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Review

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A Review on Failure Modes and Cracking Behaviors of Polypropylene Fibers Reinforced Concrete

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Abstract: Despite being strong under compression, concrete is rather weak when subjected to tensile stress. Concrete has been reinforced with a variety of materials over time in order to resist tensile stresses. Among various types of fibers, polypropylene fiber, which is available in a range of sizes, is being used to strengthen concrete. The fiber also increases the concrete's toughness, durability, and low permeability. Polypropylene fibers may be utilized in place of conventional reinforcement, according to a number of researchers. The aim of this study is to collect information from already carried out research on polypropylene fibers. Important characteristics of concrete, such as workability, compressive, tensile, and flexural strength, are reviewed. The review also explores cracking behavior and failure modes of polypropylene fiber reinforced concrete. Furthermore, durability aspects, such as water absorption, porosity, dry shrinkage, and microstructure study (scan electronic microscopy), were also reviewed. Results indicate that polypropylene fiber improved the mechanical strength and durability of concrete (particularly tensile capacity) but decreased the flowability of concrete. The optimum dose is important, as a higher dose adversely affects strength and durability due to a lack of flowability. Scanning electronic microscopy results indicate that the polypropylene fibers restrict the propagation of cracks, which improves the strength and durability of concrete. The review also indicates that shrinkage cracks are considerably reduced with the addition of polypropylene fibers. Finally, the review also provides future research guidelines for upcoming generations to further improve the performance of polypropylene fibers that reinforce concrete.

Keywords: fiber reinforced concrete; polypropylene fibers; compressive strength; failure modes and cracking behaviours

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1. Introduction

Although concrete is strong in compression, its tensile capacity is much lower [1–4]. Over time, concrete has been reinforced with a variety of compounds to help it resist tensile stress [5–7]. One such fiber that comes in a variety of diameters and is currently used to strengthen concrete is polypropylene fiber [8,9]. The fiber also increases the toughness, increases the durability, and decreases the permeability of the concrete [10,11]. Polypropylene fibers may be employed as reinforcement instead of conventional materials, according to several researchers [12–14].

Building expenses may be decreased overall if fibers are used in lieu of more conventional and energy-intensive techniques such as steel reinforcing bars and wire mesh [15]. As a consequence, labor expenses, maintenance costs, the amount of time needed to complete the project, and the build cost will all decrease. Energy will be conserved, as well, since the quantity of fiber utilized is often far lower than the volume of raw materials required to produce traditional reinforcement [16].

The use of fiber-reinforced concrete in building structures has improved because the fibers improve the concrete's toughness, flexural and tensile capacity, impact strength, and failure mode [17–20]. Furthermore, it is widely known that the elastic modulus and compressive capacity are not significantly influenced by the inclusion of fibers [21]. The research, however, demonstrated that uneven fiber insertion would impact the flowability and regularity of concrete blending and even lead to fiber bonding, which ultimately affects the reinforcing impact of strength characteristics [22–24]. Fiber addition to concrete decreases its workability depending on various factors, including the maximum aggregate size, fiber volume, type, shape, and aspect ratio.

One of the most important reasons for using fiber-reinforced concrete is to increase the elasticity and tensile capacity of concrete. Fibrous components may increase the structural stability of concrete. According to earlier research, steel, nylon, and polypropylene fibers may all be utilized to boost reinforced concrete's shear and tensile strength [25]. Concrete's mechanical performance may be enhanced by adding polypropylene without increasing its density [26]. Additionally, it has been noted that the technical characteristics of concrete, particularly tensile capacity, are marginally improved by nylon and propylene [27]. According to reports, polypropylene fibers significantly enhance the properties of concrete [28].

Concrete is a material that is regarded as being quite brittle. With increased strength comes increased brittleness. This may be caused by a lack of bonding and poor tensile strength in the cement matrix's transition zone, which prohibits the use of high-strength concrete under static and, particularly, dynamic loading [29]. Therefore, ductility augmentation must be taken into account as a vital problem in concrete science. One method for increasing the ductility and resilience of concrete structures is possible [30,31], owing to the addition of fibers to concrete, which provides a defense against dynamic loads caused by impact, fatigue, and earthquakes. Concrete's ability to absorb energy is increased by adding fibers, which also makes the structure more ductile. The primary materials for the fibers are steel, carbon, or polymer [32]. Researchers have focused the most on polypropylene among the polymer fibers because of its cheap cost, exceptional toughness, and improved shrinkage cracks [33,34].

As shown in Figure 1, polypropylene fiber is a kind of linear synthetic fiber made from propylene polymerization and is typically white in color. Its benefits are its low weight, high toughness, and resistance to corrosion. Chemical manufacturing, energy, apparel, ecological safety, and building all employ polypropylene fiber extensively [35,36]. Concrete's disadvantages in the construction sector include its less tensile capacity, poor bending resistance, and inadequate fracture resistance. The ease with which microcracks may be formed from the outside to the inside causes the concrete to become more porous. Concrete's interior is readily penetrated by water or other damaging ions, which hastens the concrete's degeneration [37]. Concrete may generate a three-dimensional random distribution network structure when polypropylene fiber is introduced, which successfully prevents the formation of microcracks [38].

