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Effect of Fiber Type and Volume Fraction on Fiber Reinforced Concrete and Engineered Cementitious Composite Mechanical Properties

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Abstract: Engineered cementitious composites (ECC) are an ultra-ductile cement-based composite material reinforced with short randomly distributed fibers. It differs from fiber reinforced concrete (FRC) in that it has a distinct ductile behavior. The study aims to assign mechanical properties, such as tensile, flexural, and compressive strength using locally available fiber rather than polyvinyl alcohol (PVA) fiber, which is not widely available in many countries, to ECC. PVA fiber is also very expensive. Instead of PVA, lightweight fibers, such as polypropylene, polyolefin, and glass fiber, as well as heavyweight fibers, such as steel fiber, were used. To assess the mechanical properties, the influences of curing, fiber volume fraction (2%, 4%, and 6%), fiber type, and fiber hybridization were adjusted in this study. The formation of multiple cracks along the specimen is the governing factor in ECC formation. The test results show that increasing the fiber volume fraction improves flexural and tensile strength. Water curing increased compressive, tensile, and flexural strength. Lightweight fiber hybridization has no effect on compressive strength, whereas heavyweight fiber hybridization improves compressive strength. For tensile and flexural strength, hybridization was associated with an improvement in all mechanical properties. The hybridization of lightweight fiber achieved ECC behavior at a lower volume fraction than the use of a single fiber volume. Relationships between tensile strength and flexural strength depending on the compressive strength of ECC were driven by demonstrating high performance.

Keywords: engineered cementitious composite; fiber content; fiber type; fiber hybridization; toughness index

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1. Introduction

Conventional concrete, invented in the 1800s, is the most widely used building material around the world. According to a study performed by Chethan and Ramegowda [1], concrete consumption was around 11.4 billion tons annually. Traditional concrete consists of fine aggregate-like sand, coarse aggregate such as gravel or crushed stones, water, and a binder such as cement. Additives may also be added to achieve desired properties such as flowability and setting time control. Conventual concrete has many advantages, such as formability, high compressive strength, and low cost. It also adopts some natural flaws such as essential brittleness and relatively low tensile strength. These flaws cause the formation of single cracks on the concrete surface. The formed cracks facilitate ingress and thus a way to attack the rebars causing corrosion followed by subsequent degradation of flexural stiffness, bearing capacity, and concrete durability. According to this degradation, action such as repairing and strengthening must be taken to restore the structural elements to perform their role [2–4].

To overcome those flaws, researchers decided to enhance concrete's performance and develop a new set of concretes that meets the new era requirements. This was initially carried out by increasing the fineness of cement particles. The trend of concrete strength was accelerated latterly by adding supplementary cementitious materials (SCMs) and superplasticizer, leading to concrete with a higher gel/space ratio while maintaining good workability processing high-performance concrete (HPC). HPC was designed to have enhanced workability, mechanical properties, and durability [5,6]. As SCM, fly ash (FA), ground granulated blast-furnace slag (GGBS), and silica fume (SF) were added as a binder separately or in diverse combinations to enhance the mechanical, physical, and durability features of concrete [7–10]. The excess addition of SCM leads to concrete brittleness causing concrete surface cracking, allowing the hazardous ingress of materials into the concrete interior [11–13]. New concrete types with better mechanical properties were processed as FRC where short fibers are added to the concrete mixture [5,14,15]. Fibers have long been used in the construction industry to improve the mechanical properties of structural elements such as beams, columns, and slabs [16]. FRC is divided into three categories according to fiber content. FRC with low fiber volume fractions less than 1% to reduce shrinkage cracking [17]. FRC with moderate fiber volume fractions between 1% and 2% have better mechanical properties such as modulus of rupture, fracture toughness, and impact resistance for controlling crack width in structures [18,19]. In the last decade or so, the third class of FRC was introduced with a high fiber volume fraction. This third class is commonly named as high-performance FRC with high fiber volume fraction or simply called HPFRC.

HPFRC generates materials with higher tensile strength, ductility, toughness, and enhanced durability aspects [20–22]. HPFRC is described as a unique form of FRC, distinguished by a low water–binder ratio, incorporation of fine cementitious materials of high-quality, high tensile strength, and high-durability features [23,24]. Embedded fibers that are randomly distributed play a vital role in delaying the crack initiation and propagation in hardened concrete, which is formed due to the presence of internal stresses in the hardened concrete. Randomly distributed fibers in the matrix form a bridging net to resist the applied loads and prevent the microcracks from prevailing [25]. Embedded fiber reduces concrete brittleness and modifies concrete's failure mode. Fibers were divided into man-made fibers and natural fibers. Man-made fibers were steel fiber, polypropylene (PP), polyethylene (PE), and polyvinyl alcohol (PVA) [26]. Steel fiber was divided into corrugated steel fiber (C.S.F), twisted steel fiber (T.S.F), and hooked steel fiber (H.S.F). Furthermore, steel fiber may be iron wires, granular iron wastes, and annular steel fibers. Mixtures with waste and annular steel fiber shows improved mechanical properties compared with conventional concrete [27,28]. HPFRC performance depends on fiber/matrix properties, fiber volume fraction, fiber geometry, fiber type, and fiber orientation in the matrix. HPFRC also exhibits tensile and softening behavior after crack initiation, which continues to expand as the load-bearing capacity decreases [25,29–31].

Concrete and mortar attain a brittle behavior because of the very weak transition zone between the matrix phase. All experimental results have demonstrated that all failures in ordinary concrete or mortar begin in the transition zone. As a result, the structural elements fail before providing any ductility. However, ductile structural elements that can withstand not only high compressive stress but also tensile and flexural strength are desperately needed in modern construction industries [32].

In the last few years, ECC has been developed to overcome conventional concrete and FRC drawbacks. ECC is a modified generation of FRC and HPFRC. It is also called bendable concrete or self-healing concrete. ECC exhibits unique features, such as ultra-high toughness, multiple microcracking behaviors, self-healing characterization, better fatigue resistance, and good durability, compared to FRC and conventional concrete [33–35].

ECC is a cement-based composite material developed from cement, fly ash, water, fine aggregate such as silica sand with a maximum grain size of 200 micrometers, and fiber, in addition to super plasticizing admixtures. Generally, fibers with a volume fraction of 2%

are used. The most commonly used fiber in the case of ECC was PVA. Some researchers partially replace PVA with PP, PO, and SF [36,37].

ECC mechanical properties are affected by fiber parameters used, such as type, content, aspect ratio, and length. An increase in the substitution of fly ash for cement is associated with a decrease in the compressive, tensile, and flexural strengths of ECC; on the other hand, tensile ductility, multiple cracking, fire resistance, fiber-matrix interface, chemical bond interface, toughness, crack width, and drying shrinkage have all been improved [38]. The aggregate size has a significant impact on the ECC. Researchers have found that compressive strength, deflection, flexural strength, and drying shrinkage decreased with increasing aggregate size; however, tensile stress and tensile strength increased [39]. It was concluded that as the fiber volume fraction and the reinforcement index (L/D) increased, the bending and ultimate strength increased, while the compressive strength and initial cracking load decreased [40]. High modulus fibers, such as C.F, S.F, and G.F, improved the strength and toughness of the composite; however, due to brittle behavior, strain hardening and ductility cannot be achieved. Low modulus fibers, such as PVA fiber, PP fiber, and PE fiber, can reduce cracking and greatly improve the ductility of the concrete mix [41]. Hybrid fiber is a combination of two or more fibers. The use of two or more fibers as a suitable combination may not only enhance the overall ECC properties, but also cause performance synergy [42]. The hybridization form of fiber affects ECC's mechanical properties favorably [41].

After the initial crack formation, ECC exhibits tensile strain hardening behavior and high tensile ductility in the range of 3–7% which is 300–700 times more than conventional concrete [43]. The initiated crack was prevented from prevailing due to the presence of fiber bridging. Added to that, it prevents the crack from opening up. Due to shrinkage, fiber attains forces through the crack which creates tensile behavior. In the case of low fiber volume fractions or weak fiber type, formation of other cracks (multiple cracking feature) will not appear as the tensile stress formed cannot bear the applied load which indicates the formation of FRC mixture, not ECC. Those data were confirmed by [44]. Conventional concrete displays localized cracking of infinite width only at about 0.01 percent tensile strain [45,46]. Typical ECC has ultimate tensile strength and strain capacity of 5–8 MPa and 3–5 percent, respectively. The compressive strength and flexural strength of ECC range from 30 to 90 MPa and 15 MPa, respectively, [46]. Under extreme loads, the strain-hardening property of ECC allows significant development of a large number of closely spaced microcracks with very specific crack width limits ranging from 50 to 80 microns [47].

ECC has self-healing properties in which unreacted binder particles hydrate after cracking to create a cement product that expands and fills cracks of constant width. This advanced and innovative building material can be used as a potential repair and retrofit material in various loading applications [48].

ECC has a competitive advantage in recent applications due to its excellent mechanical and multiple hair cracking behavior. Its capabilities in bridge decks, dampers, dam repair material, irrigation channels, viaducts, and retaining walls are notable [49].

2. Research Significance

As mentioned before, ECC was processed with only PVA fibers and in some cases PVA in addition to PP fibers or PO fibers. These fibers (PP/PO) were not used singly in processing ECC. The main objective of the research is to investigate the possibility of processing the ECC mixture using short locally available fibers instead of PVA. The formation of multiple cracks along the specimen during the bending test is the feature characterizing ECC rather than FRC, which possesses a single crack. In this research, the influence of fiber volume fraction (2%, 4%, and 6%), specimen water curing period, fiber type (lightweight fiber/heavyweight fiber), and fiber hybridization on FRC and ECC performance is also investigated. The performance of FRC and ECC are discussed in terms of compressive strength, splitting tensile strength, and flexure strength. Finally, empirical equations were employed to correlate the tensile and flexural strength with compressive strength.

3. Materials and Experimental Studies Program

3.1. Materials

In this research, to produce both FRC and ECC, Portland hydraulic cement, fine silica sand, class-F fly ash, fibers, water, and admixtures were used. Ordinary Portland cement (CEM I 42.5 N) conforming to the requirements of ESS 4756-1 was used in this research for the processing of FRC and ECC. The main chemical composition and physical characteristics of cement are provided in Table 1.

Table 1. Chemical and physical properties of cement and supplementary materials used in ECC mix.

Compound	Cement	Class-F Fly Ash	Silica Sand
Chemical Properties			
Silicon dioxide, SiO_2 (%)	21.30	63.10	99.79
Aluminum oxide, Al_2O_3 (%)	3.94	26.54	0.14
Ferric oxide, Fe_2O_3 (%)	3.80	5.40	0.016
Calcium oxide, CaO (%)	62.67	2.33	0.01
Sodium oxide, Na_2O (%)	0.44	0.85	0.01
Potassium Oxide, K_2O (%)	0.39	0.52	0.04
Magnesium oxide, MgO (%)	1.90	0.00	0.01
Loss on ignition, LOI	3.04	0.80	0.00
Physical properties			
Specific gravity (g/cm^3)	3.01–3.15	2.51–2.57	2.60
Blaine surface area (cm^2/gm)	3050	3570	-

The fly ash used in the research work was class F, conforming to the requirements of ASTM C618. The main chemical composition and physical characteristics of fly ash are provided in Table 1. Fine silica sand with a finesse modulus of 3.63 is used in processing both FRC and ECC. The fine silica sand was obtained by sieving fine aggregate with sieve No. 60 (250 μm) and retained with sieve No. 100 (150 μm) [39]. The main chemical composition and physical characteristics of the fine silica sand are provided in Table 1. In this research, three types of man-made fibers were used in processing FRC and ECC. These fibers were inorganic, such as corrugated steel fibers (C.S.F), glass fibers (G.F), and polymeric, such as polypropylene fibers (PP) and polyolefin fibers (PO). Fibers were added in a single or hybrid state in different dosages. Table 2 describes the technical specifications of each fiber type. Clean potable water with a temperature range between 22 and 25 °C was used in the mixing and curing processes. High range water-reducing admixture containing a polycarboxylate chemical composition with a specific gravity of 1.08 was added to achieve flowability. The dosage of HRWR was determined by trials to achieve the same workability, which was 100 ± 30 mm slump.

