.15	0.6	0–10

Table 3. The grading analysis outcomes of the used gravel

Sieve size (mm)	Accumulative passing %	Iraqi specification limits
20	100	100
10	49	30–60
5	5	0–10

Table 4. Specifications of steel fibers

Property	Specifications
Surface	Brass coated
Type	WSF0213
Density	7860 kg
Form	Straight
Diameter	0.2 mm
Length	13 mm
Aspect ratio	65
Tensile strength	2300 MPa
Melting point	1500 °C
Modulus of elasticity	203 GPa

Note: * Provided by the manufacturer.

Water

All of the specimens were cured and cast using tap water.

Mix proportions

Four mixtures were poured for this work. One was a reference mixture and three other mixtures contained steel fibers in three levels of 0.5, 1.0 and 1.5% (by weight of concrete). The amounts of cement, sand, gravel, and water content were fixed for all mixtures, and the only variable was the steel fiber percentages. Table 5 includes details of mixing ratios.

Mixing of concrete ingredients

To make fresh concrete, an electric mixer was used and the following mixing method was adopted:

- The first step involved mixing the sand and gravel in the mixer for two minutes.
- After that, the ingredients were combined for three minutes with the addition of half of the mixing water.
- Thereafter, the remaining water and cement were introduced, and the blending process continued for an additional ten minutes.
- When steel fibers were present, they were added while mixing the concrete materials and the mixing continued until the mixture became homogeneous.

Specimen casting, curing and testing

Cubes with dimensions of $100 \times 100 \times 100$ mm^3, cylinders with dimensions of 100×200 mm^2, prisms with dimensions of $100 \times 100 \times 500$ mm^3 were cast. Three specimens of each type were cast at the specified testing age, and an average of three samples were used for each result. Samples were lifted from the molds after approximately 24 hours and cured in tap water until testing. Cubes were used for the compressive strength, water absorption, electrical resistivity, ultrasonic pulse velocity (UPV), dynamic elastic modulus and bulk density. The compressive strength was examined following the procedure described in BS EN 12390-3 [30] with a loading rate of 0.3 MPa/sec. To determine the bulk density of concrete, the mass of the cube was measured, and the resulting value was divided by the cube's volume. The ASTM C597 [31] was followed for the UPV and dynamic elastic modulus (Equation 1) tests, while the water absorption (Equation 2) was determined as per ASTM C642 [32]. In addition, cylinders were used in accordance with ASTM C496 [33] to determine the splitting tensile strength of concrete. Moreover, the prisms were used to determine the flexural strength of concrete as per ASTM C78 [34]. The loading rate for the tensile and flexural strength tests was set at 1 MPa/min. The electrical resistivity (bulk resistivity) test was conducted as per [35] using LCR meter at 1000 Hz of frequency (Equation 3).

$$MoE = Vs^2 \times d \times (1 + n) \times (1 - 2n) / (1 - n) \quad (1)$$

where: n is the Poisson's ratio, d is the density, Vs is the pulse velocity, and MoE is the elastic modulus.

$$Wa = 100 \times (Mw - Md) / Md \quad (2)$$

where: Mw is the specimen's mass following submersion in water, and Md is the specimen's mass after being oven-dried and Wa is the percentage of water absorption.

$$R = A \times M / h \quad (3)$$

where: h is the specimen height (in cm); M is the impedance (in kΩ); A is the specimen cross-section area (in cm^2) and R is the electrical resistivity (in kΩ. cm).

RESULTS AND DISCUSSIONS

Compressive strength results

The compressive strength outcomes at 7 and 28 days are shown in Figure 1. It was found that the compressive strength increased when the fraction of steel fibers increased for both testing ages (7 and 28 days). The strength improvement was within the range of 14.2 to 39.8% at

Table 5. Mix proportions details (kg/m^3)

Mix designation	Cement	Sand	Gravel	Water	Steel fibers
N.C	360	900	850	180	–
SF0.5	360	900	850	180	39
SF1	360	900	850	180	78
SF1.5	360	900	850	180	117