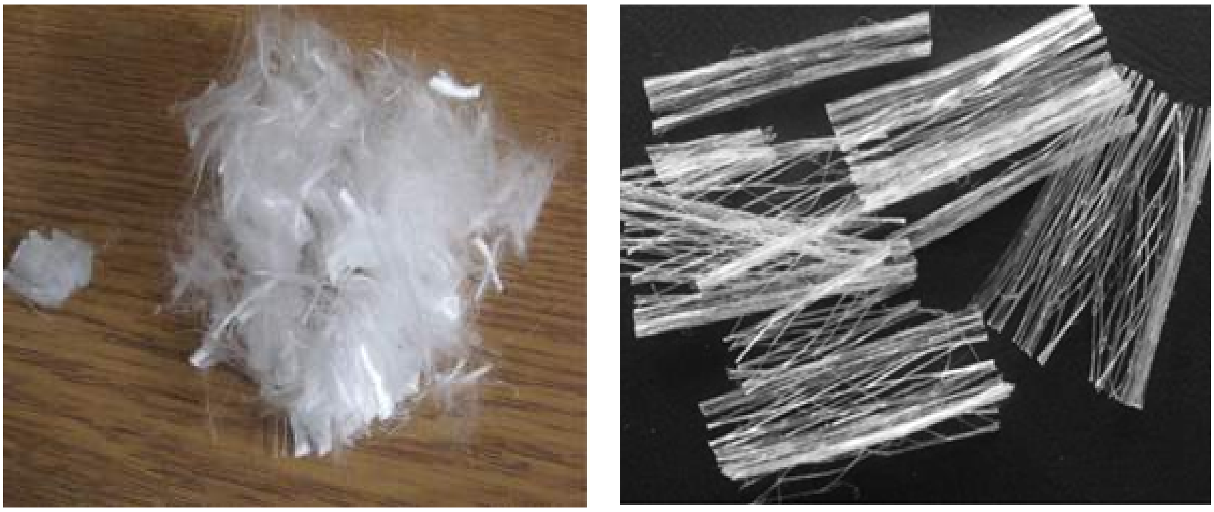


Figure 1. Polypropylene fiber [39,40].

It is commonly known that fibers of any type make concrete difficult to flow. Concrete's lower flowability is influenced by a number of fiber-related issues. Researchers revealed that polypropylene fibers used in concrete had a variety of qualities. Table 1 below catalogs the various properties of polypropylene fibers used as reinforcement in concrete. We may infer that the tensile capacity and elastic modulus of polypropylene fibers, respectively, are 300–700 MPa and around 3.0 GPa. Polypropylene fibers typically vary in length from 6 to 50 mm. One typical finding is that, according to ACI 544.5R-10, tiny fibers are more effective than thick fibers at minimizing the breadth of plastic shrinkage fractures [41].

Table 1. Properties Polypropylene Fiber.

References	[42]	[43]	[44]	[45]	[14]
Specific gravity	0.91	1.33	-	-	-
Density (gm nominal)	-	-	0.91	0.91	0.92
Tensile Strength MPa	300–700	308	-	365–600	310
Elastic Modulus MPa	3000–30,000	-	-	-	-
Length (mm)	35	6.20	6	12	50

The use of fiber-reinforced composites may be influenced by the kind, length, diameter, and quantity of used fiber. Usually, significant fiber percentages are necessary for composites to function properly and have good performance. The optimal fiber content is crucial for better concrete performance, since a larger dosage of fibers reduces concrete's flowability, which has a detrimental influence on the material's strength qualities. Since polypropylene fibers are less expensive than steel fibers, several investigations are concentrating on them. Steel fibers are pricy, prone to corrosion, and susceptible to heat expansion.

Many researchers are focused on polypropylene fibers in concrete and have reported a positive influence on concrete properties. However, a compressive review is required to collect all relevant information on polypropylene fibers used in concrete to further improve the performance of polypropylene fibers in reinforced concrete. Important properties of concrete, such as flowability, compressive, tensile, and flexural capacity, are reviewed. Additionally, the paper investigates the cracking patterns and failure mechanisms of polypropylene fiber reinforced concrete. Furthermore, most studies focus on strength properties while less studies consider microstructure structure analysis and durability properties of polypropylene fibers reinforced concrete, such as water absorption, porosity, and dry shrinkage. Results show that polypropylene fiber increased concrete's mechanical strength and durability, particularly its tensile capacity, but lowered its flowability. Results from scanning electronic microscopy show that polypropylene restricts the prevention of cracks. Finally, the assessment offers suggestions for future research that will help future generations to enhance the performance of concrete reinforced with polypropylene fibers.

2. Workability

According to ACI 116, workability refers to how easily concrete may be mixed, laid, compacted, and completed [46]. The strength of concrete often relies on how easily it can be shaped. Poor concrete workability makes it harder to compress the material, which causes more voids in the hardened concrete. The increase in voids lowers the density of the concrete, resulting in lower compressive strength.

