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Comparison of Mechanical Properties of Concrete Containing Polyolefin Macrosynthetic Fibers with Two Different Mixing Designs

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Abstract

Recent advances in polymer science, chemical synthesis, and engineering have increased the importance of polyolefins in structural applications. Polyolefin fibers have good tensile properties, wear resistance, and excellent chemical resistance, slowing the development of crack length and width. Studying the role of polyolefin fibers in two combined forms on the resistance properties of concrete is one of the main goals of this research. The samples were examined at 7 and 28 days for compression, tension, and elastic modulus tests. Two designs without fibers and four with needle and mesh fibers were combined in two water-cement ratios to investigate the effect of fiber integration on concrete properties. In these designs, the amount of super-plasticizer was permanently fixed, and the fibers were used in two volume percentages of 0.2 and 0.3 with equal lengths. Fibers reduced concrete slump loss and increased compressive strength, tensile strength, and elastic modulus, respectively 52.60, 44.29 and 26.74% compared to the original design. In total, fibers with a volume of 0.3% have resulted in higher resistance in the investigated properties of the research.

Keywords: Polyolefin fibers, Composite fibers, Compressive strength of concrete, Tensile strength of concrete, Concrete slump.

1 | Introduction

The mechanical properties of concrete, along with the low cost of raw materials, flexibility in shaping, durability, and ease of production, have made this material the most widely used building material of the 20th century. The significant compressive strength of concrete is very suitable for structural elements subjected to compressive stress, such as columns [1]. However, concrete's low tensile and bending strength prevents its

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use in horizontal structures under vertical loads. In such a situation, the structural elements must withstand stresses more significant than the tensile strength. Many researchers have investigated the performance of concrete with different composite fibers [2].

Gao et al. [3] in an article to investigate the bending strength, deformation, and toughness of concrete reinforced with mixed steel fibers and polyolefin recycled materials, they tested beam samples with the size of 550 x 150 x 150 mm. Test parameters of water-cement ratio (0.28, 0.33, 0.38, 0.43), replacement percentage of recycled aggregates (100, 50, 25, 0), and volume percentage of fibers (1.5, 1, 5) /0, 0) have been.

The experimental results showed that steel-polyolefin composite fibers significantly improved the compressive strength and flexural behavior of concrete due to the synergistic interaction of the fibers. The average compressive strength of concrete with composite fibers with different parameters varied from 34.69 MPa to 51.62 MPa. The axial bending load-deformation curves of the fiber samples had the same tendency as the load-deflection curves. Samples with steel fibers have the highest bending deformation compared to hybrid and polyolefin fibers. Also, adding steel-polyolefin hybrid fibers significantly increased the post-cracking behavior of recycled brick aggregates. The effect of steel-polyolefin composite fibers on compressive and bending strength is weaker than steel fibers but better than polyolefin fibers.

Xu et al. [4] conducted an experimental study on the mechanical properties of concrete reinforced with fibers (Cellulose fibers, polyvinyl alcohol fibers, and polyolefin fibers). The effect of individual fibers and the synergistic effect of combined fibers on axial compressive strength, tensile strength, and shear strength of concrete were investigated. The microstructures of fiber-reinforced concrete samples and the relationship between stress and strain were also observed. The results show that cellulose fibers alone increase the axial compressive strength of concrete. However, the tensile strength weakens the fracture. Polyvinyl alcohol fibers also weaken the tensile strength but have little effect on the other two strengths. Polyolefin fibers have a negative impact on all three mechanical resistances. The synergistic effect of combined fibers with the right amount of fibers can positively affect mechanical properties. It seems that the combination of 1.5 kg/m3 of cellulose fibers with 0.1 kg/m3 of polyvinyl alcohol fibers is the optimal combination to achieve the best synergistic effect. Also, it was recommended to use polyvinyl fibers with an optimal volume of 3.5 kg/m3 in the shear members, where the shear strength has increased by 9% compared to normal concrete.