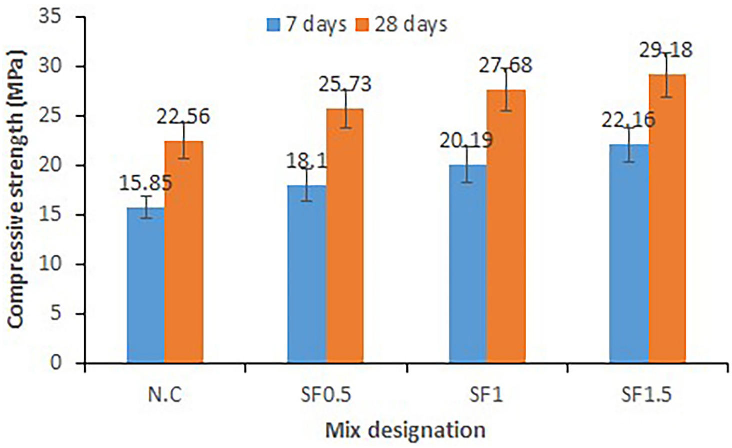

Figure 1. The results of concretes compressive strength at 7 and 28 days

7 days and between 14.1 and 29.3% at 28 days. In other words, at 1.5% steel fiber proportion, the maximum compressive strength was observed. The confining effect given by the steel fibers slows or stops the growth of cracks and prevents their expansion; thus, more energy is required for cracks to be extended, leading to an increase in compressive strength [22]. Tayeh et al. [36] achieved comparable outcomes, attributing the improved compressive strength to the fact that as the concentration of steel fibers increases, the distance between the fibers becomes shorter. Thus, they participate to a greater extent in bearing the applied load.

Splitting tensile strength

Figure 2 displays the splitting tensile strength outcomes at 7 and 28 days. It is noted from the figure above that the tensile strength improved after adding the steel fibers. At 7 days, the tensile strength was increased by 21.7% at a steel fiber ratio of 0.5% to 71.4% at a steel fiber proportion of 1.5% compared to the mixture without steel fiber. At 28 days, results indicated that the tensile strength was grown by 32.7% at 0.5% fibers to 83.7% at 1.5% fibers. The steel fibers work to reduce stresses within the concrete by transferring the tensile force to it through the matrix and contribute to curbing the development of cracks that extend across them [37]. Furthermore, in comparison to the compressive strength, the incorporation of steel fibers resulted in a considerable increase in the tensile strength of the material. This is explained by the steel fibers' bridging effect, which becomes more pronounced as their content increases, as previously discussed in the literature [38]. Comparable results were reported by Xu et al. [39], who explained the rise in tensile strength as the average distance between fibers decreased as the fiber concentration increased. The extra fibers can support the load inside the crack length by lowering the average bond stress between the matrix and fibers. As a result, the splitting tensile

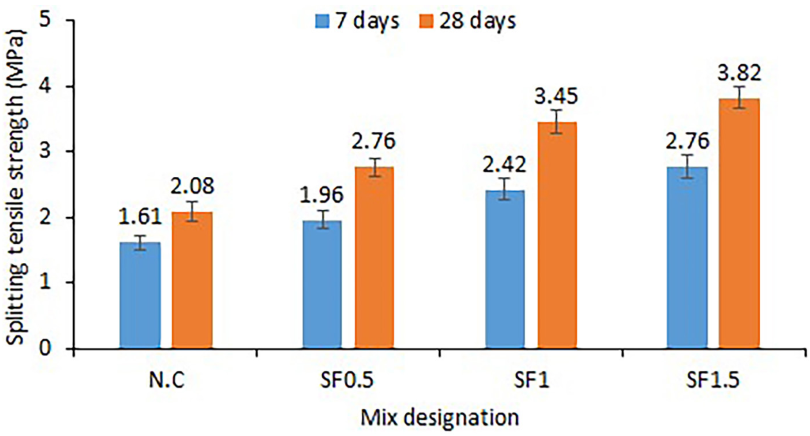

Figure 2. Splitting tensile strength results of steel fiber reinforced concrete at 7 and 28 days

strength could be enhanced by preventing the formation and extension of fractures due to the reduction in average bond stress.

Flexural strength

Figure 3 displays the results of the flexural strength of concrete at 7 and 28 days of age. The outcomes showed that the flexural strength followed the same trajectory as the findings for the tensile and compressive strengths. As the percentage of fibers rose, the flexural strength also increased correspondingly. Flexural strength reached its most incredible value at 1.5% steel fiber. The improvement rates ranged from 7.2 to 29.1% for 7 days and 8 to 27.9% for 28 days in comparison to the reference concrete. The reason behind the increased flexural strength in the existence of steel fibers is that after the matrix breaks, the load applied to the concrete is born by the fibers until the cracking of the interfacial bond between the matrix and fibers occurs [40]. The outcomes agree with the Zhang et al. [41] findings. They demonstrated that steel fibers can bind cracks, withstand external load with concrete, and restrict crack expansion when under vertical load. Additionally, the bond between steel fibers and the concrete matrix strengthens as a result of hydration products adhering to the surface of the fibers, hence enhancing mechanical strength.

