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Experimental Examination of the Effect of Length and Percentage of Steel Fibers on the Tension and Compression Strengths of Concrete

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ABSTRACT

Fiber concretes, as a new generations of concrete, have considerably attracted the attention of researchers and engineers for a couple of decades. Fibers play a very important role for improving the weaknesses of concrete, including the tensile and flexural strengths of concrete. In this paper, the effect of length and percentage of steel fibers on the tensile and compressive strengths of concrete is investigated. For this propose, three concrete samples including plain concrete and fiber concretes with steel fibers with lengths of 3 and 5 cm each with different volume ratios (i.e., 0.5, 1, and 1.5%) have been tested. In addition, the samples of the plain concrete are made to determine the effect of fibers on the strength of the concrete. Afterward, using the hydrulic jack machine, both tension and compression strength tests are performed on the concrete specimens. Based on the obtained results, it is observed that with increasing the length and percentage of steel fibers, the tensile and compressive strengths of the concrete specimens are increased. Furtheromre, the samples containing a combination of 3 and 5 cm steel fibers in concrete have lower strength than samples with only 5 cm fibers and more strength than samples with only 3 cm fibers. According to experiments, in order to increase the tensile and compressive strength of concrete, the use of 5 cm steel fibers with different percentages is preferable to 3 cm steel fibers.

Keywords: Steel fiber reinforced concrete (SFRC), hybrid fiber, tension strength, compression strength