3.2. Test Parameters and Testing Methods

3.2.1. Test Parameters

The considered parameters throughout this study were fiber volume fraction (2%, 4%, and 6%); fiber type, such as PP, PO, G.F, and C.S.F, and fiber hybridization from the previously mentioned fiber types, and curing age.

3.2.2. Considered Tests

- Compressive strength

The axial compression test was performed in conformity with the reference to ISO 401 [50]. Testing procedures were: firstly, ensure that the concrete specimen has been fully dried with a flat surface; and secondly, make sure that the machine plate is flat and clean before placing it on the universal testing machine (UTM). Samples were tested at two curing ages, 7 and 28 days.

Table 2. Technical specification of fibers.

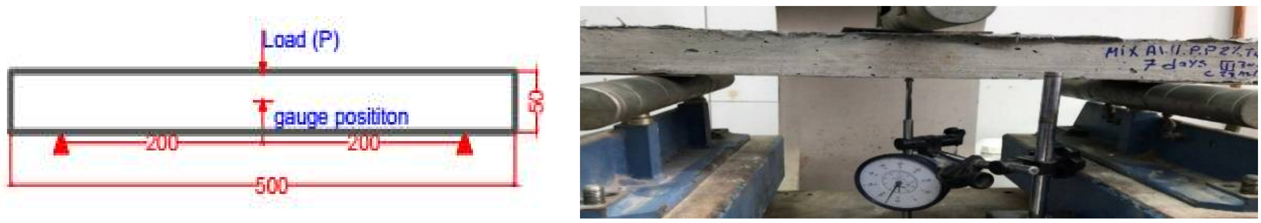
Fiber Type		Diameter (μm)	Length (mm)	Aspect Ratio (-)	Density (kg/m^3)	Ultimate Tensile Strength (N/mm^2)	Elongation (%)	Elastic Modulus n (GPa)
Lightweight fiber	Polypropylene fiber (PP)	18	15 ± 2	833.00	910	350–700	>80%	4.3
	Polyolefin fiber (PO)	900	48	53.33	900	≥500	15%	2.64
	Glass fiber (G.F)	12,000	18	1.50	2440	466	10%	-
Heavyweight fiber	Corrugated steel fiber (C.S.F)	900 ± 50	60 ± 3	66.66	7810	1000	-	200

- Splitting tensile strength

A splitting tensile strength test was performed to determine the specimen's tensile strength using UTM. A continuous diametric compressive load was applied along the length of the cylindric sample until failure occurred. The test procedures were performed according to British Standard BS 1881: part 118:1993 and ASTM C78-94. Specimens were tested at one curing age of 28 days.

- Flexural strength

A three-point bending test according to BS EN 196-1 [51] was carried out to evaluate the flexural strength for all mixtures. One dial gauge was used to measure the mid-span displacement. The clear span between the two supports was 400 mm. The applied load and mid-span point displacement were recorded during the test. The test method is shown in Figure 1.



(**a**) Test configuration (**b**) Experimental configuration

Figure 1. Three-point bending test.

3.3. Mixing Procedure

One mixing procedure was adopted in the processing of all the mixes to study single and hybrid fiber influences on ECC mechanical properties. ECC was mixed according to Felekoglu and Tosun-Felekoglu [52]—dry powder ingredients (fine sand/fly ash/cement) were mixed for 2 min, then water and HRWR admixture (polycarboxylate material) were added and mixed for 3 min. A highly flowable matrix was obtained at the end of the matrix mixing procedure (before fiber addition). Then fiber was added gradually for 2 min. After that, the matrix was mixed for 3 min. It was reported that the ultimate tensile strength and ductility improved with changes in mixing procedure, such as longer mixing time, faster-mixing speed, and high torque, all helping to reduce fiber lumps. Immediately after that, the workability of the fresh mixture was checked using the slump test. The performed mixing procedure is shown in Figure 2.

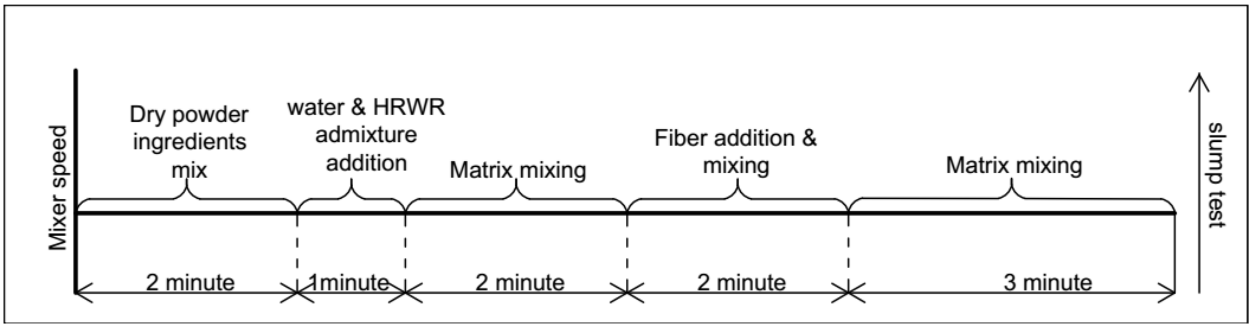


Figure 2. Mixing sequence of procedures applied in this study.

3.4. Specimens Preparation, and Curing

After the workability measurements, the fresh FRC and ECC mixtures were then cast into six steel cubes with dimensions of 100 mm × 100 mm × 100 mm for compression strength test, and six wooden beams with dimensions of 500 mm × 100 mm × 50 mm (length × height × depth) were cast for flexural strength test, and for splitting tensile strength examination, cylinders of dimension 150 mm × 75 mm (diameter × height) cylinders mold were cast. After casting, all specimens were vibrated on the vibration table with frequency 115 V/60 Hz until the surface became relatively smooth in appearance.

The specimens were kept In the molds after casting for 24 h at room temperature, and soon after that they were demolded. The specimens were then cured in water (20 ± 2 °C) for 7 and 28 days. Curing water with 7.5 Ph was changed weekly.

3.5. Mix Design of ECC

The mixture proportions used for both FRC and ECC adapted from Victor Lee's proposed mix with a ratio of 1:1.2:0.8 cement: fly ash: sand with a W/C ratio of 0.56 is presented in Table 3. The water to binder ratio is 0.255. The FRC and ECC mixtures were prepared in a rotary mortar mixer. The mixture consists of two parts, cement matrix ingredient and fiber ingredient. The cement matrix ingredient was Portland cement where its content was 578 kg/m^3, class-F fly ash content was 693.5 kg/m^3, the sum of cementitious material was 1271.5 kg/m^3, silica sand content was 462.25 kg/m^3 for 2.0% volume fraction as given in Victor Lee's [53] proposed mixture (other sand contents were determined using the absolute volume equation to yield 1 one meter cube), water content was 323.5 kg/m^3, and water to cementitious material ratio was 0.255. The amount of HRWR was chosen by trial and error to achieve a sticky consistency (around 100 ± 30 mm slump).

Table 3. Mix proportions in kg/m^3 for FRC and ECC mixtures.

	Mixture id		Cement	Fly Ash	Sand	Water	HRWR	PP	PO	C.S.F	G.F
Mixtures reinforced with single fiber	Mixture 1	2% PP	578	693.5	462.25	323.5	5.00	2.0	-	-	-
	Mixture 2	4% PP	578	693.5	411.45	323.5		4.0	-	-	-
	Mixture 3	6% PP	578	693.5	360.65	323.5	6.50	6.0	-	-	-
	Mixture 4	2% PO	578	693.5	462.25	323.5	4.00	-	2.0	-	-
	Mixture 5	4% PO	578	693.5	411.45	323.5		-	4.0	-	-
	Mixture 6	6% PO	578	693.5	360.65	323.5		-	6.0	-	-
	Mixture 7	2% C.S.F	578	693.5	462.25	323.5	3.00	-	-	2.0	-
	Mixture 8	4% C.S.F	578	693.5	411.45	323.5	3.50	-	-	4.0	-
	Mixture 9	2% G.F	578	693.5	462.25	323.5	8.00	-	-	-	2.0
	Mixture 10	4% G.F	578	693.5	411.45	323.5	10.00	-	-	-	4.0

Table 3. *Cont.*

	Mixture id		Cement	Fly Ash	Sand	Water	HRWR	PP	PO	C.S.F	G.F
Mixtures reinforced with single fiber	Mixture 11	2% PP &2% PO	578	693.5	411.45	323.5	6.00	2.0	2.0	-	-
	Mixture 12	2% PP &1% PO	578	693.5	386.05	323.5		2.0	1.0	-	-
	Mixture 13	1% PP &2% PO	578	693.5	386.05	323.5		1.0	2.0	-	-
	Mixture 14	4% C.S.F &2% PP	578	693.5	309.85	323.5	6.00	2.0	-	4.0	-
	Mixture 15	2% C.S.F &2% PP	578	693.5	411.45	323.5		2.0	-	2.0	-

The fiber ingredient varied in content and type. Fiber type and ingredients were the governing parameters in processing both FRC and ECC. Based on varying fiber content, two kinds of mixes were processed in this research work: single fiber mixes and hybrid fiber mixes. Ten FRC and ECC mixes were designed using a single fiber as a filler. Five RFC and ECC mixes were designed using hybrid fiber as a filler. Fiber volume fraction varies from 2 to 6% in both single and hybrid mixtures. All mixes were designed to study the effect of fiber type and volume fraction on the mechanical properties of both FRC and ECC.

4. Test Results and Discussions

4.1. Cracking Behavior

As mentioned before, one of the research goals was processing ECC with an alternative type of fiber rather than PVA. Multiple cracking behaviors propagated along the specimen due to the bending test is a unique property characterizing ECC, different than FRC [53]. Tables 4 and 5 summarize the crack pattern throughout the three-point bending test for specimen reinforced with different fiber types and volume fractions. From these tables, ECC was observed in the case of single light fibers, such as polypropylene and polyolefin, at 4% or more fiber volume fraction. On the other hand, hybrid fiber reinforcement could be achieved from a total fiber volume fraction of 3%. The rest of the specimens were FRC due to the formation of a single crack.

If the applied load (p_c) reaches a value that exceeds the matrix maximum capacity, it starts to crack. According to the cracking behavior, formation of FRC or ECC can be stated. ECC is formed as the applied tensile load on the specimens (p_c) is lower than fiber bridging capacity (p_o) at any of the already formed cracks. After that, the applied load moved to the nearest flaw which may be borne by the fiber bridging capacity causing the formation of other cracks. That action lasted till the applied load exceeded the fiber bridging capacity causing specimen fracture. This shows that multiple cracking behaviors will continue when the applied tensile load is lower than the capacity of bridging fiber (p_o) [53].

According to previous research, ECC was processed using PVA fiber with volume fraction (Vf) ranges from 1.5 to 2.5%. PVA tensile strength, σ_u, ranges from 1420 to 1620 MPa. The product value of Vf * σ_u for ECC mixtures ranges from 21.3 to 40.5. The product of σ_u * Vf for different mixes are given in Tables 4 and 5. From the results, it was found that the minimum value of σ_u * Vf that achieves ECC behavior is 26 in the case of single fibers and about 20 in the case of hybrid fibers. These values match the typical values for ECC mixtures using PVA fibers that are in the range of 21.3–40.5.

4.2. Effect of Fiber Volume Fraction and Curing

In this section, the effect of fiber volume fraction, and curing on FRC and ECC mechanical properties in terms of compressive strength, splitting tensile strength, flexural strength, and cracking behavior are discussed.

Table 4. ECC and FRC crack pattern of mixtures reinforced with a single fiber.