Bulk density

Figure 4 displays the density values of fiber-reinforced concrete at 28 days. The findings revealed that higher steel fiber content had higher total density values. The density-increasing values ranged from 2.1% for a fiber content of 0.5% to 3.8% for a fiber content of 1.5% related to the plain concrete. Steel fibers have a higher

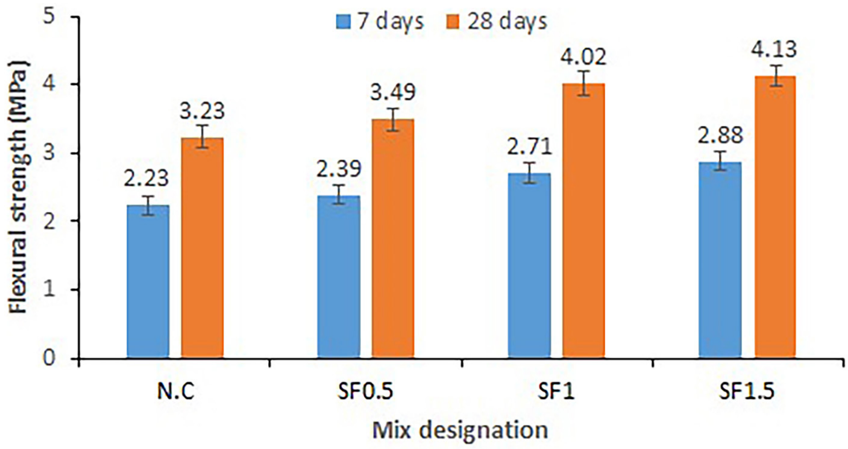

Figure 3. Flexural strength findings of steel fiber reinforced concretes at 7 and 28 days

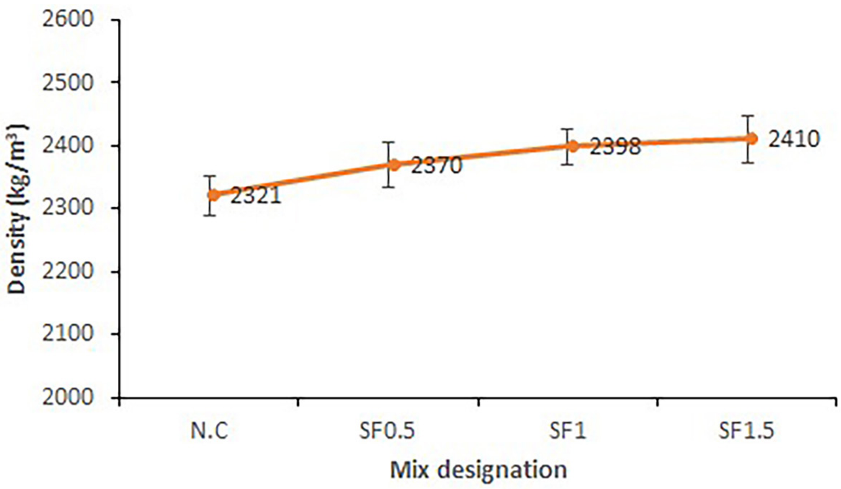

Figure 4. Density results of steel fiber reinforced concrete at 28 days

density than concrete, which is the cause of this density rise [42]. However, it is noted that the increase in density was relatively small, as it was less than 4%. This is explained by the low rate at which steel fibers were added, which was 1.5%. Zaid et al. [8] also observed a similar trend in their work.

Ultrasonic pulse velocity

Figure 5 presents an illustration of the UPV findings. The findings demonstrated that the pulse velocity increased with the proportion of fibers. The mixture containing 0.5% recorded a speed higher than the reference mixture by 4%. While for the 1.5% ratio, the increase was 10.1% compared to the fiber-free specimens. The velocity depends on the amount of gaps in the concrete mix and the concrete density [43]. Therefore, the concrete density bosting due to including steel fibers and reduction of voids, especially at 1.5% fibers, could explain the increase in UPV values.