1. INTRODUCTION

Fiber concrete is a new generation of concrete that has been studied and used in developed countries for decades. With the help of fibers, concrete weaknesses, including tensile, bending, and even compressive strength, can improve [1, 2]. In general, fibers affect the mechanical properties of concrete in all failure modes [3]. Hundreds of years ago, Native Americans and Mexicans realized that adding natural fiber to the building materials would increase the strength of the materials and buildings resistance. In Iran country, the thatch has been made by blending clay and straw for a long time. As a kind of plant fiber, adding straw prevents the straw from cracking and thus increases its resistance after drying. But the use of fibers in concrete in the present form goes back to Russia and later in the United States about 70 years ago. Afterward, several pieces of research have been performed on different types of fiber-containing concretes. In recent years, many laboratory studies have been done on concrete with a variety of fibers such as steel fiber reinforced concrete (SFRC), glass fiber reinforced concrete (GFRC), carbon fiber reinforced concrete (CFRC), polypropylene fiber reinforced concrete (PPFRC), and also natural fibers including palm and coconut trees or even fibers from recycled materials like worn tires, plastic bottles, different types of sacks, carpets, and so on. In this regard, researchers have tried to examine and measure the different fibers properties of concrete. Boulekbache et al. investigated the shear strength of the concrete by adding steel fibers. They found that the shear strength of the concrete will increase with increasing the fibers' dimensional ratio and percentage [4]. Examining concretes containing natural coconut fibers, found that coconut fibers have the highest strength among natural fibers. In addition, they perceived that it improves the mechanical concrete properties in comparison with the conventional plain concrete. Due to the significant strength increase in this type of fiber is more economical than other types [5]. Other researchers have developed concretes containing several types of fibers. They believed that the combination of different types of fibers (multi-fiber) in comparison with the single-fiber type could cover the weaknesses of concrete [6-8]. Nowadays, material recycling and waste disposal is a significant issue. Therefore, many researchers have tried to use these materials in concrete, which has improved the concrete properties in many cases. By adding produced recycled materials such as turnery chips, metal caps of beverage bottles, soft drink cans, and disposable metal powders to conventional concrete, Murali et al. observed an increase in tensile, compressive, and bending strengths [9]. Guendouz et al. used recycled plastic bottles as fibers and fine-grained concrete alternatives [10]. Some researchers have utilized other recycled materials to improve the concrete properties [11-15]. After the research phase, recently, these types of concretes have entered into the operational and engineering construction phase in very limited numbers, and the fiber concrete structures have been built in the United States, Canada, Japan, Germany, etc. In 2020, one building was made of carbon fiber concrete at the Dresden College of Technology, Germany. This type of concrete has also been employed in constructing airport runways, industrial halls floors, bridges pier and deck, defense structures, arsenals, etc. Adding fibers prevents and postpones cracks in concrete and increases tensile, bending strength, and ductility, which is its weaknesses; finally, it increases the structure's ductility and shows better behavior against dynamic loads [5, 16, 17]. Increasing the strength of concrete by adding the fibers can lead to reducing the dimensions of sections, save reinforcement consumption, increase the life of the building, reduce cracking, and thus reduce the permeability of concrete. Moreover, in high-strength concretes that have brittle behavior, adding fibers prevents brittle failure, particularly in tension. Because with increasing the compressive strength of the concrete, its tensile strength does not increase. On this basis, irreparable damage and catastrophic circumstances can occur due to quick and sudden tensile failure. Other advantages of adding fibers to the concrete include, but are not limited to, the following benefits: improving the strain capacity, increasing shock and blast resistance, increasing fatigue strength, increasing energy absorption capacity, preventing brittle concrete failure, and much greater bearing capacity after cracking. One of fiber concrete's biggest challenges is its distribution, especially in reinforcement sections. The appropriate distribution of the fibers is tremendously crucial in terms of efficiency (e.g., high and low concentration of the fibers in some places). Therefore, mixing fibers in the concrete requires more precision. Furthermore, the concrete performance will reduce due to the fibers and also make it difficult to compact in the formwork. Also, utilizing reinforcement instead of fibers will be more economical in many cases, especially since there is granulation of cement and non-uniform distribution. Researchers have studied different types of fiber properties in many articles by conducting various experiments. By mixing several types of fibers, such as steel and polypropylene, or one type with several different lengths and percentages, they tried to find the best and most optimal combination. In 2006, Markovich showed that combining different short and tall fibers in concrete could be more effective than using just a specific length. Bridging between two sides of the cracks, the short fibers connect and prevent the microcracks, and the tall fibers do the same for the larger ones. Thus, in order to improve the quality of concrete, it is better to use two different lengths of short and tall fibers together by using different percentages of fibers and combining steel fibers with different geometries and lengths [18]. Hoon Park Sung et al. made and measured a super-capable concrete specimen and could plot the tensile stress diagram of the specimens. However, adding short fibers besides long fibers may result in better performance in strain hardening and cracking behavior of concrete; they perceived that the overall shape of the diagrams depended on the long steel fibers. Among the fibers with different geometries, long twisted steel fibers had the best performance because after cracking, the best behavior of the sample was the strain rate and cracking behavior. When used singly, short and smooth fibers had the weakest performance [19]. Dong Joo Kim et al. performed a bending test by combining short and long fiber types with different percentages. They found that the combination of short and long fibers could give better results than using one length, by examining the strain, deflection, bending, and tensile strength of concrete specimens; they also found better concrete performance when using the long fibers either in length or diameter

[20]. Ahmed et al. examined concrete under bending by combining several types of steel fibers, polyvinyl and polyethylene [21]. Banthia and Gupta also studied the combination of several types of polypropylene and steel fibers with different lengths [22]. Yu et al. investigated the mechanical properties and strick resistance by combining short and long steel fibers with different percentages in green concrete [17]. Khalil et al. used single, double, and triple combinations of hooked steel fibers, corrugated plastic, fine steel, and polypropylene to study the strength of fiber concrete with different composition ratios. They understood that the best concrete in terms of compressive, tensile, and bending strengths contained 0.25% of hook fibers, 0.25% of fine steel fibers, and 0.25% of polypropylene fibers by volume [23]. Sivi Kumar and Centanam did similar research on the composition of metallic and non-metallic fibers [6]. The main goal of the present article is to experiment examine the effect of length and percentages of steel fibers on the compressive and tensile strengths of concrete samples. Previous researches have investigated a more limited number of fibers and experimented with fewer samples. They also examined high-strength concretes mostly, and little research has been performed on the effect of steel fibers on conventional concretes. Therefore, this research work aims to perform more extensive tests on conventional concrete (concrete with a strength of 20 to 25 MPa) with a more comprehensive scheme on the length as well as the percentage of steel fibers. To the lucid perception of the length as well as the percentage of steel fibers, the obtained results between the plain concrete and the SFRC specimens are compared.