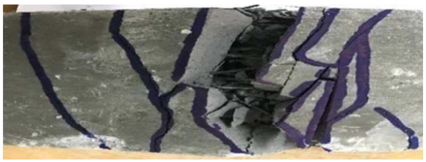
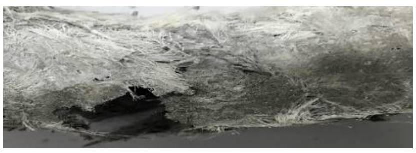
Type of Fiber	Volume Fraction	Crack		Mixture Type	σ_u (MPa)*V_f (%)
		Crack Pattern	Crack Type		
Polypropylene	2%		Single crack	FRC	14
	4%		Multiple cracks	ECC	28
	6%		Multiple cracks	ECC	42
Polyolefin	2%		Single crack	FRC	13
	4%		Multiple cracks	ECC	26
	6%		Multiple cracks	ECC	39
Glass fiber	2%		Single crack	FRC	9.32
	4%		Single crack	FRC	18.64
Corrugated steel fiber	2%		Single crack	FRC	20.00
	4%		Single crack	FRC	40.00

Table 5. ECC and FRC crack pattern of mixtures reinforced with hybrid fiber.

Type of Fiber/Volume Fraction			Crack		Mixture Type	σ_u (MPa)*V_f (%)
PP	PO	C.S. F	Crack Pattern	Crack Type		
2%	2%	-		Multiple cracks	ECC	27
2%	1%	-		Multiple cracks	ECC	20.5
1%	2%	-		Multiple cracks	ECC	20
2%	-	4%		Single crack	FRC	54.00
2%	-	2%		Single crack	FRC	34.00

4.2.1. Compressive Strength

The effect of fiber volume fraction on compressive strength is also shown in Figure 3 and Table 6. As shown in this figure, generally, the increase in volume fraction of light fibers, such as polypropylene, polyolefin, and glass fibers, has an adverse effect on the compressive strength. This behavior is observed either at 7 days or 28 days. In the case of polypropylene fibers, as an example, at age of 28 days, the reduction in compressive strength is 9.48% and 14.45% for mixtures with 4% and 6% compared with the mixture reinforced with 2% polypropylene volume fraction. This general behavior is due to the lower modulus of elasticity of polymeric fibers and the high-volume fraction of fiber reduces the interfacial bonding strength. This trend was reported by Aydın and Baradan [25] and Kamal and Khan [54].

In contrast, with specimens reinforced with steel fibers either for 7 days or 28 days, the increase in fiber volume fraction enhances the compressive strength. The enhancement in 28 days of compressive strength due to the increase in the fiber volume fraction from 2% to 4% is 14.10%. This favorable effect of using steel fibers on the compressive strength is due to the higher modulus of elasticity of steel fibers compared with plain concrete. This trend was confirmed by Wang and Liu [55].

For polypropylene fiber, compressive strength at 28 days increases by 29.50%, 30.90%, and 29.20%, for 2%, 4%, and 6% volume fractions compared with 7 days compressive strength, respectively, as shown in Figure 3a. This development for polyolefin fiber mixes is 31.40%, 30.40% and 22.00% for 2%, 4%, and 6% volume fractions, respectively, as shown in Figure 3b. For glass fiber, the increase at 28 days compressive strength compared with 7 days is 29.60% and 32.35% for 2% and 4% volume fractions, respectively, as shown in Figure 3c, whereas this increase is 49.30% and 61.80% for 2% and 4% corrugated steel fiber volume fraction, respectively, as shown in Figure 3d. Overall, the 28-days compressive strength for FRC and ECC mixtures reinforced with single fiber compression shows strength enhancement ranging from 21.99% to 38.89%. For FRC and ECC mixtures with hybrid fibers, compressive strength development due to the curing process ranges from 17.16% to 40.75%. The enhancement in compressive strength is due to the continuous hydration of the high-volume cementitious materials [52]. All specimens' mechanical properties are summarized in the following table.

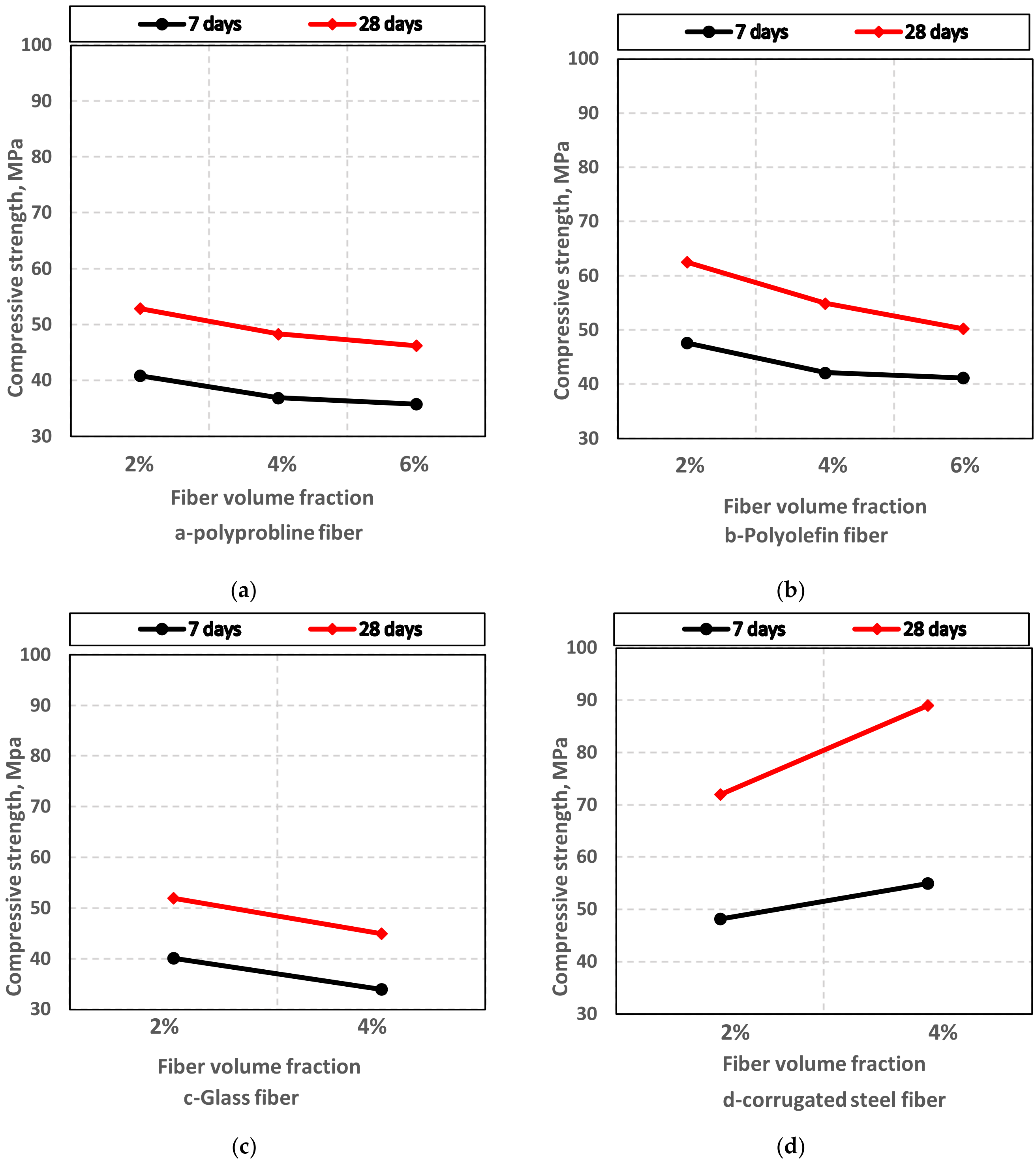


Figure 3. Compressive strength of FRC and ECC; (**a**) PP, (**b**) PO, (**c**) G.F, (**d**) C.S.F.

Table 6. Mechanical properties of FRC and ECC specimens at 7 and 28 days.

Fiber Type	Fiber Volume Fraction (%)				Compressive Strength (MPa)		Splitting Tensile Strength (MPa)	Flexural Strength (MPa)	
	PP	PO	G.F	C.S.F	7-Days Curing	28-Days Curing	28-Days Curing	7-Days Curing	28-Days Curing
Single fiber	2%	-	-	-	40.83	52.88	4.14	4.16	5.13
	4%	-	-	-	36.90	48.30	6.08	6.08	6.98
	6%	-	-	-	35.75	46.20	6.81	7.07	8.48
	-	2%	-	-	47.60	62.55	4.50	4.50	5.48
	-	4%	-	-	42.10	54.90	6.22	6.22	7.49
	-	6%	-	-	41.15	50.20	7.07	6.81	8.20
	-	-	2%	-	40.10	52.00	4.70	5.92	6.75
	-	-	4%	-	34.00	45.00	6.00	8.07	9.54
	-	-	-	2%	48.20	72.00	8.10	8.35	9.27
	-	-	-	4%	55.00	89.00	11.85	12.15	14.85
Hybrid fiber	2%	2%	-	-	44.00	61.30	7.80	8.13	9.72
	2%	1%	-	-	37.70	49.00	7.00	7.31	8.29
	1%	2%	-	-	40.00	52.80	7.20	8.10	8.25
	2%	-	-	4%	40.55	43.33	12.86	13.10	15.53
	2%	-	-	2%	47.20	54.30	10.19	10.70	12.23

Finally, FRC and ECC mixtures tested in compression have a unique mode of failure compared to plain mortar. Figure 4 shows the unique fracture mode of fiber-reinforced mortar with several diagonal cracks on the outer surface of the samples without spalling due to fiber bridging (ductile failure), rather than the typical explosive crushing of conventional concrete. This phenomenon occurs due to inherent concrete material brittleness (brittle failure) [56]. Similar observations were made by Wang and Liu [55] and Li [57].

(**a**) (**b**)

Figure 4. Mode of failure due to compressive strength for plain mortar (**a**) and ECC (**b**).

4.2.2. Splitting Tensile Strength

Figure 5 and Table 6 exhibit the average splitting tensile strength results of the different specimens. From the figure, it was established that an increase in fiber volume fraction has a positive effect on splitting tensile strength. For polypropylene fiber, the increase in 28 days' splitting tensile strength is 48.85% and 64.49% for mixes with 4% and 6% fiber volume fraction compared with 2% volume fraction, respectively. For polyolefin fiber, this increase is 38.22% and 57.11%. Polymeric fiber addition can significantly improve the tensile strength of the mixtures [58]. This enhancement is due to the increase of glass fiber from 2% to 4% being 27.65% as shown in Figure 5c. From Figure 5d, for mixes with corrugated steel fiber, the enhancement at 28 days for splitting tensile strength due to the use of 4% volume fraction is 46.35% compared with 2% volume fraction. Thus, the magnitude of the tensile strength depends on the strength of the matrix and the bridging ability of the fiber [59]. The lower fiber volume content results in lower fiber bridging ability. Therefore, the ability to prevent cracks accompanied by apparent strain hardening behavior is lower. These results were confirmed by several researchers [54,60–62].

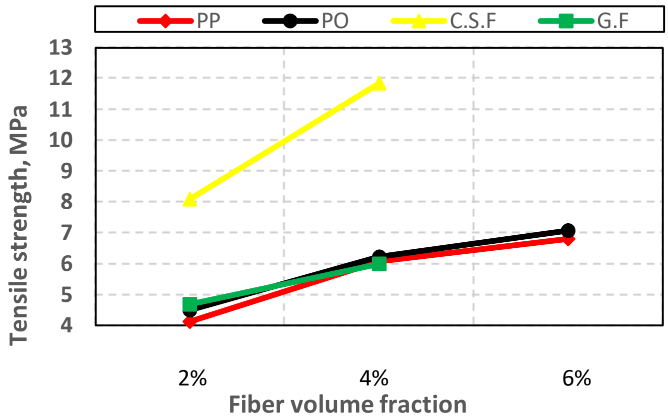


Figure 5. Splitting tensile strength of FRC and ECC.

Figure 6 illustrates the 28-days splitting tensile strength test specimen for ECC reinforced with single fibers of polypropylene, polyolefin, corrugated steel fiber, and glass fiber with different fiber volume fractions. The null samples without fiber addition ruptured into two parts in contrast to samples reinforced with fiber that attain a unique behavior with propagated cracks along with the sample.