On the other hand, the literature [44] indicated that the quality of concrete could be categorized according to the value of the UPV into excellent, good, doubtable, poor and very poor quality is linked with the UPV value ranges > 4500, 3500–4500, 3000–3500, 2000–3000 and < 2000 m/s, respectively. Accordingly, the reference and steel fiber-containing mixtures are classified as good-quality concrete.

Dynamic elastic modulus

Figure 6 presents the outcomes for the dynamic elastic modulus (MoF). The figure indicated that the reference mixture (devoid of steel fiber) had the lowest modulus of elasticity, measuring 32.92 GPa. In contrast, there was a discernible increase in the MoF proportionate to

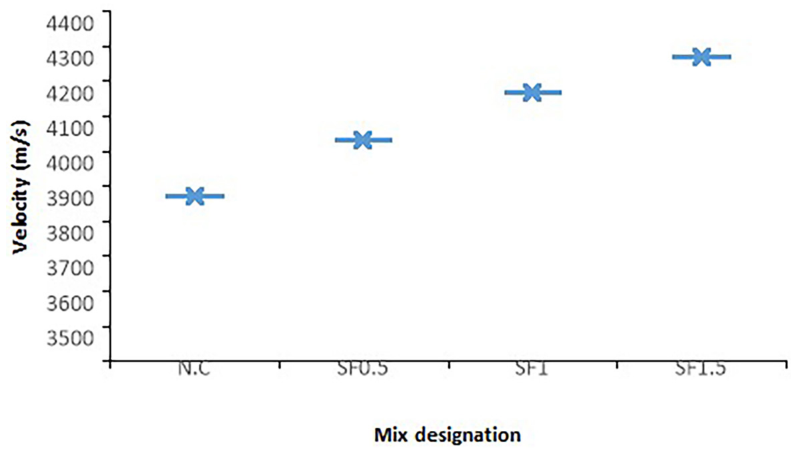

Figure 5. UPV results of steel fiber reinforced concrete at 28 days

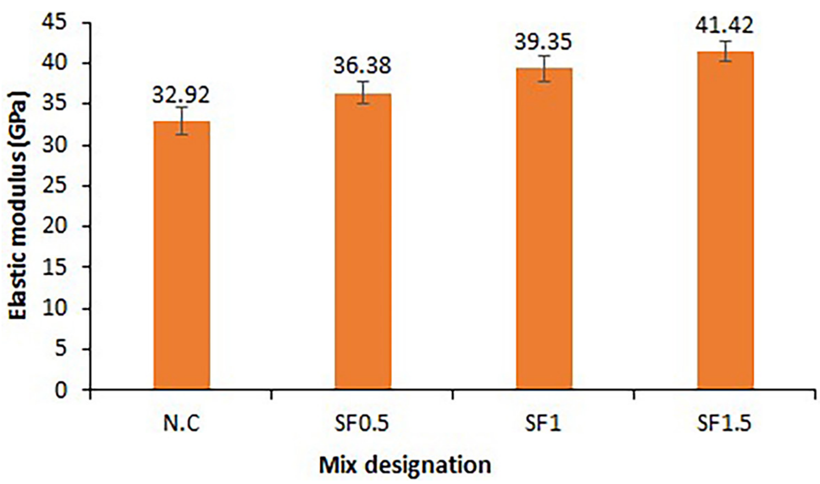

Figure 6. Results of the steel fiber reinforced concrete's dynamic elastic modulus after 28 days

the fiber content in the steel fiber mixtures. The highest elastic modulus of 41.42 GPa (25% higher than the reference mixture) was achieved at a fiber addition rate of 1.5%. The strong bonding properties provided by steel fibers with the concrete matrix contribute significantly to delaying or reducing the occurrence and development of cracks, which leads to an increase in the elastic modulus of concrete [45]. Moreover, the MoF depends on the compressive strength, UPV and density of the material [46, 47]. Therefore, increasing these properties (as in the present work) ultimately leads to enhance the elastic modulus property.

Water absorption

Concrete's water absorption results after 28 days are shown in Figure 7. Results showed that the steel fiber-free mixture had an absorption rate of 7.97%, whereas the fiber-containing mixtures had absorption rates of 7, 5, and 3.98% (12.2, 37.3, and 50.1% less than the plain concrete). In other words, the absorption rate declines as the fiber content in the mixture rises. The reason for this is to improve the quality of concrete by reducing voids and micro-cracks in the matrix [7]. The results align with the information found in the literature [18]. Moreover, according to Zaid et al. [48], the addition of steel fibers limits the development and propagation of pores in concrete, leading to reduced permeability. The UPV findings of the current study can support this claim. Furthermore, according to previous research [49, 50], concrete with an absorption rate of less than 10% is thought to have good durability. Therefore, all mixtures, whether free or containing steel fibers, exhibit good durability.