2. MATERIALS AND METHODS

2.1. Materials

-Aggregate: Dokoohak mines located in the northwest of Shiraz were utilized to prepare both coarse and fine aggregates for the experimental tests of this research, which was performed in the concrete structure and technology laboratory of the Shiraz University of Technology (SUTech). These mines were made of silica. Aggregates were used in saturated surface dry (SSD) condition. As shown in Figure 1, the maximum aggregate size was limited to 19 mm. The sand and gravel aggregation test were performed according to the ASTM-C136 standard [24] to ensure appropriate categorization.

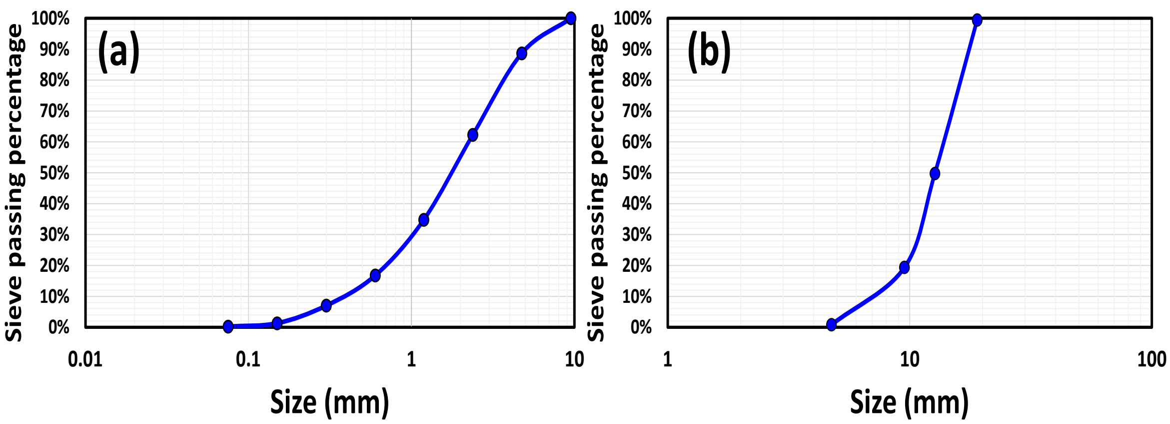

Figure 1. Grading diagram for materials: (a) sand and (b) gravel

- Cement: Cement type (II) of Firoozabad was utilized to make the concrete with the maximum compressive strength in 28 days was 470 kg/cm^2, and the specific surface area was 3000 cm^2/g. The chemical characteristics are given in Table 1.

Table 1. The chemical characteristics of the cement

Name	**SiO2**	**AL2O3**	**Fe2O3**	**CaO**	**MgO**	**SO3**	**K2O**	**Na2O**	**L.2.I**
Value (%)	20.7	5.7	3.3	64.8	1.4	1.9	0.8	0.1	1

-Water: The piped drinking water of Shiraz city was employed in this experiment.

-Steel fibers: According to the ASTM-A510 standard [25], two types of steel fibers with 700 to 1200 MPa of tensile strength were implemented. According to Figure 2, two steel fibers were utilized with a diameter of 0.8 mm and both 3 and 5 cm lengths along with two hooks at both ends.

Figure 2. Two 3 and 5 cm lengths steel fibers

2.1.2. Concrete Mixing Design

The mixing design and the ratio of materials to produce concrete were calculated in accordance with ACI-211 standard [26, 27]. The concrete mixing design is presented in Table 2. It is worth mentioning that aggregates were used in SSD mode. The slump for the mixing plan was 75 mm, and after measuring the slump for conventional concrete on different days, the slump was changed to about 80 mm and about 60 to 70 mm for the fiber concrete. The specific gravity of the fresh concrete was between 2435 and 2445 Kg/m^3 and steel fibers concrete was between 2440 and 2450 Kg/m^3.