(**a**) PP2% and PO2%

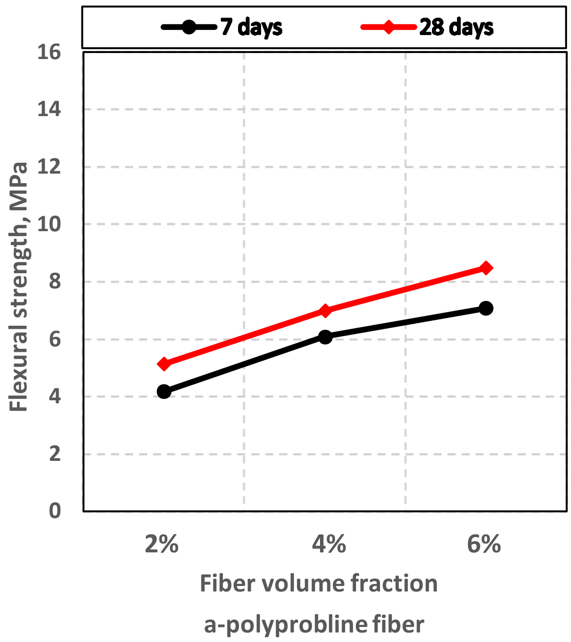
(**b**) C.S.F2% and PP2%

(**c**) Conventional concrete

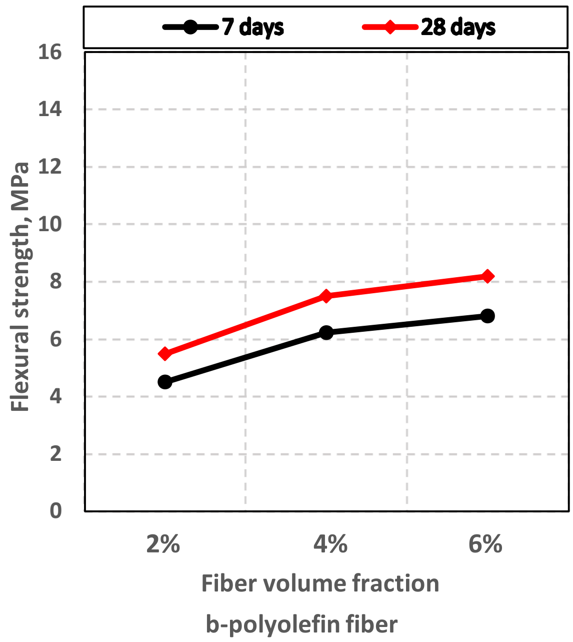
Figure 6. Mode of failure in splitting tensile strength test.

4.2.3. Flexural Strength

Table 6 and Figure 7 display the 7, and 28-day flexural strength results for different FRC and ECC mixtures. For polypropylene fiber, flexural strength development at 28 days compared with 7 days increased by 23.24%, 14.81%, and 20.10% for 2%, 4%, and 6% fiber volume fraction, respectively, due to curing. The corresponding deflection was also enhanced due to curing. The recorded enhancement for polyolefin fiber mixes is 22.00%, 20.65%, and 20.13% with the corresponding improvement in the deflection. For corrugated steel fiber, flexural strength development was 16.60% and 23.59% for fiber volume fractions 2% and 4%, respectively; due to curing, the corresponding deflection was enhanced. In the case of using glass fiber, accretion was 34.10% and 13.23% for 2% and 4% fiber volume fractions, respectively; due to curing, the corresponding deflection was increased.



(**a**)



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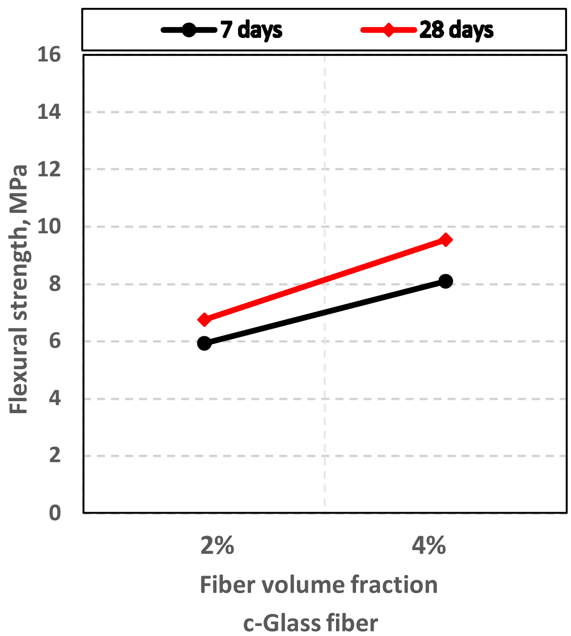
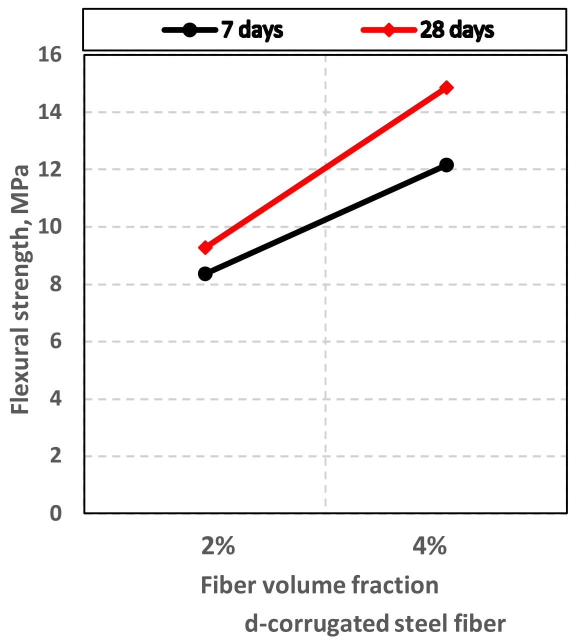


(**c**)



(**d**)

Figure 7. Flexural strength of FRC and ECC; (**a**) PP, (**b**) PO, (**c**) G.F, (**d**) C.S.F.

For FRC and ECC mixtures reinforced with a single fiber, overall flexural strength enhancement due to curing ranges from 13.23 percent to 34.10 percent. For FRC and ECC mixtures with hybrid fibers, peak stress development due to the curing method ranges from 20% to 22.82%. These results were confirmed by [55,63] who stated that hydration in the ECC exhibits noticeable improvement in the mechanical properties of ECC.

It was established from Table 6 that increasing the fiber volume fraction of polypropylene, polyolefin, glass fiber, and corrugated steel fiber affects the flexural strength and the corresponding deflection favorably. This behavior is observed either in 7 days or 28 days. In the case of polypropylene fibers, at 28 days, the increase of fiber volume fraction was associated with an increase in flexural strength by 35.96% and 65.35% for mixtures with 4% and 6% compared with the mixture with 2% volume fraction. As mentioned before, for beams without fiber addition only peak stress was recorded as it formed only a single crack and then ruptured. These results were confirmed by [60,64] and Kamal and Khan [54].

The typical flexural failure mode of plain concrete and FRC specimens without short fibers is a single crack localized at the maximum moment region (mid-span in the case of a three-point loading test) [55]. In the case of ECC specimens, multiple fine cracks were initiated along the specimens. Uniform expansions were observed in almost all cracks after the formation of many microcracks. This result clearly demonstrates that bridging activity of the fibers is initiated, which prevents the predominance of single cracks and allows the formation of multiple microcracks. The first crack in all of the ECC specimens began inside the midspan of the beam.

For polypropylene fiber, flexural strength at 28 days increases by 23.30%, 14.80%, and 19.94%, for volume fractions of 2%, 4%, and 6% compared with 7 days compressive strength, respectively, as shown in Figure 7a. This development for polyolefin fiber mixes is 21.70%, 20.41%, and 20.40% for volume fractions of 2%, 4%, and 6%, respectively, as shown in Figure 7b. For glass fiber, the increase at 28-days compressive strength compared with 7 days is 14.02% and 17.70% for 2% and 4% volume fractions, respectively, as shown in Figure 7c, whereas this increase is 14.40% and 25.31% for 2% and 4% corrugated steel fiber volume fraction, respectively, as shown in Figure 7d. Overall, the 28-days flexural strength for FRC and ECC mixtures reinforced with single fiber compressive shows strength enhancement ranging from 14.02% to 25.31%. For FRC and ECC mixtures with hybrid fibers, flexural strength development due to the curing process ranged from 1.85% to 20.76%.

4.3. Effect of Fiber Type

This section discusses the effect of fiber type on the mechanical properties of FRC and ECC in terms of compressive strength, tensile strength, flexural strength, and crack behavior.

4.3.1. Compressive Strength

Generally, from Figures 8 and 9, the maximum compressive strength was obtained when using steel fiber. For example, at a 2% fiber volume fraction the specimen reinforced with steel fiber exceeds a specimen reinforced by glass fiber, polyolefin fiber, and polypropylene fiber by 38.46%, 15.10, and 36.15%, respectively, at 28 days of curing. The same trend was also reported within 7 days of curing. Thus, it is recommended to use steel fiber to obtain high strength. These results were confirmed by Zhang and Yu [60].

4.3.2. Splitting Tensile Strength

For the tensile splitting test, Figure 10 shows the results of specimens reinforced with different fiber types. The corrugated steel fiber specimen exhibits the highest splitting tensile strength with an excess of 72.34%, 80%, and 95.65% compared with specimens reinforced with glass fiber, polyolefin fiber, and polypropylene fiber, respectively, at a 2% fiber volume fraction.

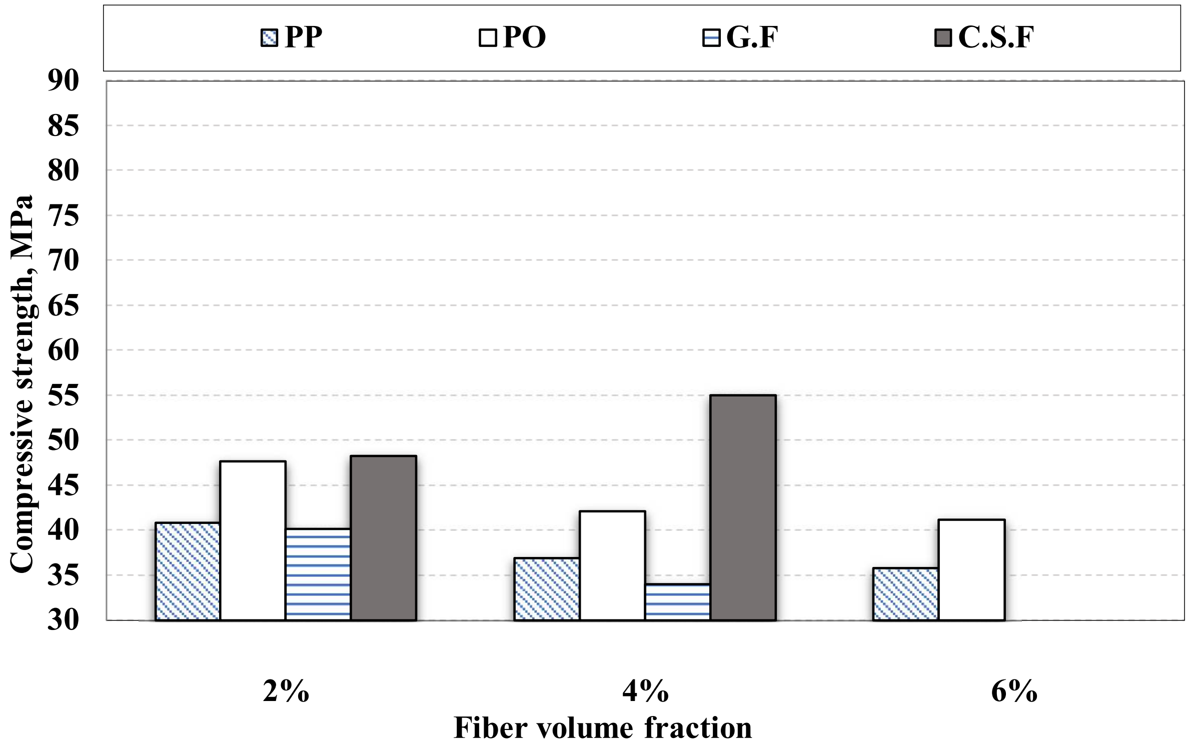


Figure 8. Compressive strength at 7 days due to fiber type change.