Ghanem et al. [5] evaluated the strength and hardness of concrete reinforced with composite fibers. Provide regression equations to assess the strength and toughness of composite fiber-reinforced concrete. One hundred-two concrete samples were tested to investigate the effect of composite fibers on the strength and toughness of fiber-reinforced concrete. The amount of fibers varied between 0 and 0.2 percent. Steel fibers and polyolefin have been combined in different proportions, and their effect on compressive strength and toughness has been studied. Adding 0.2 percent of the volume of hooked steel fibers, compared to plain concrete, increases the fracture index and toughness by about 58.78 percent and 19.27 percent, respectively. When the fibers were combined, the increase of the mentioned parameters compared to normal concrete was about 81% and 31.42%, respectively.

Bhosale et al. [6] investigated the properties of fresh and hardened concrete, including the combination of polyolefin and polypropylene fibers. Twelve mixtures containing different percentages of fibers were considered. The mixtures consist of polyolefin fibers in volume fractions of 0.5, 1, and 1.5, some of which are replaced by polypropylene fibers in volume fractions of 0.1 and 0.2. The properties of the mixtures were evaluated using drop and reverse slump tests in the fresh state and compressive, splitting, and bending tests in the hardened state.

The primary research has been combining polymer and steel fibers by studying the scientific articles on concrete containing composite fibers. However, in this research, the fibers are a combination of polymer-polymer types because while improving the strength of concrete, it does not increase its weight. Both types of combined fibers are from the polyolefins family; a small percentage was used to make the concrete economically efficient while achieving a more desirable concrete. Two types of fibers were combined in needle and network shapes, which were investigated with two different volumes. The research aims to show the effects of polyolefin composite fibers with two different needle and mesh shapes on compressive strength, tensile strength, and modulus of elasticity, as well as fresh concrete, by describing the properties of synthetic fibers.

2 | Properties of Materials Used in Concrete

2.1 | Fine and Coarse Aggregate

Since the bond between polymer additives with cement and aggregates is powerful, its strength properties depend on the properties of aggregates. For a good concrete mix, the aggregates must be clean, hard, and dry, free from dust, and absorbed organic and chemical substances, clay coatings, and other fine materials that can cause concrete deterioration. In fact, the bond strength between reduces polymer and aggregate materials. Proper grading of aggregates ensures minimum void volume in the aggregate. Aggregates that make up 60 to 75% of the total volume of concrete. The sand used was local natural sand with a specific gravity of 2.65. Coarse aggregate is crushed stone with a maximum size of 19 mm and a specific weight equal to 2.70. The modulus of softness of sand is 2.8 and is within the standard range. The standard grading of aggregate used can be seen in *Figs. 1* and *2*.

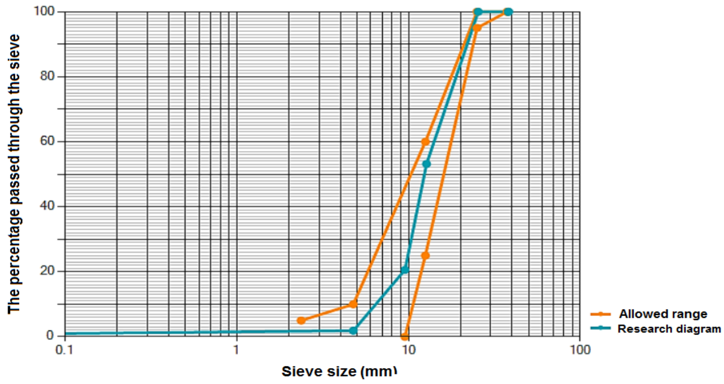

Fig. 1. The training curve of the sand used in the research compared to the permissible limits of ASTM.