Electrical resistivity

Figure 8 presents the electrical resistivity findings. The outcomes demonstrated that the 0.5%

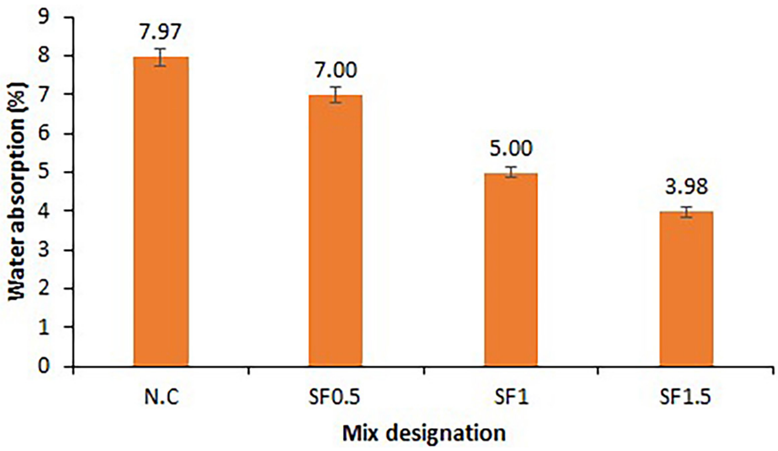

Figure 7. Results of steel fiber reinforced concrete's water absorption after 28 days

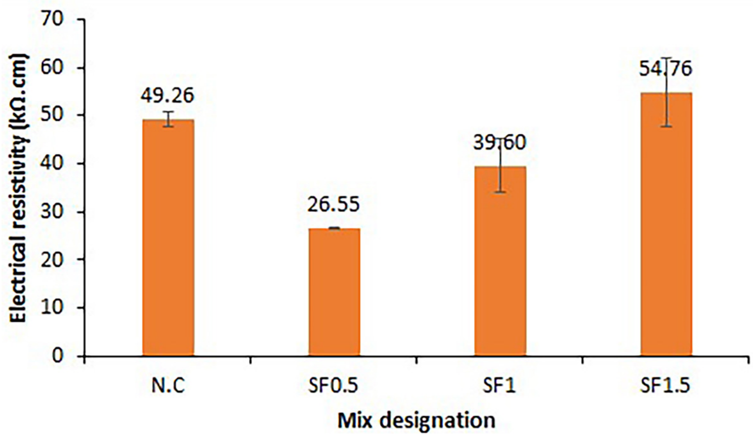

Figure 8. Electrical resistivity results of concrete specimens at 28 days

steel fiber reduced the electrical resistivity by 46.1%, while the decline in resistivity decreased to 19.6% at the 1% fiber addition. In contrast, adding 1.5% fiber improved the electrical resistivity by 11.2%. In other words, the electrical resistivity increased as the percentage of fibers increased, although the results were negative for percentages of 0.5–1%. The reason for the low electrical resistivity of these percentages of fibers because these fibers are metal and have high electrical conductivity [51]. On the contrary, when added in particular amounts, steel fibers can also fill in some of the gaps between the aggregates, increase compactness, and enhance electrical resistivity [52], which may explain the improvement of the electrical resistance of concrete at 1.5% steel fiber content. The concrete electrical resistivity is important because it is directly related to the corrosion of the reinforcing steel within the concrete. Higher electrical resistance in the concrete provides greater protection for the embedded reinforcing steel [53]. In addition, Cleven et al. [54] also stated that small fiber addition ratios greatly influence the electrical resistance of steel fiber-reinforced concrete compared to larger ratios. This may explain the findings of this study: the electrical resistivity decreased significantly at low fiber content, then the reduction lessened with increasing fiber ratio. It ultimately increased electrical resistance compared to the reference mixture at a high ratio (1.5%).