Any kind of fiber generally made concrete less able to flow. Similar patterns may be detected, as seen in Figure 2 and Table 2. According to research, adding polypropylene fiber to concrete increased the harshness and decreased the workability of the mixture [47]. When the proportions of polypropylene fibers were enhanced, the slump value of the concrete mixture decreased. When polypropylene fibers were added at concentrations of 300, 600, 900, 1200, and 1500 g/m^3, the flow was reduced by 25.9, 39.7, 48.3, 56.9, and 65.5 percent, respectively, in comparison to the control concrete [48]. The slump cone of ordinary concrete supplemented with polypropylene fibers derived from plastic packaging with the same contents practically decreased by the same amount [49]. Another study found a similar relationship between decreased workability and an increase in fiber content [50]. According to research, combining steel with polypropylene enhanced the concrete compressive capacity and flexibility [51]. The research discovered that the combination of steel and polypropylene enhanced the compressive capacity and elastic modulus [44]. Fiber's addition causes concrete mixes to become less fluid, which may be the cause of the increase in fiber surface area. Additionally, the fiber increased the frictional resistance between the fiber and the concrete component, necessitating the use of extra cement paste to reduce internal conflict [1]. Although fibers in concrete have several advantages, they make newly mixed concrete less workable [52,53].

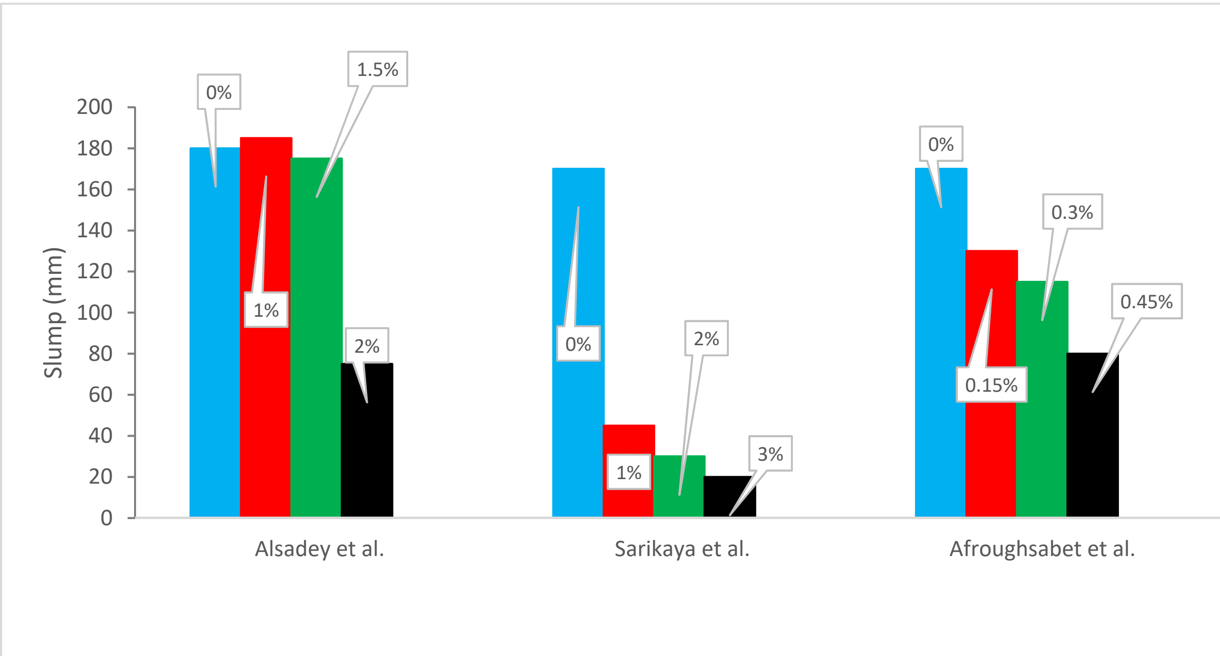


Figure 2. Slump Flow: Alsadey et al. [44], Sarikaya et al. [54] and Afroughsabet et al. [39].

Table 2. Slump Flow of Concrete with addition Polypropylene Fibers.

Ref.	Polypropylene Fibers (%)	Length (mm)	Slump (mm)	Remarks
[44]	0, 1.0, 1.5 and 2.0	6	180, 185, 175 and 75	Decreased
[48]	0, 0.0625, 0.1250, 0.1875, 0.2500 and 0.3125	12	58, 43, 35, 30, 25 and 20	Decreased
[39]	0, 0.15, 0.30 and 0.45	27.1 to 32.6	170, 130, 115 and 80	Decreased
[54]	0, 1, 2 and 3	-	170, 45, 30 and 20	Decreased
[55]	0, 0.2, 0.3 and 0.5	12	50, 60, 60 and 40	Improved up to 0.3% addition of fibers and then declined
[56]	0, 0.4, 0.8, 1.0 and 1.5	6 to 19	710, 700, 688 and 670	Decreased

Concrete's slump value is decreased with polypropylene fibers. For various volume fractions of polypropylene fibers, the slump value decreases from 13 percent to 60 percent [57]. For many years, numerous scholars have tried to improve the initial qualities of concrete. Concrete may be given a remarkable boost in terms of its new features, such as workability and flowability, by the use of a superplasticizer [58,59].

According to Song et al. [31], fibers with short lengths flow more easily than fibers with longer lengths. Limited-length fibers increase the surface area of the fiber cement paste, improving its ability to bond [26]. It is advisable to use a suitable superplasticizer that only affects workability when the fiber-cement ratio is higher. According to research, fine fibers are what make a mixture less workable, and for the optimum balance of qualities for both newly-poured concrete and hardened materials, tiny and medium fibers should be used together [60]. Even when fully compacted, concrete with a higher fiber-to-cement ratio has a tendency to void due to the ineffective bonding of the components [61].