Table 2. The mixing design of the concrete

Material	Weight (kg/m^3)
Gravel	935
Sand	983
Cement	320
Water	205

Adding steel fibers to concrete samples was as follows: volume percentages of 0.5%, 1%, and 1.5% were used to make each of 3 cm, 5 cm, and a combination of both fibers. Conventional concrete was also made with the same mixing design to verify the experimental results. The utilized percentages were obtained based on the concrete volume. To calculate the weight of steel fibers, the required concrete volume was multiplied by the fibers volume to obtain the fibers volume. Afterward, it multiplied by the fiber density, which was 7850 kg/m^3.

2.1.3. The Mixing Method

First, the sand and gravel in SSD mode were added to the mixer. Afterward, some water was added to it. The mixer was rotated for a couple of minutes. Then, the cement and the rest of the water were added, and the mixer was rotated for a couple of minutes again. Finally, the fibers were added to the rotating mixer gradually, and after 3 to 4 minutes of spinning, the sample molds fill with concrete. Due to the concrete waste and material dissipation, it should be pointed out that 10% of the material must be considered more than required [28].

2.1.4. Concrete Placing in Molds

After completing mixing materials, it is time to pour concrete into the molds. The 15x15 cm cubic molds were prepared for compressive strength. Reciprocally, the 15x30 cm cylindrical molds were prepared for tensile strength. Experience has shown that the slump value of steel fibers concrete is about 10 to 20 mm less than that of fiber-free ones. Sometimes it is necessary to mix the areas manually with the highest fiber density when pouring concrete, so the mixing is more uniform, and fibers are almost equal everywhere. On this basis, the concrete placing was conducted in three steps for each mold, and the compaction was carried out after each step. It is worth mentioning that in case of low accuracy, the compaction can cause honeycombed (porosity) concrete due to the fibers.

2.1.5. Curing Concrete

The molds of the concrete were opened after 24 hours. Subsequently, the concrete samples were embedded into a water pone for 28 days at room temperature.

2.2. Test Methods

2.2.1. Compressive Test

After removing and drying the cube samples, they should be placed under the jaw in the perpendicular direction of poured concrete according to EN-12390-3 standards [29] (as shown in Figure 4(a)). The sample surface for example the loading jaw surface must be flat, and the sample should be placed in the middle completely. Loading speed should be set between 0.2 to 1 MPa per second according to the regulations. Therefore, it was tuned as 0.6 in the current study.

2.2.2. Tensile Test

In order to test the tensile strength, the Brazilian test (split) under the ASTM-C496 standard [30] method was utilized. After removing and drying the samples, they were ready for the test. The dimensions were measured first. The sample length, which is placed in the lying position, is longer than the jaw length of the jack. Thus, a rigid steel plate should be placed under the sample, and to distribute the load uniformly, a flat steel bar that is longer than the sample should be placed on the top (as shown in Figure 4(b)). Loading speed should be set between 0.7 to 1.4 MPa per minute.

Figure 4(a). The compression strength test of the concrete

Figure 4(b). The tensile strength test of the concrete

3. RESULTS AND DISCUSSION

3.1. Compression Test Results

The compression tests of steel fiber samples demonstrated that when the load was increased, especially at the peak until it was reached about 50 to 60% of the resistance of the sample peak, most of the sample edges cracked and collapsed due to the fibers. Although the sample core was cracked, the shape didn't change, and the edges samples were cracked and collapsed because of low fiber concentration at this position (as shown in Figure 5). It was perceived that the high percentage of fibers could cause more same occurrence, and it was the highest rate when the percentage of the fibers was only equal to 0.5%. The higher the fiber percentage, the lower the concrete collapse, except for small cracks at the sample edges. Consequently, the presence of the fibers and the concrete integrity can prevent its collapse and destruction.