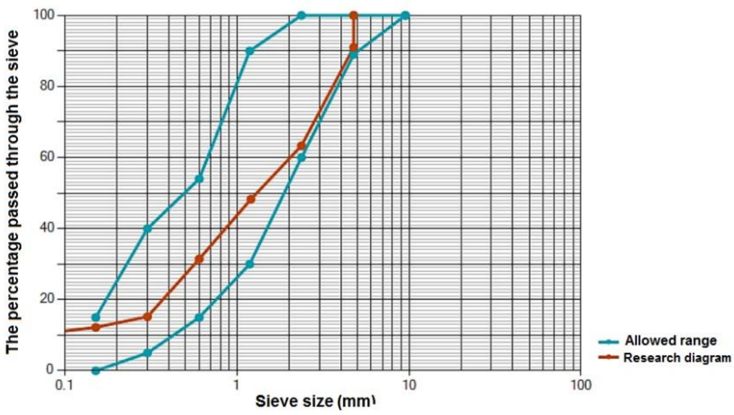

Fig. 2. The graining curve of the sand used in the research is compared to the permissible limits of ASTM.

2.2 | Cement and Water

The cement used in the concrete mix is Portland Type 2 of Golestan Plant, following the 389 standard. Also, the water used in making concrete is from the drinking water of Tunkabon City, which has a balanced pH.

2.3 | Plasticizer

The efficiency of concrete depends on its construction materials, including water aggregates, in terms of distribution, shape, size, cement materials, and age (according to the duration of curing and hydration), which can be improved by adding chemicals, such as super-plasticizers. Corrected the Increasing the amount of water or adding chemicals increases the efficiency of concrete, and on the other hand, when the amount of water decreases compared to cement, the strength of concrete increases. The research used a super-plasticizer with a permissible consumption amount of 0.8 to 2%, as per the specifications in *Table 1*.

Table 1. Specifications of super-plasticizer used in concrete mix design.

Liquid	Physical condition
Brown	Color
ISIRI 2930	Standard
kg/dm3 1.08 ± 0.02	Special Weight
4 to 5	Ph
1.0	The amount of chlorine ions
4	alkalinity

2.4 | Needle-Shaped Polyolefin Fibers

With its single-stranded and flexible form, this fiber form creates a good connection with cement. It has a maximum tensile strength of 700 and a modulus of elasticity of up to 7000 MPa. This polymer fiber does not absorb water and has shown high resistance against acids and alkalis. It also has a specific weight of 0.91 grams per cubic meter. Monofilament fibers have high Young's modulus and hardness, and when these fibers are used in high amounts in concrete, they act similarly to the effect of steel fibers. Therefore, they may be more resistant to compressive capacities. In this research, 60% of the total volume of fibers added to the concrete designs are single-fiber fibers. The characteristics and appearance of needle fibers are presented in *Table 2* and *Fig. 3*.

Table 2. Characteristics of needle fibers.

Percentage of Length Increase	Color	the Maximum Amount Allowed in Concrete, kg/m^3	Thickness mm	Length mm
15	Gray	3.5	0.05	54

2.5 | Polyolefin Network Fibers

Mesh fibers with a maximum tensile strength of 500, a modulus of elasticity of up to 4500 MPa, and a density of 0.91 were used in the research. These polymer fibers also did not absorb water and showed high resistance to acids and alkalis. This form of fiber increases in length by about 10% during the mixing process and creates a favorable connection with cement materials. 30% of the total volume of fibers added to concrete designs are network fibers. The characteristics and appearance of network fibers are available in *Table 3* and *Fig. 4*.

Fig. 3. Needle-shaped polyolefin fibers.

Table 3. Characteristics of network fibers.

Percentage of Length Increase	Color	The Maximum Amount Allowed in Concrete, Kg/M3	Thickness mm	Length mm
10	white	1	0.12	54

Fig. 4. Polyolefin network fibers.

3 | Materials Mix Design

The designs presented in the research include two designs without fibers with two different water-cement ratios and four designs with combined polyolefin fibers to achieve a characteristic strength of 25 MPa in concrete without fibers. The ratio of water to cement is 0.48 in design one and 0.5 in design two, and the amount of water and super-plasticizer is constant in all designs. In concrete, network and needle-shaped polyolefin fibers were added in two volume percentages of 0.2 (1.82 kg/m3) and 0.3 (2.73 kg/m3). The details of the designs of the samples can be seen in *Table 4*.