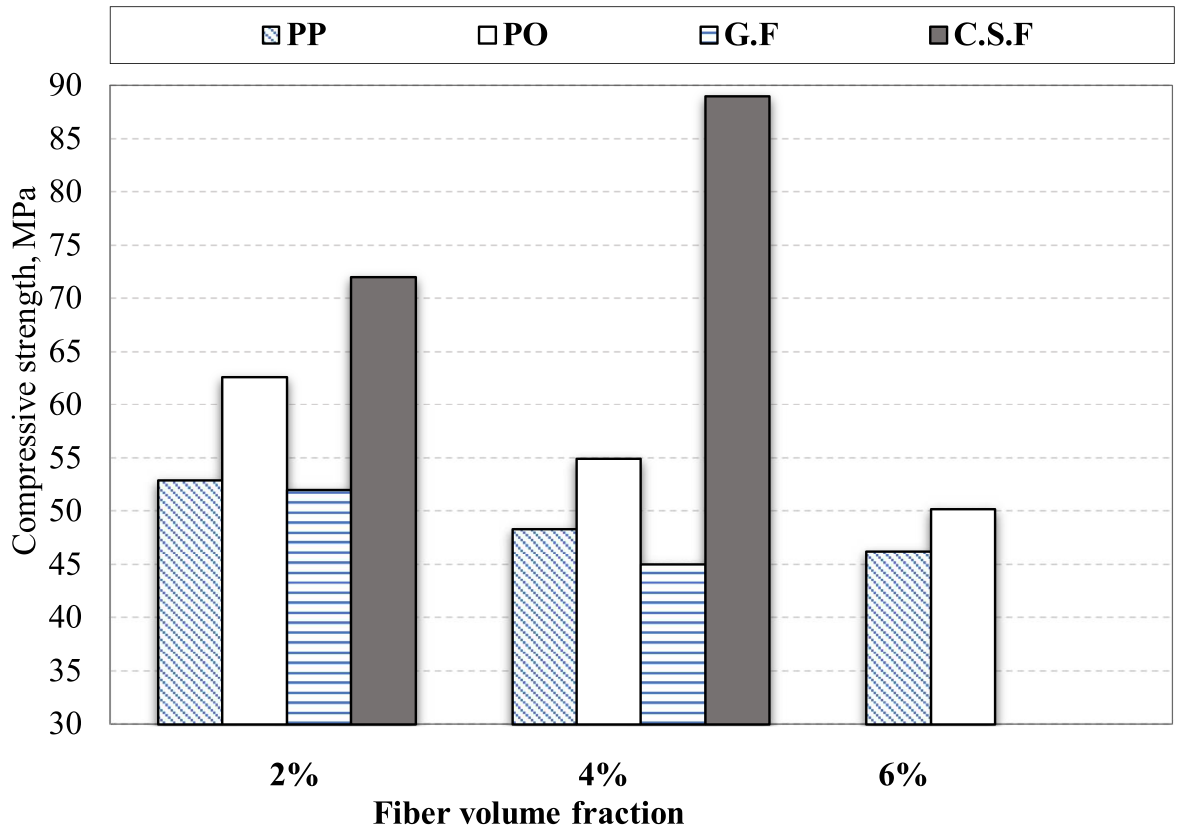


Figure 9. Compressive strength at 28 days due to fiber type change.

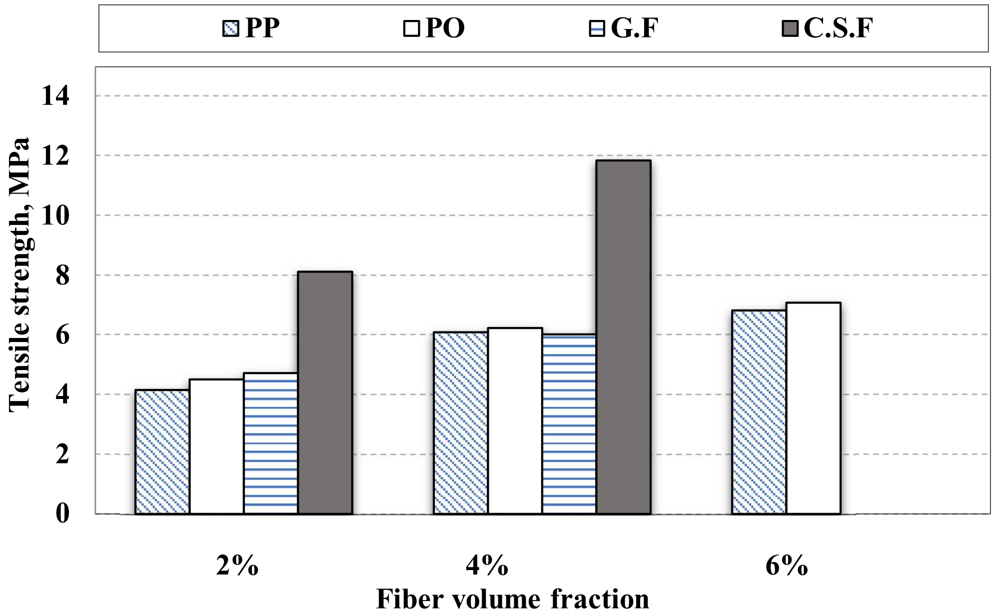


Figure 10. Splitting tensile strength at 28 days due to fiber type change.

4.3.3. Flexural Strength

The flexural strength results for ECC beams reinforced with different fibers are obtained at 7 and 28 days as illustrated in Figures 11 and 12. Corrugated steel fiber specimens recorded the maximum flexural strength with a difference of 37.33%, 69.16%, and 80.70% compared with specimens reinforced with glass fiber, polyolefin fiber, and polypropylene fiber.

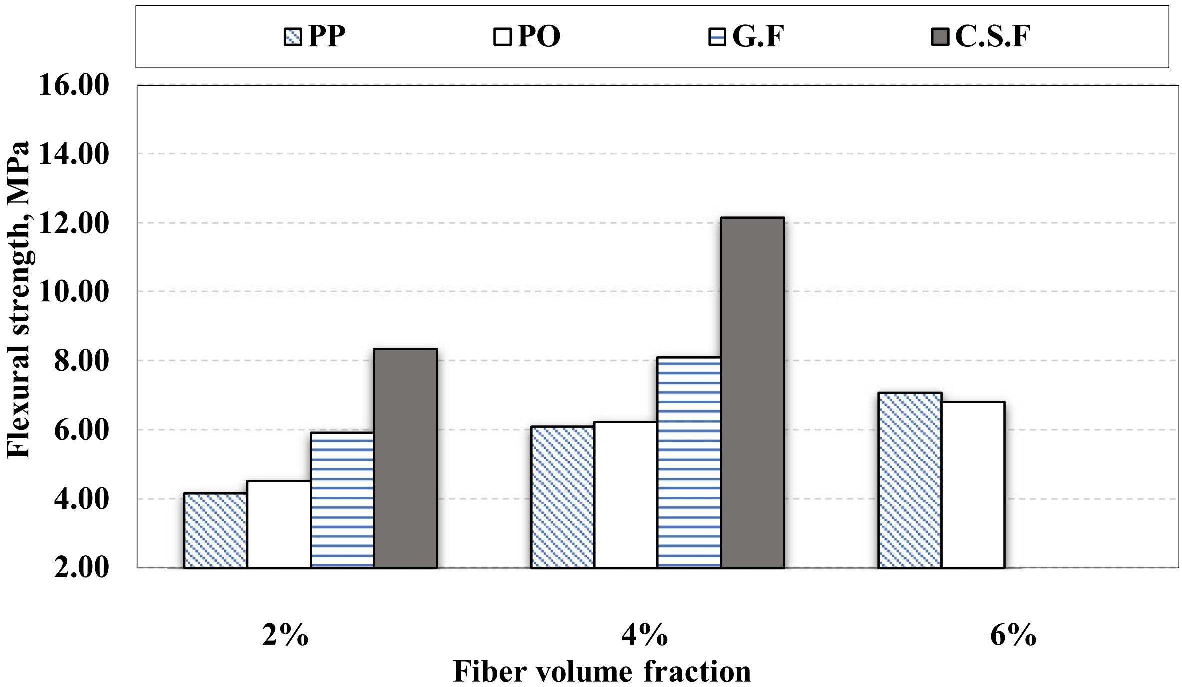


Figure 11. Flexural strength at 7 days due to fiber type change.

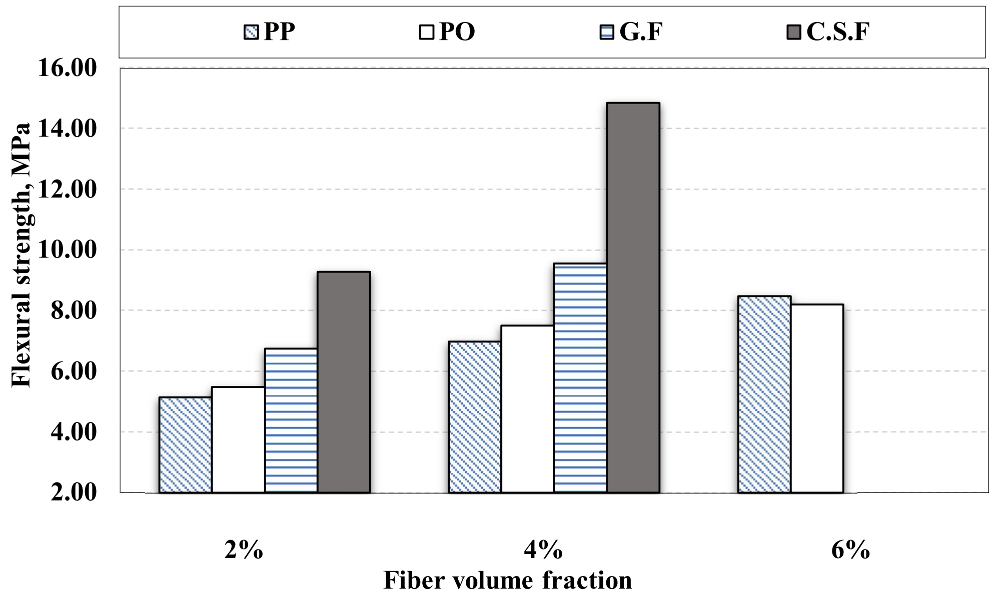


Figure 12. Flexural strength at 28 days due to fiber type change.

4.4. Effect of Fiber Hybridization

In the following section, the effect of fiber hybridization on mixture mechanical properties (compressive strength, splitting tensile strength, and flexural strength) is investigated.

4.4.1. Compressive Strength

Figures 13 and 14 exhibit the achievement in compressive strength that occurred in both curing ages resulting from fiber hybridization.