Figure 5. Cubic specimens containing steel fibers after breaking

As can be seen in Figure 5 on the right, the concrete sample, after failure and cracking, can preserve the configuration due to the presence of the fibers. This behavior can be considered as a warning before the destruction of the structural members and the building. Likewise, as shown in Figure 5 on the left, a small shock and impact were applied to the concrete sample to identify the fibers inside. Despite the high load and impact after failure, the skeleton was still retained, and only the sample edge was cracked. Unlike the fiber-contained sample, the plain concrete sample (conventional) had a brittle fracture, collapse, and no-bearing (as shown in Figure 6). The obtained results of the tensile and compressive capacities of the concrete specimens are reported in Table 3.

Figure 6. Simple cubic specimens after breaking

Table 3. The results of the tensile and compressive capacities of the concrete specimens

Type of fiber	Symbol	Compression load (KN)	Compression strength (MPa)	Tensile load (KN)	Tensile strength (MPa)
Plain concrete (without fiber)	P	483.75	21.50	142.23	2.01
$\rho = 0.5\,\%$ $L = 3\ cm$	S-3-0.5	505.76	22.48	147.75	2.09
$\rho = 0.5\,\%$ $L = 5\ cm$	S-5-0.5	651.53	28.96	187.53	2.65
$\rho = 0.5\,\%$ $L = (3,5)\ cm$	S-hyb-0.5	472.68	21.01	137.23	1.94
$\rho = 1\,\%$ $L = 3\ cm$	S-3-1	571.32	25.39	144.50	2.04
$\rho = 1\,\%$ $L = 5\ cm$	S-5-1	619.99	27.56	191.92	2.71
$\rho = 1\,\%$ $L = (3,5)\ cm$	S-hyb-1	575.28	25.57	182.00	2.57
$\rho = 1.5\,\%$ $L = 3\ cm$	S-3-1.5	605.93	26.93	187.39	2.65
$\rho = 1.5\,\%$ $L = 5\ cm$	S-5-1.5	607.73	27.01	279.29	3.95
$\rho = 1.5\,\%$ $L = (3,5)\ cm$	S-hyb-1.5	652.28	28.99	245.59	3.47

3.2. Tensile Test Results

The samples showed a very low strength in conventional concrete tensile testing and failed almost quickly. The failure was without warning and very brittle into half-equal cylinders, as shown in Figure 7(a). Ductility and strain were not desirably observed in these samples. Reversely, the tensile test results of the steel fibers samples were quite different. These samples had more resistance than conventional samples, and their resistance drop was not rapid. They were tested in such a way that the samples reached the resistance peak, then the resistance drop descended slowly, and bearing and ductility were very good for a long time. The sample was crushed and largely cracked but still resisted (see Figures 7(b), 7(c), and 7(d)). Despite the high strain, the samples resisted reaching 60% of the sample peak for a long time until the machine was turned off. The breakdown was visible with a warning in these samples and was not sudden at all. The fibers prevent the two half-cylinders from separating even after a very large failure, and fibers sewed together the sample sides of the crack. Since the fibers prevented concrete from failure in both compression and tensile tests, after lots of force to open the crack and pull the fibers out, these fibers were observed compared with the ones shown in Figure 8, and the hooks on both ends and the waves were smooth.

(a) (b) (c) (d)

Figure 7. The results of the tensile tests

Figure 8. Fibers in the initial state (top) and fibers after extraction from concrete (bottom)

After testing and loading, the compressive strength could be calculated from Eq. (1), and the tensile strength from Eq.(2).

$$S_c = \frac{F}{A} \quad (1)$$

$$S_t = \frac{2F}{\pi LD} \quad (2)$$

Where S_c and S_t represent the compressive and tensile strengths of the concrete samples, respectively. Also, *F* represents the tolerated force, and *A* represents the surface 15x15 cm area of the sample. In addition, *L* is the length and *D* is the diameter, which is 30x15 cm, respectively.