3. Mechanical Strength

3.1. Compressive Strength

The compressive capacity of concrete reinforced with polypropylene fibers is displayed in Figure 3 and Table 3. A study reported that the addition polypropylene fibers by 1.5%, the compressive strength increased by 36% [62]. The findings of the fiber-reinforced specimens demonstrate that, as compared to concrete with no fibers, the compressive capacity was increased when fibers were used, regardless of their shape or volume proportion. Additionally, the findings show that a rise in the fiber volume percentage improved compressive strength. The fibers' capacity to prevent fracture extensions, lessen stress concentration at the tips of cracks, alter crack directions, and slowly break development rate may be used to explain this gain in compressive strength [63]. However, at greater doses, compressive strength was shown to be declining.

The increased amount and length of fibers in new concrete, as well as improper compaction during specimen casting, which led to the creation of air spaces, might all contribute to the decrease in compressive capacity at higher doses. According to research, fibers also boosted the compressive capacity of concrete up to a point before it decreased because it was too difficult to work with [12]. Even at a higher percentage, the concrete's compressive capacity is less than that of the control. The compressive strength is improved by the limitation (confinement) of the fiber across the sample. Lateral expansion brought on by compression and restrained by the fibers increases compressive strength. Due to their strength, the fibers can sustain strain and shear [64]. In contrast, polypropylene fibers had no statistically significant influence on the compressive strength of concrete [65].

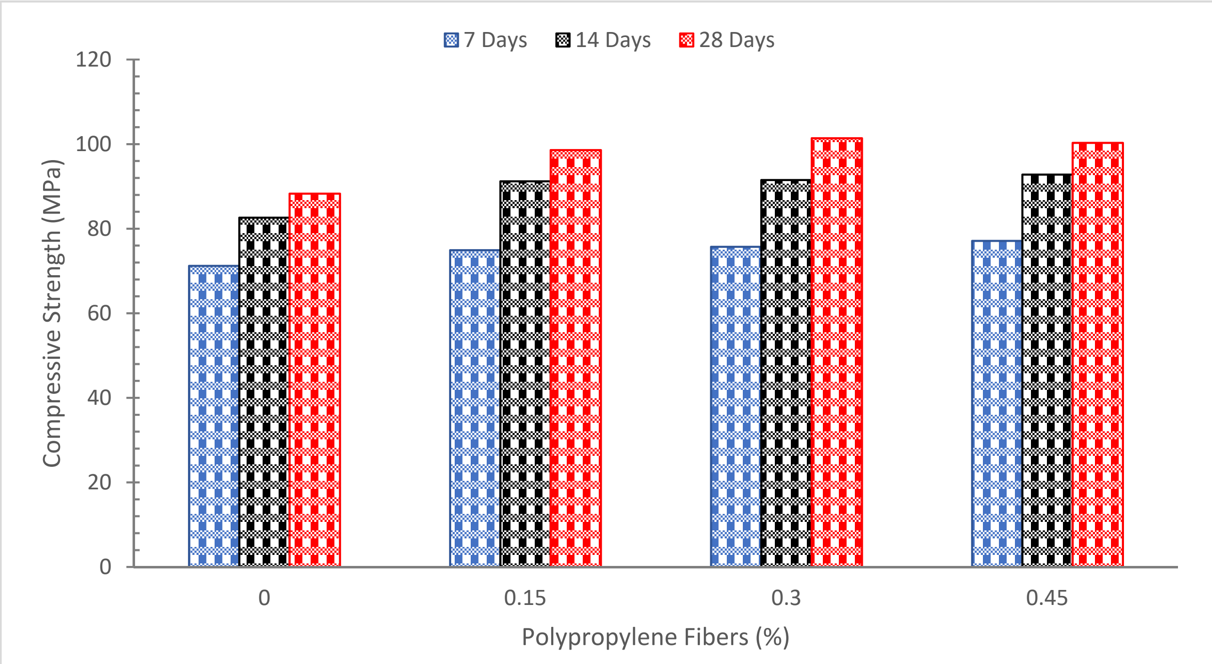


Figure 3. Compressive Strength of Concrete: Data Source [39].

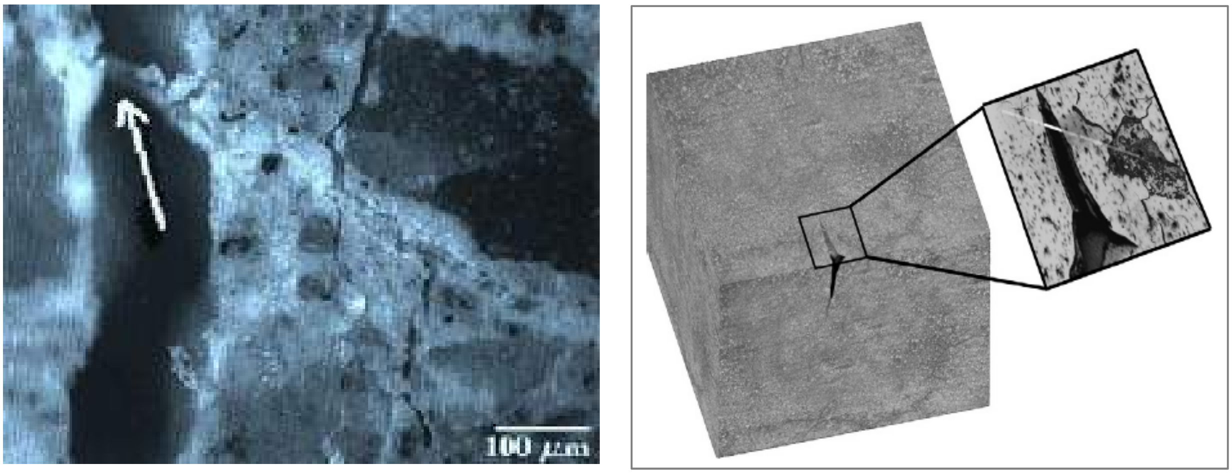
Table 3. Compressive Strength of Concrete with addition Polypropylene Fibers.