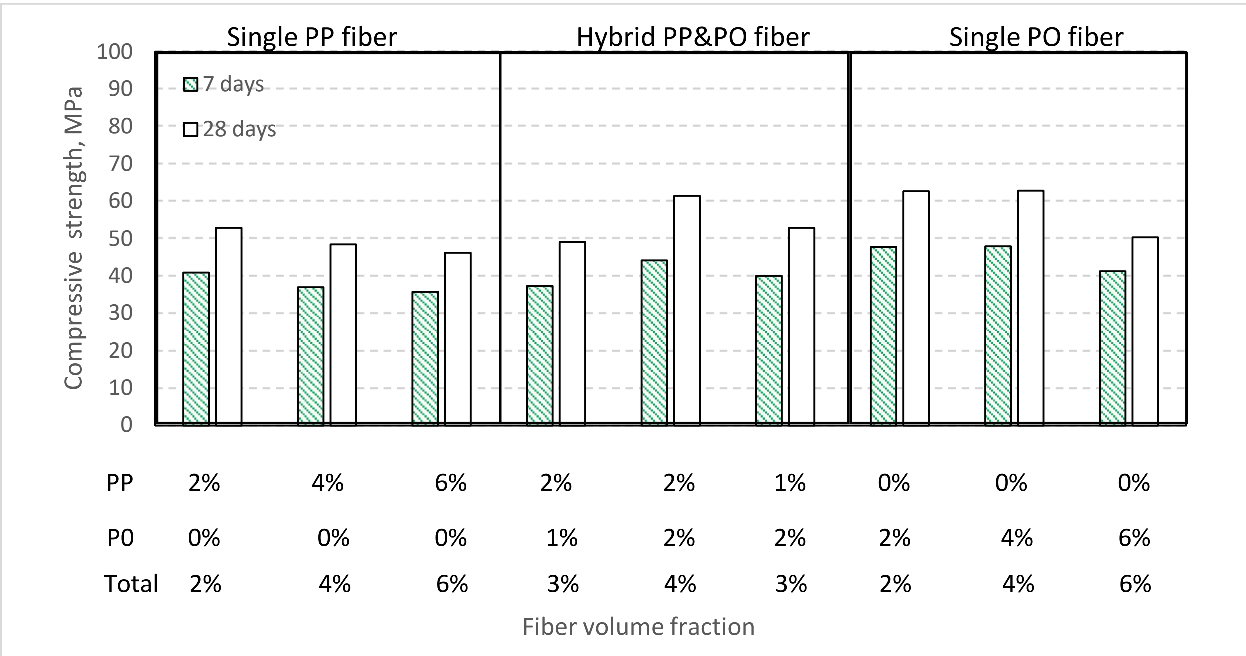


Figure 13. Effect of lightweight fiber hybridization on 7 and 28-day concrete compressive strength.

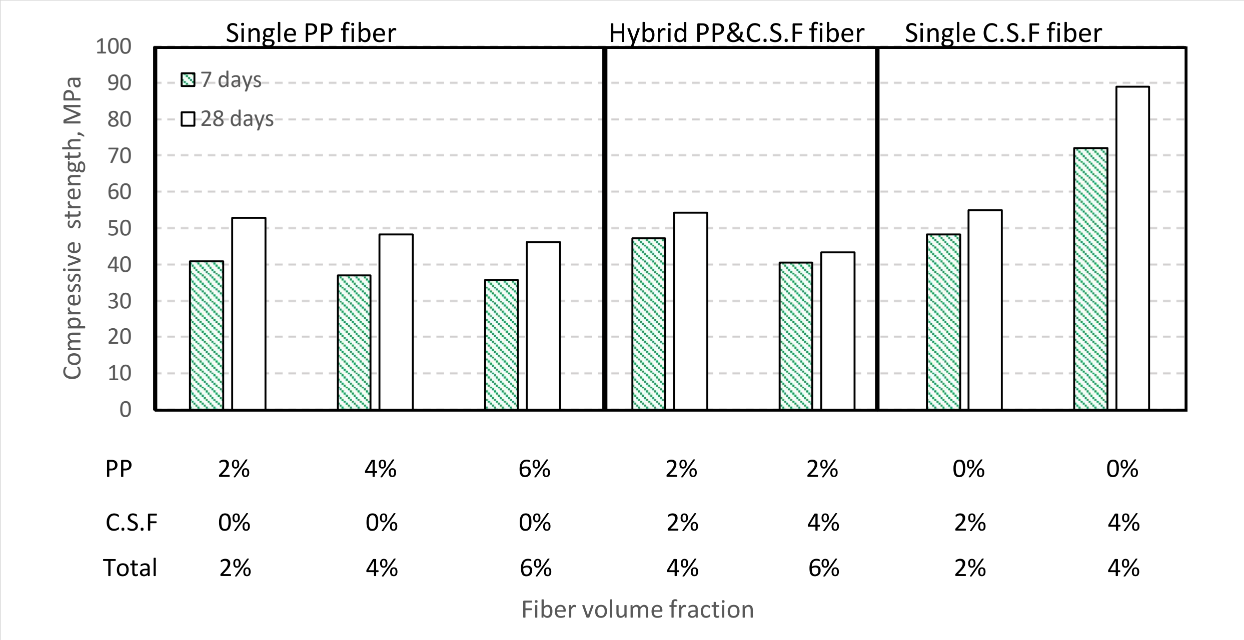


Figure 14. Effect of lightweight and heavyweight fiber hybridization on 7 and 28-day concrete compressive strength.

The compressive strength of the mixture reinforced with PP 2%-PO 0% decreased by 40.83 to 37.2 MPa in the case of the addition of PO fibers by 1%. In contrast, when adding PO at the same dosage the compressive strength of the mixture reinforced by PP 2%-PO 0% increased from 40.83 to 47.2 MPa by 15.92%. While comparing the specimen reinforced by single fiber polypropylene 4% with the specimen with hybrid fibers in lower or the same dosage the compressive strength increased.

The addition of lightweight fiber, such as polypropylene to heavyweight fiber, such as steel fiber, has an adverse effect on compressive strength compared to single heavyweight fiber as shown in Figure 14.

4.4.2. Splitting Tensile Strength

Figures 15 and 16 represent the effect of fiber hybridization on 28-day concrete tensile strength. From these figures, hybridization has an effective role in enhancing tensile strength. Hybridization with 2% polypropylene fiber with 1% polyolefin fiber enhanced the tensile strength by 69.08% compared with the specimen reinforced with 2% polypropylene fiber. The addition of 2% polyolefin fiber enhanced the tensile strength by 88.40%, which is higher than the enhancement that occurred in the first case by 2.79%. Adding 1% PO fiber with 2% PP fiber yields higher tensile strength than all PP single fiber mixtures with different fiber volume fractions.

If 4% PP fiber volume fraction is compared with a hybrid mixture reinforced with a total fiber volume fraction of 3% or 4%, it can be concluded that it exhibits lower tensile strength. The previous results proved that hybridization of PP with PO fiber exhibits a favorable effect.

The addition of lightweight fiber to heavyweight fiber improves the flexural strength for both curing ages as shown in Figure 16. For example, at 28 days of curing, addition of 2% polypropylene to a specimen with 2% steel fiber enhanced the tensile strength by 25.80%.

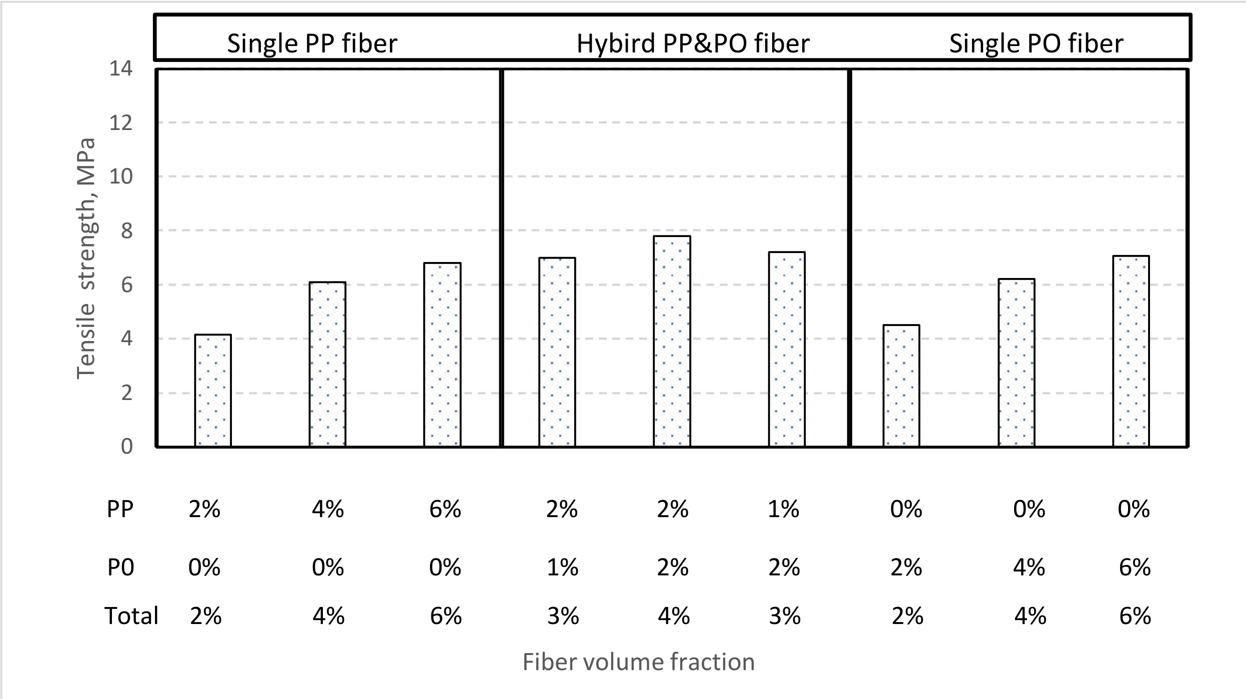


Figure 15. Effect of lightweight fiber hybridization on 28-day concrete tensile strength.

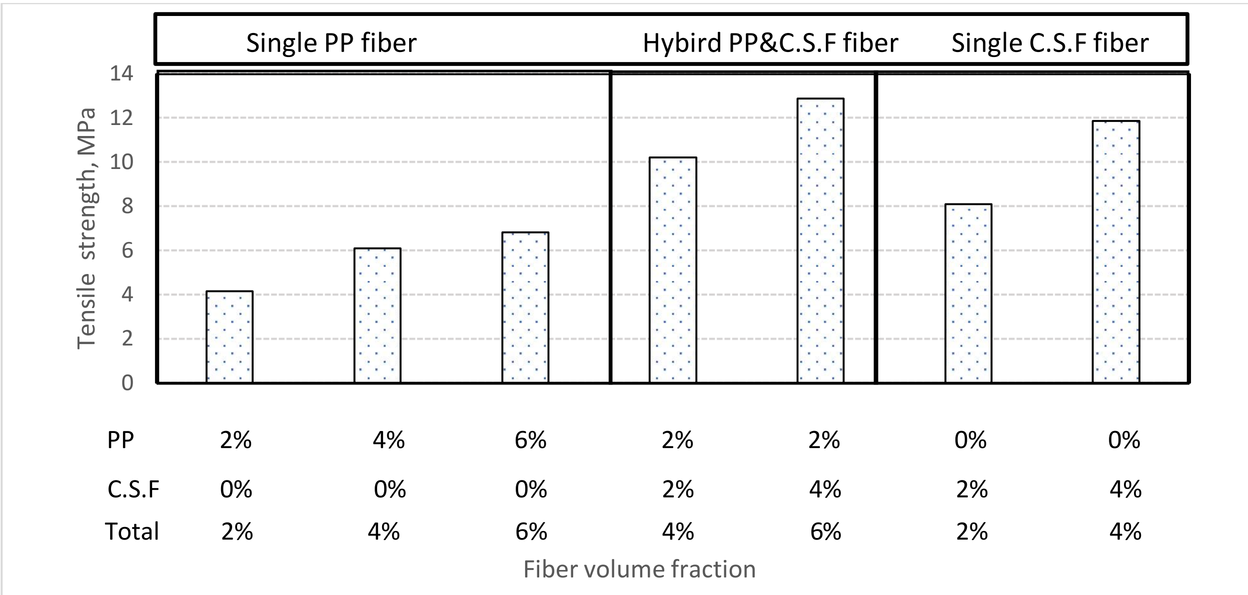


Figure 16. Effect of lightweight with heavyweight fiber hybridization on 28-day concrete tensile strength.

4.4.3. Flexural Strength

Figures 17 and 18 show the effect of fiber hybridization on flexural strength within 7 and 28-day curing ages. Flexural strength was enhanced by 75.72% and 61.59% due to the addition of 1% polyolefin fiber with 2% polypropylene fiber compared with specimen reinforced with 2% polypropylene fiber for both curing ages. While the addition of 2% polyolefin enhanced the flexural strength by 95.43% and 89.47% on 7 and 28-days curing ages, The addition of 1% polyolefin fiber with polypropylene fiber yields higher flexural strength than all PP single fiber mixtures with different fiber volume fractions.