On the other hand, electrical resistance values can be relied upon to classify the level of protection against corrosion of reinforcement in concrete as follows [55, 56]: very low, low to medium, high, and very high if the electrical resistance values (in kΩ.cm) are smaller than 5, 5 to 10, 10 to 20, and greater than 20 kΩ.cm. In this study, all reference and fiber-containing mixtures had resistivity values of higher than 20 kΩ.cm. This suggests it is possible to protect the rebar against corrosion to a high degree.

Mode of failure

The failure mode under flexure of the reference specimen and those containing steel fibers is shown in Figure 9. It is noted from the figure that all samples failed due to a crack in the middle third of the sample, which is the expected pattern of failure. It was also found that once the ultimate load was reached for the reference sample, the specimen cracked and separated into two parts. In contrast, the samples containing fibers did not separate, and the two parts remained connected together as a result of the bridging effect of the fibers [57]. It was also found that the crack generated was less wide as the percentage of steel fibers boosted, as the sample containing 1.5% steel fibers showed a fine crack while maintaining its shape before cracking without separation. Moreover, it can be concluded from the above figure that the failure pattern had changed from brittle to ductile in the presence of steel fibers.

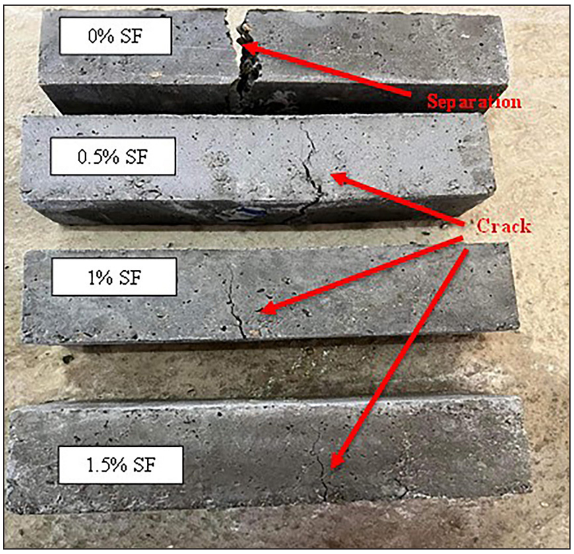

Figure 9. Failure mode of steel fiber reinforced concrete specimens and plain concrete

Statistical relationships

Relationships were constructed between the compressive strength and other properties, such as splitting tensile strength, flexural strength, hardened density, UPV, water absorption and electrical resistivity, as presented in Figure 10. The closer the correlation coefficient (R-square) is, the lower the dispersion. It can be seen from the figure that linear equations were found between the compressive strength and all other properties except for the electrical resistivity, which was polynomial. The relationship between electrical resistivity and compressive strength is non-linear, which is weaker than the linear relationships with other properties. This may be because electrical resistivity is influenced by multiple factors, such as the structure of the voids within the concrete, rather than just their size or quantity [58]. Nevertheless, the R^2 values for all formulas were not less than 0.93, which indicates a strong bond between the compressive strength and other mechanical and durability characteristics.