Table 4. Mix design of concrete samples (kg/m3).

Mixed Design Code	Cement	Water	Gravel	Sand	Lubricating	Polyolefin Fibers	
						Needle	Network
CO1	395.8	190	992	885.1	1.1	-	-
CO2	380	190	992	894.6	1.1	-	-
C1-0.2	395.8	190	992	885.1	1.1	1.27	0.55
C1-0.3	395.8	190	992	885.1	1.1	1.91	0.82
C2-0.2	380	190	992	894.6	1.1	1.27	0.55
C2-0.3	380	190	992	894.6	1.1	1.91	0.82

4 | The Order of Making the Samples

The complete mixing of materials is necessary to produce uniform and quality concrete. In order to make concrete samples, after the appropriate combination of aggregate, dry Portland cement is mixed with the materials according to the mixing plans for one minute, and fibers are added by hand. After that, water and super-plasticizer were added, and The act of combining the ingredients for 5 minutes was done well (*Fig. 5*). The next step was concreting, which was done by pouring the concrete into standard molds already greased with suitable oil. The concretes were poured into the molds during three stages and by pounding 25 times with a metal rod to better compact and homogenize the mixture (*Fig. 6*). After manufacturing, all samples were placed in the open air of the laboratory and removed from the molds after 24 hours for processing (*Fig. 7*). The samples were placed in a water tank at a suitable temperature entirely below the water level to process the concretes until they reached the desired age and strength. (*Fig. 8*).

Fig. 5. Materials after complete mixing.

Fig. 6. Fresh concrete after compaction in molds.

Fig. 7. Concrete samples after being removed from the mold.

Fig. 8. Concrete samples 24 hours after construction.

For the compressive strength test, cubic samples with dimensions of 15 cm and tensile strength were considered on cylindrical samples with dimensions of 20 x 10 cm. *Table 5* shows three compressive strength samples, and two tensile strength samples were made for testing at 7 and 28 days. Twenty-five samples were tested for compressive strength and 20 samples for tensile strength.

Table 5. Number of tested samples for each mixture design.

Mixed Design Code	Compressive Strength		Tensile Strength		Modulus of Elasticity
	7- Day	28- Day	7- Day	28- Day	28- Day
CO1	2	3	-	2	3
CO2	2	3	-	2	3
C1-0.2	2	3	-	2	3
C1-0.3	2	3	-	2	3
C2-0.2	2	3	-	2	3
C2-0.3	2	3	-	2	3

5 | Concrete Tests

5.1 | Slump

The concrete slump test measures the consistency of fresh concrete before it hardens and is in its fresh state. This work is done to check the performance of the concrete and, thus, the ease of concrete flow [7]. This test uses a cone-shaped metal mold, which is open on both sides and has attached handles. The tool typically has an inside diameter of 100mm at the top and 200mm at the bottom, with a height of 305mm. The cone is placed on a hard, non-absorbent surface. This cone is filled with fresh concrete in three stages, and each time, it is hit 25 times with a metal rod; in the third stage, the concrete surface becomes completely smooth and uniform (*Fig. 9*). At the end, the cone is completely pulled up, and the amount of concrete falling is measured compared to the initial level.

Fig. 9. Poured concrete in the slump cone.

5.2 | Tensile and Compressive Strength

The tensile and compressive strength of concrete is one of the significant characteristics used in the design and analysis of concrete applications. However, the behavior of concrete is mainly governed by compressive strength. The tensile strength of concrete provides approximately 10% of the compressive strength [8]. Indirect tensile strength or splitting is generally higher than direct tensile strength and lower than flexural strength. This method is used to design light members of concrete structures to evaluate the shear strength of concrete and determine the extension length of reinforcement. Indirect testing consists of testing a cylindrical specimen with symmetrical compressive stress that produces uniform tensile stresses along the diameter of the specimen.