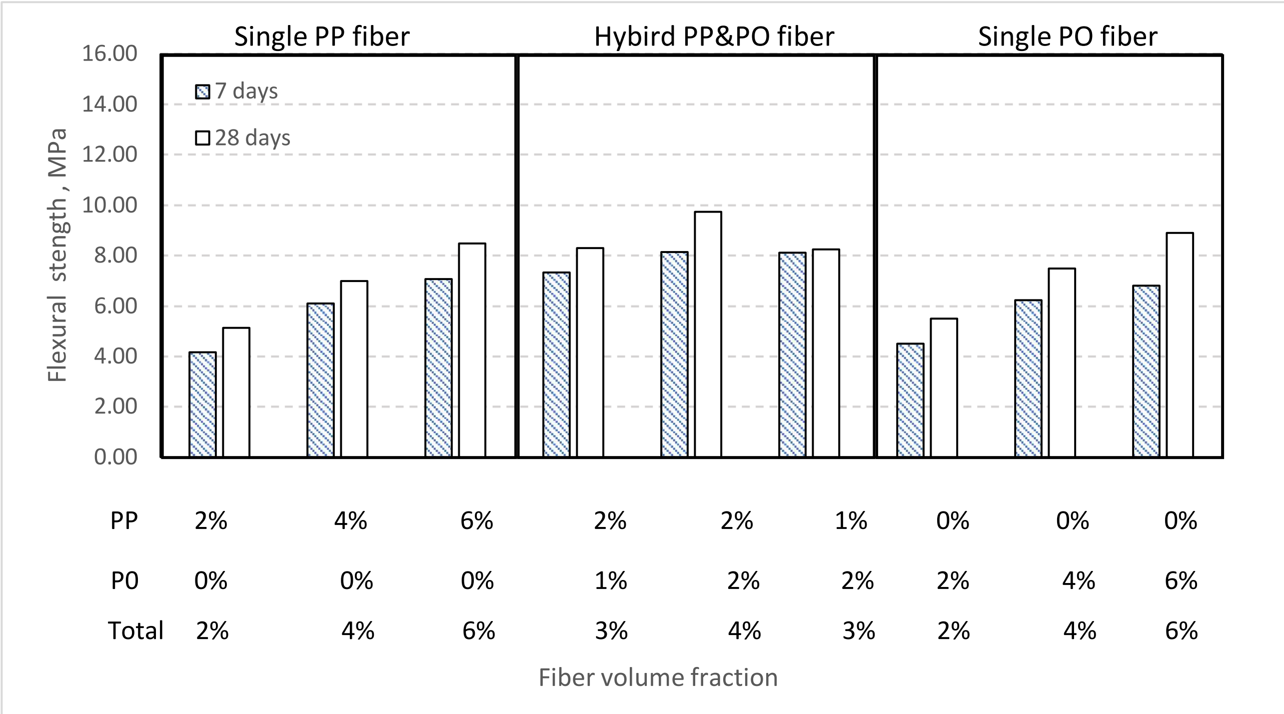


Figure 17. Effect of lightweight fiber hybridization on 7 and 28-day concrete flexural strength.

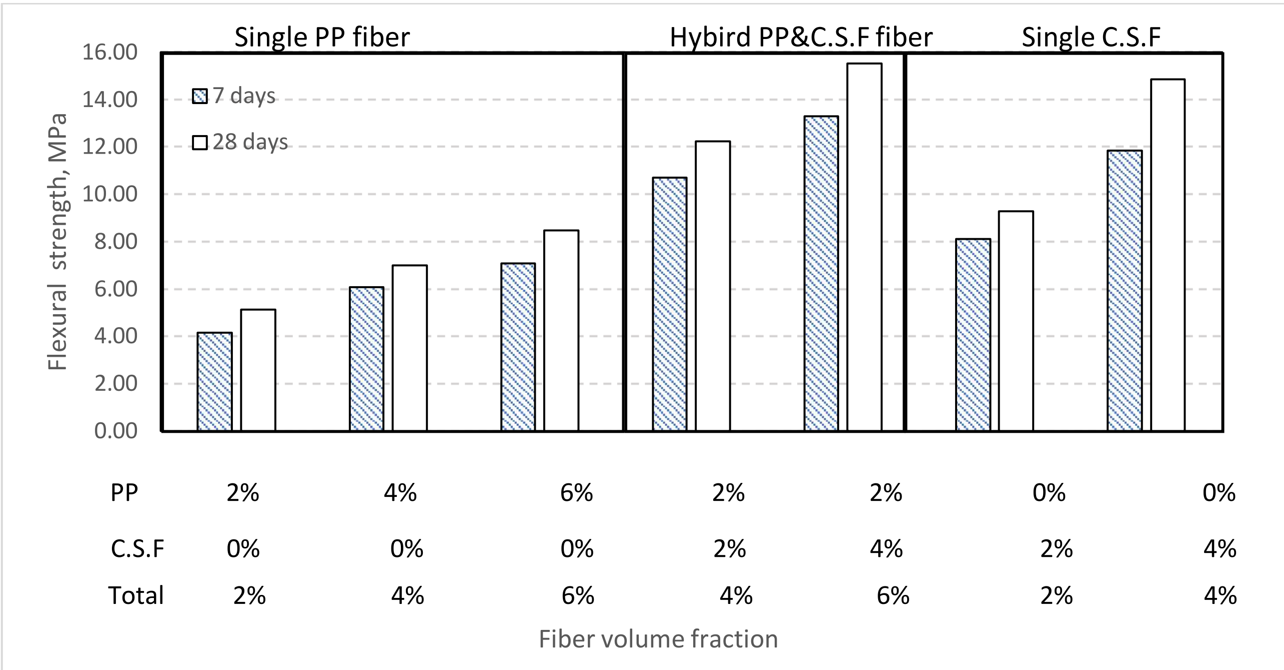


Figure 18. Effect of lightweight with heavyweight fiber hybridization on 7 and 28-day concrete flexural strength.

A hybrid mixture with a total volume fraction of 3% or 4% exhibits higher flexural strength compared with a specimen reinforced with single PP fiber at 4% and a 6% volume fraction which proves hybridization effectiveness.

A hybrid mixture with polyolefin 2% and polypropylene 1% exhibits higher flexural strength compared with polyolefin single fiber reinforcement up to 6% fiber volume fraction.

The addition of lightweight fiber to heavyweight fiber improves the flexural strength for both curing ages as shown in Figure 18. For example, in 28 days of curing, addition of polypropylene by 2% to a specimen with 2% steel fiber enhanced the flexural strength by 31.93%.

4.5. Relationships

4.5.1. Relationship between Tensile Strength and Compressive Strength

Experimental results of compressive strength, tensile strength, and flexural strength at 28 days of water curing are presented in Table 6. Tensile strength versus compressive strength at 28 days for different types and volume fractions of fiber is plotted in Figure 19. From this figure, the tensile strength value ranges from 7.5% to 15% for compressive strength depending on the type of fiber and fiber volume fraction. Furthermore, the increase in volume fraction increases the tensile strength/compressive strength percentage.

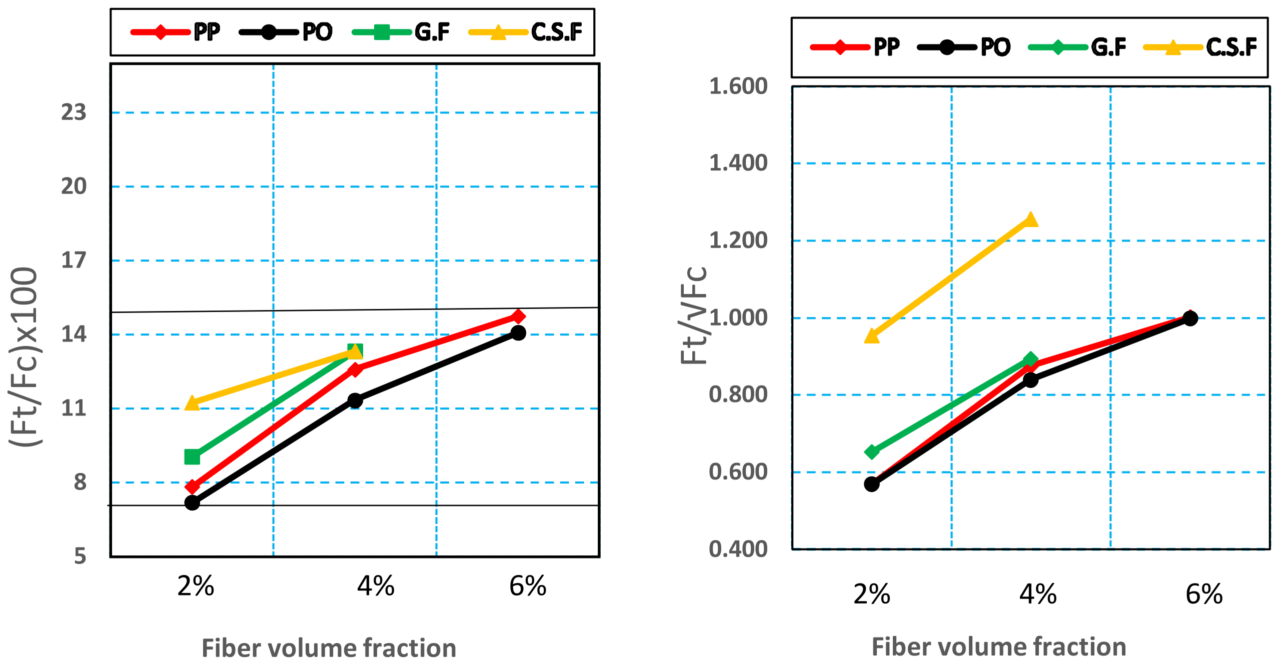


Figure 19. Relationship between tensile strength and compressive strength of FRC and ECC specimen.

The general relationship between compressive strength and tensile strength can be expressed as:

$$F_t = \alpha\sqrt{F_C}$$

where F_t is the tensile strength in MPa, α is the factor depending on fiber type and fiber volume fraction, and F_C is the compressive strength in MPa and equal to (F_t/F_C). This formula is suggested because most of the international codes give the value of tensile strength as a function of root compressive strength.

From this figure, the ratio between tensile strength and root compressive strength (α) ranges from 0.60 to 1.25 depending on fiber volume fraction and fiber. α values are plotted in Table 7. The above equations were tested using an external data set, which demonstrated an excellent predictive ability of the equations with minimum relative errors around (1.60:10.71)%, as shown in Table 8. The predicted values of the tensile strength using the proposed equation were also verified by using the absolute fraction of variance (R^2) which yields a value of 0.90, as shown in Figure 20.

Table 7. Values of α factor from the experimental test results.

		Fiber Type			
		PP	**PO**	**G.F**	**C.S.F**
Fiber volume fraction	2%	0.569	0.569	0.652	0.955
	4%	0.875	0.840	0.894	1.256
	6%	1.002	0.998		

Table 8. Verification of proposed α values using external data set.