Ref.	Polypropylene Fibers	Diameter (mm)	Length (mm)	Compression Strength (MPa)
[66]	0, 0.5, 1.0, 1.5, 2.0, 2.5%, 3.0 and 3.5	0.04	6.2	28 Days 30.12, 31.26, 32.93, 34.18, 35.28, 36.86, 37.45 and 37.27
[67]	0, 0.5, 1.0, 1.5 and 2.0	-	12	7 Days 23.95, 29.93, 41.1, 45.9, 40.5 28 Days 33.7, 40.9, 30.80, 31.61 and 26.50
[68]	0, 0.25, 0.50, 0.75 and 1.0	-	12	7 Days 14.34, 15.44, 14,.92, 13.88 and 13.18 14 Days 15.95, 17.15, 16.50, 15.29 and 14.90 28 Days 17.32, 18.21, 17.88, 16.62 and 16.20
[42]	0, 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0	-	35	M25 28.0, 29.0, 31.5, 31.0, 30.0, 29.0 and 28.5 M30 36.7, 37.2, 38.5, 39.2, 36.6, 35.5 and 34.5
[43]	0, 0.5, 1.0, 1.5 and 2.0	0.0445	6.2	M30 25, 25, 22, 25 and 20 M40 20, 27, 24, 23 and 25
[44]	0, 1.0, 1.5 and 2.0	0.018	6	25.0, 26.0, 26.0 and 28.0

Table 3. *Cont.*

Ref.	Polypropylene Fibers	Diameter (mm)	Length (mm)	Compression Strength (MPa)
[69]	0, 0.25, 0.50 and 0.75	0.50	30 and 25	Fiber length = 30 mm 38.90, 40.83, 46.73 and 50.63 Fiber length = 25 mm 38.90, 43.14, 51.13 and 53.73
[70]	0, 0.05, 0.10 and 0.15	-	19	7 Days 6.01, 6.00, 5.88 and 6.15 14 Days 6.27, 5.23, 9.36 and 8.70 28 Days 9.87, 6.49, 9.96 and 10.26
[71]	0, 0.5, 1.0, 1.5 and 2.0	-	24	28 Days 38.50, 42.14, 44.61, 46.00 and 41.72
[72]	0, 0.1, 0.2, 0.3, 0.4 and 0.5	0.034	12	7 Days 21.90, 23.65, 23.76, 23.78 and 20.20 28 Days 33.40, 37.33, 38.80, 35.60 and 33.30
[45]	0, 0.30, 0.60, 0.90 and 1.20	-	12	36.09, 33.25, 33.65, 29.86 and 27.49
[48]	0, 0.0625, 0.1250, 0.1875, 0.2500 and 0.3125	0.0115	27.1 to 32.6	7 Days 62.1, 63.8, 64.2, 66.8, 67.3 and 67.6 28 Days 82.5, 82.6, 83.0, 83.8, 84.4 and 84.8
[73]	0, 0.05, 0.10 and 0.20	-	-	28 Days 63.4, 64.9, 62.2 and 61.5
[39]	0, 0.15, 0.30 and 0.45	0.75 to 0.022	12	7 Days 71.2, 74.9, 75.7 and 77.1 14 Days 82.6, 91.2, 91.5 and 92.8 28 Days 88.3, 98.6, 101.4 and 100.3
[54]	0, 1, 2 and 3	0.018 to 0.040	6 to 19	28 Days 49.76, 45.88, 45.17 and 44.19
[55]	0, 0.2, 0.3 and 0.5	0.022	12	7 Days 32.95, 33.88, 36.15 and 37.56 28 Days 41.30, 42.32, 44.05 and 46.09 91 Days 46.65, 48.96, 50.21 and 53.56
[56]	0, 0.4, 0.8, 1.0 and 1.5	0.016	12	14 Days 30.0, 35.7, 40.0, 47.0 and 50.0 28 Days 39.0, 43.3, 48.5, 57.0 and 61.0

It is evident from the micrographs in Figure 4 that the fibers are situated inside the crack's breadth and act as connecting bridges. The fibers' property inhibits the separation of cracked concrete fragments. It was discovered to be particularly successful in reducing crack areas as well as the widths and lengths of shrinkage cracks. The average number of cracks and crack area was reduced by 60% when fibers at 0.1 percent were used [74]. Figure 4b shows a schematic illustration of how fibers may act as a bridge to a connection and stop cracks from spreading.