3.3. Discussion of the obtained results

For 3 cm fibers, the compressive and tensile strength for the concrete sample with 0.5% of fibers compared with the conventional concrete increased by 4.5% and 3.8%, respectively. Concrete with 1% of 3 cm fibers compared with 0.5% of fibers showed an increase of 12.97% in compression and a decrease of 12.97% in tension. Concrete with 1.5% of 3 cm fibers compared with 1% of fibers demonstrated an increase of 6.05% in compression and 29.68% in tension. For a 5 cm fiber, with 0.5% of fibers compared to conventional, the compressive strength and tensile strength increased by 34.68% and 31.75%, respectively. Concrete with 1% of 5 cm fibers compared to 0.5% of fibers showed a 5% decrease in compression and a 2.34% increase in tension. Concrete with 1.5% of 5 cm fibers compared with 1% of fibers showed a decrease of 2% in compression and a 45.52% increase in tension. For composite fibers, the compressive strength with 0.5% of fibers compared with conventional concrete decreased by 2.3% and in tensile strength by 3.7%. Concrete with 1% of composite fibers compared to 0.5% of fibers showed an increase of 21.7% in compression and 32.6% in tension. Concrete that had 1.5% composite fibers compared to 1% of fibers showed an increase of 13.38% in compression and 34.9% in tensile. Based on the obtained results and the observed values of compressive and tensile strengths, it seems that the tensile and compressive strengths increase while the length of fibers increases. Moreover, with increasing the fibers percentage, both tensile and compressive strengths are increased as well. In addition, as the compressive strength increases, the tensile strength also increases in a particular type of concrete. Except for the concrete with 0.5% of 5 and 3 cm composite fibers, all samples with fiber, both in tensile and compressive strengths, had better results than the non-fiber samples. As reported in reference [3], long fibers have the greatest impact on concrete strength. The fibers bond and thus increase the strength of the concrete. Thus, the longer the fibers, the better the bond. In a sample with 0.5% of composite fibers, the 3 cm fiber was 0.25%, and the 5 cm fiber was about 0.25% volume. More load and strength were tolerated in these samples by 5 cm than 3 cm fibers. Therefore, the low 0.25% volume seems to show a significant bearing capacity, which improves the strength. Due to the short length of 3 cm fibers, the sides of the crack cannot sew well; as they have a smaller sewing area, they are pulled out of the concrete quickly unless the wide distribution of 3 cm fibers in concrete leads to better performance. In general, for the same fiber percentages, the samples with 5 cm fibers had the highest resistance. The important point is that the mixing of 5 cm fibers was stronger than 3 cm ones due to the longer length. Also, it was harder to mix with an increase in the fiber percentage, and the slump was low. From the economic point of view, fibers with a volume of 1.5% are not very cost-effective, and it is better to use reinforcement instead of fibers. To significantly improve the tensile strength of concrete for special structures with high-level engineering such as superstructures, bridges, dams, tunnels, etc., it seems that using 1 to 1.5% of steel fibers (5 cm or composite steel fibers) accompanied with reinforcement can have optimal performance.