This test was done based on the ASTM C496 standard on cylindrical samples with dimensions of 20 x 10 cm [9]. The sample was placed horizontally between two metal strips inside the fragile concrete device, and the test was performed (*Fig. 10*). The relation $T=2P/\pi ld$ was used to calculate the tensile strength value. P is the load caused by sample failure, l is the height, and d is the diameter of the standard cylindrical sample [10].

Fig. 10. Placing the cylindrical sample in the machine.

Compressive strength is the ability of the structure to carry loads on its surface without any cracking or deflection. In fact, the material under compression tends to decrease in size, while in tension, we encounter an increase in the sample length [11]. The compressive strength of concrete depends on many factors, such as water-cement ratio, cement strength, quality of concrete materials, quality control during concrete production, etc. The compressive strength test was performed according to the ASTM C39 standard on cubic samples with a dimension of 15 cm [12]. The exact weight of the compressed samples was obtained with a scale one day after they were taken out of the water. After that, the sample was placed in the machine's center from the flat part and tested (*Fig. 11*).

Fig. 11. Placing the cubic sample in the machine.

5.3 | Modulus of Elasticity

Concrete is a heterogeneous and multi-phase material whose behavior is influenced by its ingredients' elastic properties and morphology. The modulus of elasticity of concrete is used to measure the hardness of concrete, which is a good indicator of resistance. Concrete with more elastic value can withstand more stresses against brittleness [13]. This elasticity allows the concrete to regain its original shape after applying the load. In general, concrete has an elastic modulus in the range of 30 to 50 GPa. Stress and strain are always related, and one leads to the other. Pressure can also be caused by reasons other than the applied stress [14].

6 | Test Results

6.1 | Slump

The results of the current drop test are shown in *Table 6*. All mixtures with fibers have lower flow loss compared to the control. Since, in this study, the amount of plasticizer considered is the same for all mixtures, it can be seen that the slump flow is significantly reduced with the addition of fibers. It can be concluded that the lower the percentage of macro fibers in concrete, the higher the flow loss. The highest slump loss was observed in design one concrete, containing 0.3 percent. The lowest slump loss was observed in the design of two concretes, with 0.2 percent of composite fibers compared to normal concrete.

Table 6. Slump results of concrete samples.

Mixed Design Code	Slump (cm)
CO1	8.5
CO2	9
C1-0.2	7
C1-0.3	6.5
C2-0.2	7.5
C2-0.3	7

6.2 | Compressive Resistance

The compressive strength in each test was obtained by averaging three samples, the results of which are presented in *Table 7*. Fiber concrete has a higher resistance than the control sample, which reaches its maximum at 28 days of concrete. The strength of designing one fiber sample with 0.2% of fibers increased by 26.94% at 28 days and with 0.3% of fibers by 27.45% compared to its resistance at seven days. Also, the resistance of designing two fiber samples with 0.2% of fibers at 28 days increased by 22.78 and with 0.3% of fibers by 25.22% compared to its resistance at seven days. The highest resistance was achieved in design 1, with a water-cement ratio of 0.48 among the samples.

Table 7. Results of compressive strength of concrete samples.

Mix Design Codes	Age of Concrete	
	7-Day	28- Day
CO1	22.75	26.1
CO2	22.13	25.45
C1.0.2	30.8	39.1
C1.0.3	31.25	39.83
C2.0.2	21.2	26.03
C2.0.3	24.7	30.93

As can be seen, the 28-day strength of design one concrete with 0.2% fibers increased by 49.80% compared to the 28-day strength of the control sample, and in the sample with 0.3% fibers, this increase was 52.60%. The 28-day strength of two concrete designs with 0.2% fibers increased by about 3% compared to the 28-day strength of the control sample, and in the sample with 0.3% fibers, this increase was 21.53%.