(a) (b)

Figure 4. (**a**): Microscopic view of fiber and crack. (**b**): Prevention of crack (bringing by fibers) [75], used as per Elsevier Permissions.

According to research, the addition of polypropylene fibers to the mix boosts the compressive capacity of concrete by 5 to 15%. The same data also shows that, in terms of improving compressive strength, steel fibers had a more considerable influence than polypropylene fibers. This is explained by the fact that steel fibers are more effective in bridging macro-cracks and, as a consequence, have a greater elastic modulus and strength than polypropylene fibers. This increases compressive strength [39].

The compressive capacity of the concrete is only marginally impacted by the addition of polypropylene fiber. Concrete's compressive strength was marginally reduced as fiber concentration increased. In concrete, fiber insertion increases the interfacial transition zone (ITZ), which may have an impact on compressive strength. With the inclusion of 0.3 percent of fibers, a maximum 10 percent drop in compressive capacity (in comparison to the control concrete) was noted [76]. In a study, compressive strength decreased when polypropylene fiber amounts greater than 0.2 percent were added to the binary mixture of steel (0.8 percent fixed) and polypropylene fiber (0–0.4 percent) [77]. However, the inclusion of polypropylene fibers raised the compressive capacity of concrete by up to 0.2 percent. Steel fibers may have an impact on the rise in compressive capacity (up to 0.2 percent polypropylene fiber with 0.8 percent steel fiber).

Under compression, many fiber-reinforced concrete failure mechanisms were seen. The tested cylinders' mechanisms of failure, both with and without fibers, are shown in Figure 5. The control samples with 0 kg/m^3 exhibit localized crushing at the top/bottom ends of the cylinders and splitting fractures along the height (Figure 5a). Plain concrete has been observed to be susceptible to this form of failure, which is typically brought on by the concrete's friction angle and the abrasion of the sample surface against the loaded steel plate (for the samples that failed at the end portion). Shear failure became the predominant form of failure as a result of the addition of macro poly fibers to the concrete (Figure 5b,c). This form of failure is listed as a potential failure mechanism for plain concrete, and it is often brought on by friction between the surface of the concrete and the loaded steel plate (in the case of the vertically split sample) (for the samples that failed at the end portion). Shear failure was a significantly different form of failure due to the addition of macro poly fibers to the concrete (Figure 5b,c).

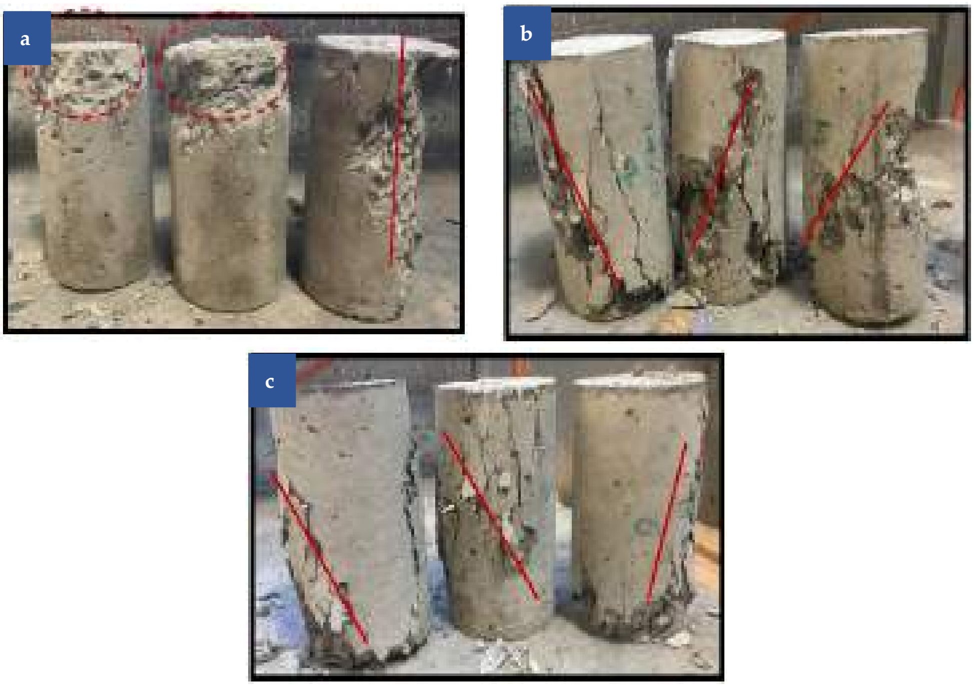


Figure 5. Compressive Failure modes: (**a**) 0%, (**b**) 4 kg/m^3 and (**c**) 6 kg/m^3 [78]; open access source.

3.2. Tensile Strength

Polypropylene fibers increased the tensile strength of concrete, as seen in Figure 6 and Table 4. It is clear that, similar to compressive strength, concrete's tensile strength increased to some amount with the addition of polypropylene fibers. The tensile qualities of concrete are shown to benefit from the addition of polypropylene fibers to a concrete mixture. In the concrete matrix, the fibers serve as crack deterrents. With fiber addition up to roughly 0.25 percent over the control (0 percent fiber) concrete's tensile strength, concrete's tensile splitting strength was found to be higher than the control concrete [76].