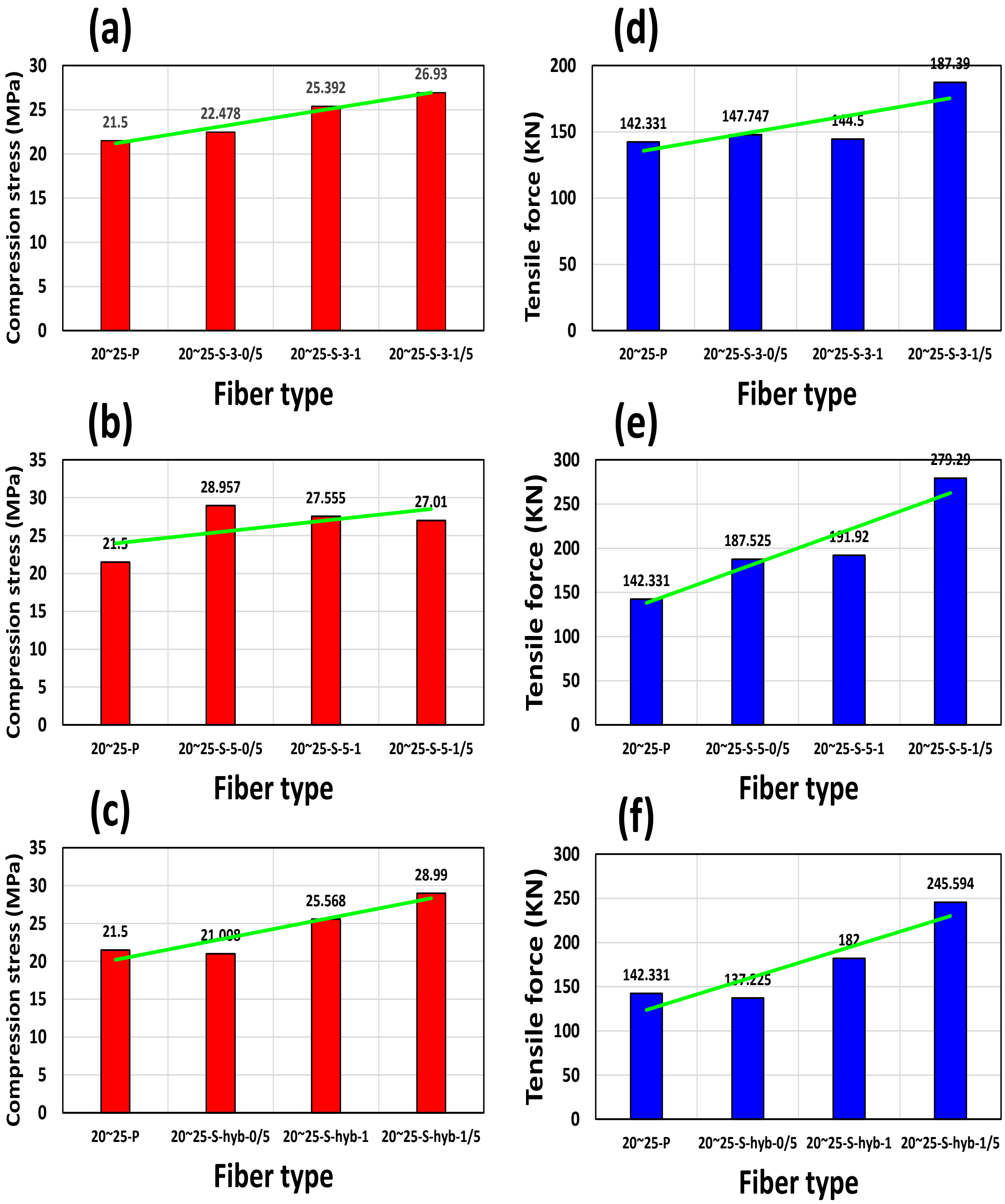

Figure 9. Diagram of the strength of concrete samples in terms of percentage of steel fibers: (a) compressive strength of fibers 3 cm, (b) compressive strength of fibers 5 cm, (c) compressive strength of composite fibers, (d) tensile strength of fibers 3 cm, (e) Tensile strength of fibers 5 cm, (f) Tensile strength of composite fibers.

4. CONCLUSION

In this research, the effect of fiber length and percentage on compressive and tensile strength of the concretes in the strength range of 20 to 25 MPa were experimentally evaluated. Three concrete samples with a volumetric composition of fibers of 0.5, 1, and 1.5% were studied and tested for lengths of 3 and 5 cm as well as their composition. The cubic and cylindrical samples were respectively fabricated for compressive and tensile tests. The compressive and tensile strengths using a hydraulic jack were respectively measured upon the cubic and cylindrical samples. The obtained results demonstrated that the tensile and compressive strengths increased by increasing the length and percentage of steel fibers in concrete samples. Furthermore, it was observed that the samples with the combination of 3 and 5 cm steel fibers had less strength than 5 cm samples and more strength than 3 cm samples, respectively. On this basis and with regard to the comparative obtained results, the 5 cm steel fibers are recommended compared to 3 cm steel fibers to increase the tensile and compressive strengths with different percentages. Consequently, in order to considerably improve the tensile strength of concrete for special structures, it is suggested that use 1.5% of steel fibers with length 5 cm (or a combination of 3 and 5 cm length) accompanied with reinforcement.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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