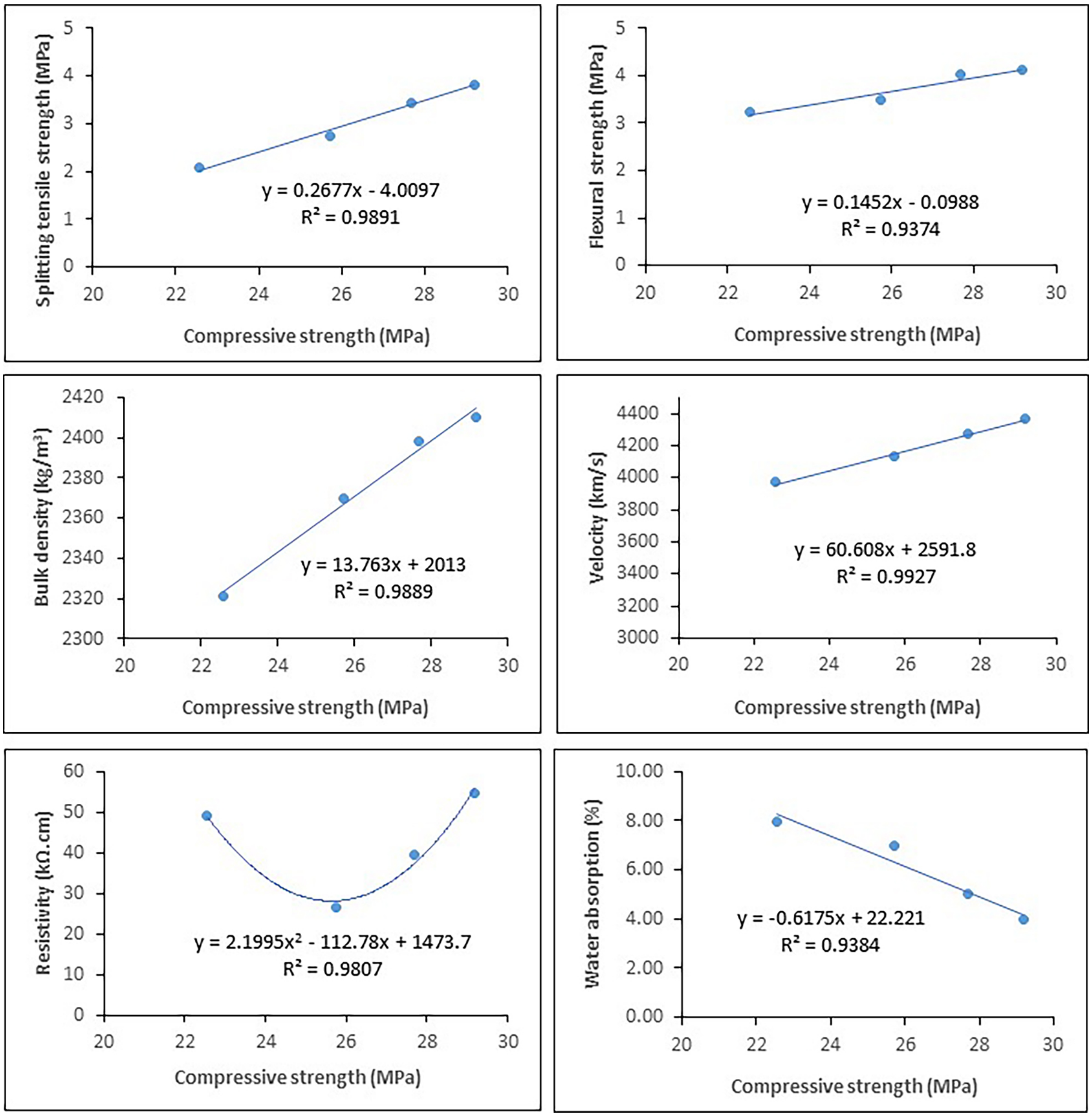

Figure 10. Relationships between the compressive strength and other properties of steel fiber reinforced concrete at 28 days

CONCLUSIONS

The purpose of this study is to examine the characteristics of concrete with varying levels of steel fibers. Tests were conducted on compressive strength, flexural strength, tensile strength, density, ultrasonic pulse velocity, dynamic elastic modulus, water absorption, mode of failure and electrical resistivity. Statistical relationships were also established between the compressive strength property and most other properties. According to the above, the conclusions shown below were obtained:

1. The mechanical properties of concrete at 7 and 28 days improved proportionally by adding steel fibers. The maximum enhancements were achieved at 1.5% steel fibers, which were 29.3%, 83.7% and 27.9% for compressive, splitting tensile and flexural strength, respectively, at 28 days.
2. UPV, dynamic elastic modulus and hardened density increased with the increase of steel fiber content in the mix compared to the reference sample. The improvement ranges were 2.1 to 3.8% for the density and 4 to 10.1% for the UPV and 10.5 to 25.8% for dynamic elastic modulus at 0.5 to 1.5% steel fiber percentages.
3. The water absorption resistance was promoted significantly after including steel fibers. The absorption was lower than the control specimen

by 12.2, 37.3 and 50.1% for steel fiber levels of 0.5, 1 and 1.5%.

4. The greater the amount of steel fiber, the higher the electrical resistivity. However, the resistivity values of 0.5 and 1% steel fiber ratios were lower than the plain mix by 46.1 and 19.6%, respectively. On the contrary, the resistance exceeded the reference mixture by 11.2% at the 1.5% addition ratio.
5. The failure mode results demonstrated that the brittle failure mode of concrete transformed into a ductile one after adding steel fibers.
6. The statistical relationships established between compressive strength and the other mechanical durability properties showed a strong linkage, as the correlation coefficient (R^2) was not less than 0.93.
7. Considering all the tests carried out, the best mechanical and durability performance was recorded at a steel fiber content of 1.5%.

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