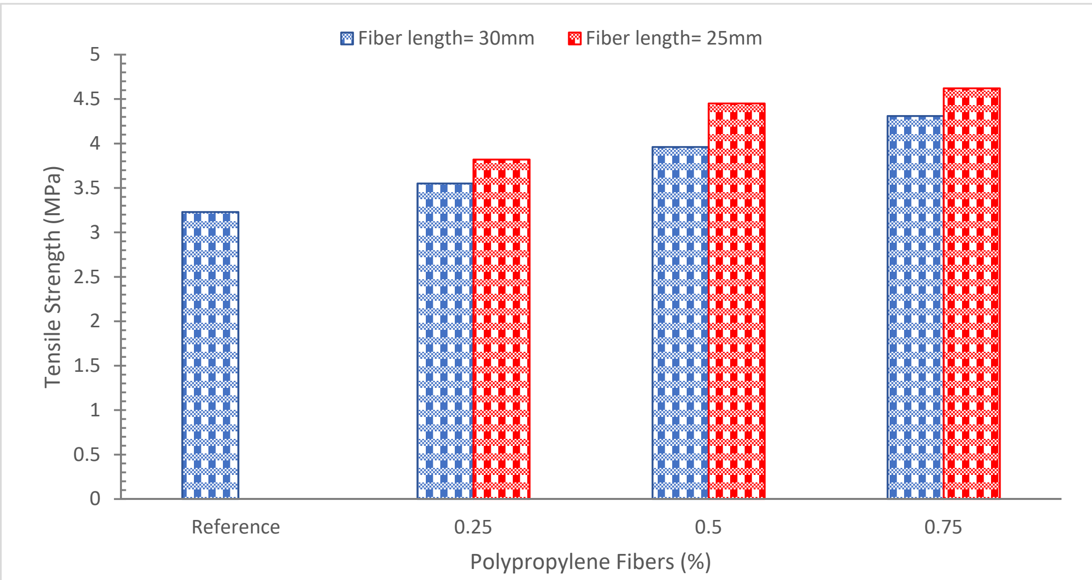


Figure 6. Tensile Strength: Data Source [69].

Table 4. Tensile Strength of Concrete with addition Polypropylene Fibers.

Ref.	Polypropylene Fibers (%)	Diameter (mm)	Length (mm)	Split Tensile Strength (MPa)
[66]	0, 0.5, 1.0, 1.5, 2.0, 2.5%, 3.0 and 3.5	0.04	6.2	28 Days 1.95, 2.68, 3.72, 4.25, 4.66, 5.21, 5.46 and 5.37
[67]	0, 0.5, 1.0, 1.5 and 2.0	-	12	7 Days 1.80, 2.30, 3.43, 3.52 and 2.10 28 Days 2.52, 3.22, 3.40, 3.52 and 2.90
[42]	0, 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0	-	35	M25 3.20, 3.25, 3.30, 3.20, 3.15, 3.10 and 3.00 M30 3.50, 3.60, 3.90, 3.55, 3.50, 3.00 and 2.70
[43]	0, 0.5, 1.0, 1.5 and 2.0	0.0445	6.2	M30 2.2, 2.6, 1.8, 1.8, and 1.0 M40 2.4, 1.9, 1.5, 2.0 and 1.0
[69]	0, 0.25, 0.50 and 0.75	0.50	30 to 25	Fiber length = 30 mm 3.23, 3.55, 3.96 and 4.31 Fiber length = 25 mm 3.23, 3.82, 4.45 and 4.62
[71]	0, 0.5, 1.0, 1.5 and 2.0	-	24	28 Days 3.42, 3.86, 3.98, 4.38 and 3.66
[45]	0, 0.30, 0.60, 0.90 and 1.20	-	12	2.95, 3.40, 3.18, 3.11 and 2.65
[48]	0, 0.0625, 0.1250, 0.1875, 0.2500 and 0.3125	0.0115	27.1 to 32.6	7 Days 2.0, 2.7, 2.9, 4.3, 4.4 and 5.7 28 Days 2.5, 3.7, 4.0, 5.8, 6.4 and 8.0
[39]	0, 0.15, 0.30 and 0.45	0.75 to 0.022	12	7 Days 4.63, 5.13, 5.17 and 5.34 14 Days 5.27, 5.95, 6.10 and 6.30 28 Days 5.81, 6.47, 6.45 and 6.72
[55]	0, 0.2, 0.3 and 0.5	0.022	12	7 Days 2.67, 2.81, 2.85 and 3.01 28 Days 3.22, 3.49, 3.66 and 3.68 91 Days 3.89, 3.97, 4.03 and 4.16

It is also said that fibers increased tensile strength more effectively than compressive strength [79]. Instead of preventing fractures, fiber stops them. Fibers have been shown to improve the behaviors of post-cracked concrete [53]. According to research, the addition of steel fibers and polypropylene fibers considerably boosted the compressive strength, splitting tensile, and flexural strength of self-compacting lightweight concrete, as well as its compressive and flexural strength [78]. According to reports, non-metallic fiber (polypropylene) may be added to concrete to reduce shrinkage cracks while still giving it appropriate tensile strength [80]. The increase was caused by the fibers' activity in bridging across the fractures, which at first prevented the development of microcracks. Stress is transferred to the bridging fibers after flexural failure, which delays the onset of cracks and boosts splitting tensile strength [81].