Fiber	Compressive Strength (MPa)	Tensile Strength (MPa)	Predicted Tensile Strength Using α (MPa)	Error (%)	Ref.
PP 2%	48.64	4.45	4.00	11.25	[65]
	29.00	3.18	3.06	3.78	[66]
	36.00	3.32	3.414	2.83	
PO 2%	39.29	4.48	4.96	10.71	[67]
PO 4%	120	8.32	9.20	10.75	[68]
G.F 2%	62.00	6.32	5.13	1.60	[69]
C.S.F 2%	48.90	6.92	6.67	3.75	[55]

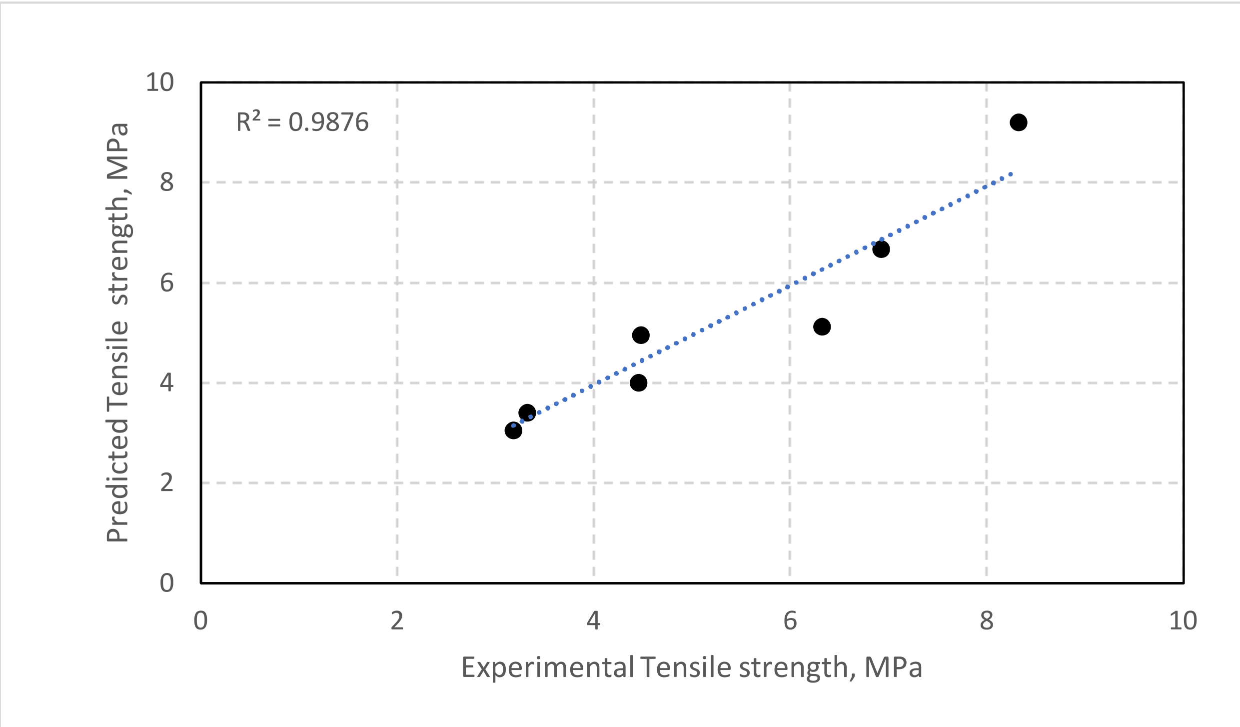


Figure 20. Comparison of predicted splitting tensile strength to experimental tensile strength.

4.5.2. Relationship between Flexural Strength and Compressive Strength

The relationship between compressive strength and flexural strength is represented using the following regression equation depending on specimen mechanical properties and plotted in Table 6

$$FS = \beta \sqrt{F_c}$$

where FS is the flexural strength in MPa, F_C is the compressive strength in MPa, and β is the factor depending on fiber type and fiber volume fraction and is equal to (F_t/F_C). Specimen flexural strength is plotted versus compressive strength for different types and fiber volume fractions in Figure 21. From this figure, the flexural strength/compressive strength ratio ranges from 9% to 22% depending on the type of fiber and fiber volume fraction. Furthermore, for the same fiber type, the increase of volume fraction increases the flexural strength/compressive strength percentage.

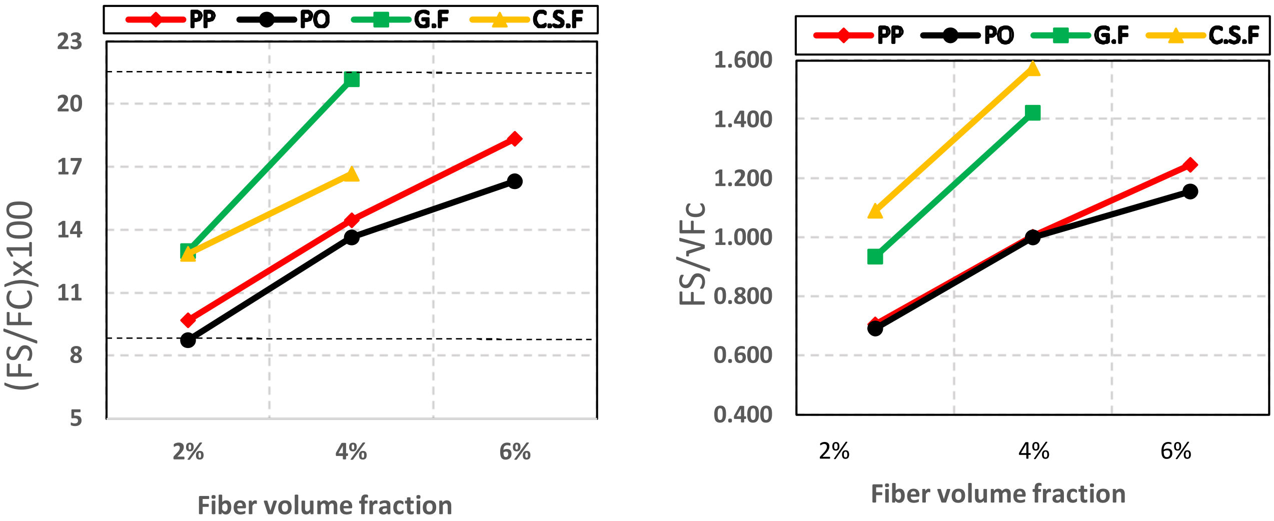


Figure 21. Relationship between flexural strength and compressive strength of FRC and ECC specimens.

Furthermore, from Figure 21, the ratio between flexural strength and root compressive strength (β) ranges from 0.75 to 1.57 depending on fiber volume fraction and fiber. β values are plotted in Table 9. The relationship between compressive strength and flexural strength is verified using an external data set, which demonstrated an excellent predictive ability of the equations with minimum relative errors, around (0.48:15.55)%, as shown in Table 10. This finding was also verified by using the absolute fraction of variance (R^2) which yields a value of 0.96, as shown in Figure 22.

Table 9. Values of β factors from the experimental test results.

		Fiber Type			
		PP	**PO**	**G. F**	**C.S.F**
Fiber volume fraction	2%	0.705	0.69	0.94	1.09
	4%	1.004	1.01	1.42	1.57
	6%	1.250	1.16		

Table 10. Verification of proposed β values using an external data set.

Fiber	Compressive Strength (MPa)	Flexural Strength (MPa)	Predicted Flexural Strength (MPa)	Error (%)	Ref.
PP2%	44.59	4.48	4.74	5.80	[70]
	33.90	4.26	4.10	3.90	[67]
PP 4%	39.60	7.00	6.90	1.40	[67]
PO 2%	42.60	5.20	4.50	15.55	[67]
G.F 2%	53.70	6.98	6.90	1.15	[71]
	60.00	6.70	7.28	8.65	[69]
	123	10.35	10.4	0.48	[72]

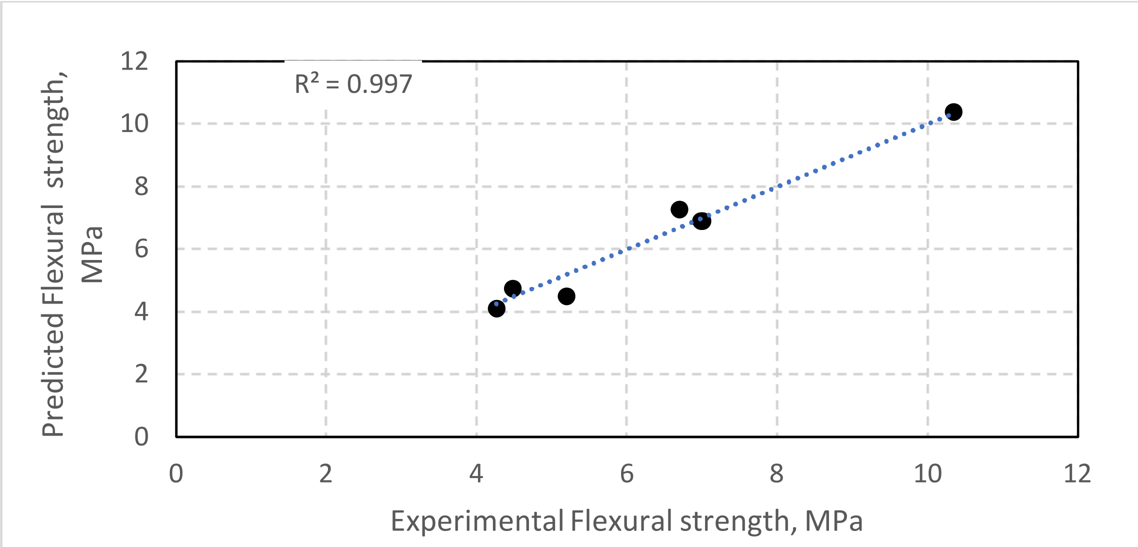


Figure 22. Comparison of predicted flexural strength to experimental flexural strength.

5. Conclusions

This paper experimentally investigated the possibility of processing ECC with another type of fiber instead of PVA. Furthermore, the influences of curing, fiber volume fraction, fiber type, and fiber hybridization on the mechanical properties of fiber reinforced mixtures were investigated. The main conclusions based on the experimental and test results are the following:

- Based on multiple cracking, which is a unique behavior characterizing ECC from FRC, ECC was observed for specimens reinforced with 4% and 6% single lightweight fiber (polypropylene and polyolefin) due to created tensile behavior at the crack location. ECC could not be achieved with heavyweight fiber (steel fiber).
- Hybridization of lightweight fiber achieved multiple cracking patterns in a total volume fraction of 3%, which is less than a single fiber reinforcement specimen. Hybridization of heavyweight fiber with lightweight fiber does not achieve multiple cracking.
- Increasing lightweight fiber volume fraction decreased the specimen compressive strength but the increase of heavyweight fiber improves the compressive strength. For tensile and flexural strength, increasing both fiber types improved their values.
- Fiber hybridization is not effective for compressive strength while using lightweight fiber hybridization but in the case of hybridization of lightweight fiber with heavyweight fiber it improves the compressive strength.
- For tensile and flexural strength, fiber hybridization is effective. At 3% hybrid lightweight reinforcing, the specimen shows tensile strength higher than all single fiber reinforcements. In the case of flexural strength, 4% hybrid lightweight reinforced specimens possess higher flexural strength than all lightweight single fiber specimens. Hybridization of a heavyweight at 3% total volume fraction possesses higher tensile and flexural strength compared with 6% single polypropylene fiber by 49.60%, and 44.22%, respectively.
- Relationships between tensile strength and flexural strength depending on the compressive strength of ECC were determined. Relationships were verified using other data sets. This demonstrated the excellent predictive ability of the equations with minimum relative errors around (0.48:15.55)% for tensile strength and (1.60:11.25)% for flexural strength. Thus, tensile strength and flexural strength could be predicted using compressive strength values.

- The statistical data tool's absolute fraction of variance (R^2) was performed for external data sets to confirm the proposed equation accuracy. The absolute fraction of variance (R^2) for experimental tensile strength and predicted tensile strength was 0.91. R^2 equals 0.96 for predicted flexural strength compared with experimental flexural strength.

6. Recommendations

It is recommended to use ECC in footings and seismic zones due its ductile behavior.

7. Future Work

Applying the processed materials in repairing deteriorated structures and comparing them with traditional repairing schemes due its ductile performance.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

ECC	Engineered cementitious composite
FRC	Fiber-reinforced concrete
PVA	Polyvinyl alcohol
OPC	Ordinary Portland cement
SCMs	Supplementary cementitious materials
HPC	High-performance concrete
FA	Fly ash
GGBS	Ground granulated blast-furnace slag
SF	Silica fume
HPFRC	High-performance fiber-reinforced concrete
C.S.F	Corrugated steel fiber
T.S.F	Twisted steel fiber
H.S.F	Hooked steel fiber
PP	Polypropylene fiber
PE	Polyethylene
G.F	Glass fiber
PO	Polyolefin fiber
C.S	Compressive strength

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