Fig. 12 shows the concrete sample with composite fibers after the pressure test. Single-strand fibers mixed with network fibers can quickly form a broader network structure, reduce the stress concentration of concrete at the beginning of cracks, and thus increase compressive strength. Compared with the failure pattern of plain concrete, it can be concluded that the cracks on the surface of concrete reinforced with fibers are finer, more numerous, and widely distributed. It indicates that fiber-reinforced concrete is not entirely crushed under axial stress, and fibers play an essential role in strengthening the crack resistance, which causes multiple deviations from the crack propagation path and the occurrence of secondary cracks.

Fig. 12. Cracking pattern of concrete samples after pressure test.

6.3 | Tensile Strength

The tensile strength results in *Table 8* are the average results between two cylindrical samples. The tensile strength of concrete and compressive strength in samples containing fibers increased. The tensile strength of design one concrete with 0.2% fibers increased by 41.09% compared to the control sample, and in the sample with 0.3% fibers, this increase was 44.29%. The strength of the design of two concretes with 0.2% fibers increased by 19% compared to the control sample, and in the sample with 0.3% fibers, this increase was 26.25%.

Table 8. Tensile strength results of concrete samples.

Mixed Design Code	28 -Day Tensile Strength (MPa)
CO1	2.19
CO2	2.4
C1-0.2	3.09
C1-0.3	3.16
C2-0.2	2.85
C2-0.3	3.03

According to the cracking pattern of the sample after the tensile test (*Fig. 13*) in the initial stage of concrete cracking, several primary fibers eliminate micro-cracks and prevent expansion. When the tensile stress breaks the samples, the stress is transferred to the coarser and stronger monofilament fibers, so it can stop the large cracks and improve the crack tensile strength significantly.

Fig. 13. Cracking pattern of concrete samples after tensile test.

6.4 | Modulus of Elasticity

The modulus of elasticity of concrete is a function of compressive strength, and increasing the compressive strength of concrete causes the elastic modulus to rise. The results of the research are shown in *Table 9*. This value is 1.31% higher in design 1 than in design 2 of concrete without composite fibers. In design 1, with 0.2 and 0.3% fibers, respectively, a 25.54 and 26.74% increase in elastic modulus was observed compared to the sample without fibers. In design 2, this increase in fiber-containing concrete was about 2% and 10.28%, respectively.

Table 9. Modulus of elasticity at the age of 28 days of concrete samples (GPa).

Mixed Design Code	Elastic Modulus
CO1	20.79
CO2	20.52
C1-0.2	26.10
C1-0.3	26.35
C2-0.2	20.76
C2-0.3	22.63

7 | Conclusion

Several practical results can be drawn from the research findings and the main conclusions of this research. First, fiber-reinforced concrete is recommended for compression members requiring high crack resistance. In total, the following results were obtained:

I. Composite fibers caused concrete slump reduction, with the highest amount of slump reduction in design one concrete containing 0.3% composite fibers with 23% reduction and the lowest amount of slump in design two concrete with 0.2% composite fibers with 16.6% reduction ratio. It was observed to be normal concrete.

II. There was a significant increase in compressive and tensile strength in concrete sample design 1, with 0.3 percent of fibers being 52.60 and 44.29 percent, respectively.

III. The lowest increase in strength compared to the control concrete was in design sample 2 with 0.2 composite fibers, which increased its compressive strength by 3% and tensile strength by 19%.

IV. The elastic modulus at its maximum value is 26.35 GPa with a 26.74% increase compared to concrete plan 1.

V. Polyolefin composite fibers have significantly improved the concrete cracking pattern and have controlled larger cracks with the presence of micro cracks and their branching.

VI. Concrete with mixed polyolefin fibers has improved the resistance of concrete in pressure, tension, and elastic modulus, and its use is reasonable and economical.

Author Contribution

Conceptualization, Methodology, S. A. Y., Software, Validation, formal analysis, and investigation, H. F.; writing-creating the initial design, E. N. M.; writing-reviewing and editing, S. A. Y. All authors have read and agreed to the published version of the manuscript.

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Data Availability

All the data are available in this paper.

Conflicts of Interest

The authors declare no conflict of interest.

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