A kind of macro synthetic polypropylene fiber, called macro poly fibers, was developed and made in a novel continuously deformed shape for superior performance and the best concrete anchoring, making them more structurally compliant [82]. Due to the enhanced tensile strength of synthetic fibers, which helps carry more loads, the drying shrinkage of multi-filament and fibrillated fibrous concrete was decreased by 40% when compared to normal concrete. Fibers improved ductility and increased residual tensile strength as compared to concrete without fibers [83]. Microfibers increase the tensile strength of concrete and stop microcracks from developing at the beginning of the hardening process. Microfibers also act as a load-bearing element in concrete, boosting ductility and avoiding macrocracks [84].

Additionally, fibers with a volume percentage of 0.5 to 2.0% have a far bigger impact on the tensile strength of concrete than fibers with a volume percentage of less than 0.5% [85]. It was found that increasing the fiber content from 0% to 20% by weight almost tripled the tensile strength [86]. Tensile stress is reduced when the fiber content passes above this level. Instabilities in the atoms and molecules included in the concrete mix design may cause concrete to break under strain. By incorporating them, they serve as a link that keeps the fibers together [87].

3.3. Flexural Strength

The flexural strength of concrete with polypropylene fibers added is shown in Figure 7 and Table 5. As can be observed, much as with compressive strength, the introduction of fibers increased the flexural strength of concrete to a considerable level.

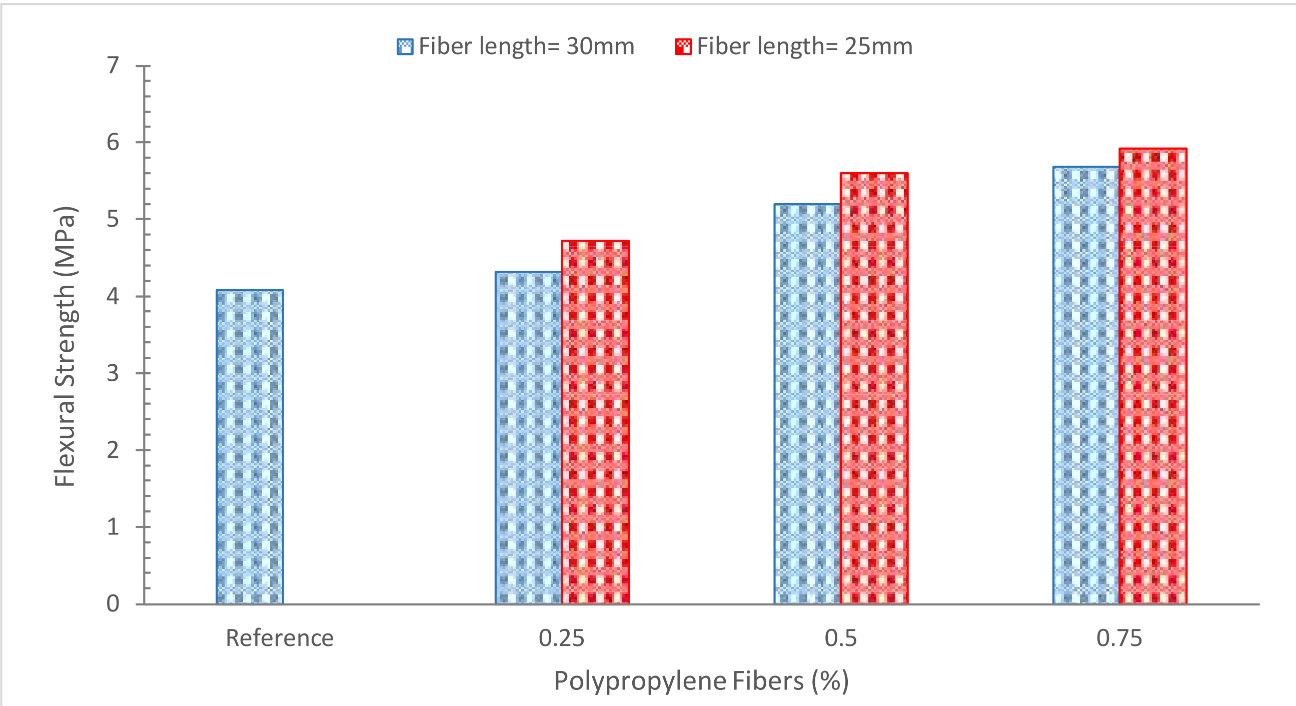


Figure 7. Flexural Strength: Data Source [69].

Table 5. Flexural Strength of Concrete with addition Polypropylene Fibers.

Ref.	Polypropylene Fibers (%)	Diameter (mm)	Length (mm)	Flexure Strength (MPa)
[66]	0, 0.5, 1.0, 1.5, 2.0, 2.5%, 3.0 and 3.5	0.04	6.2	28 Days 2.73, 4.70, 6.61, 7.74, 8.41, 9.46, 10.25 and 10.29
[68]	0, 0.25, 0.50, 0.75 and 1.0	-	12	14 Days 4.53, 7.00, 5.98 and 4.10 28 Days 5.21, 8.58, 7.47 and 4.62
[43]	0, 0.5, 1.0, 1.5 and 2.0	0.0445	6.2	M30 9.0, 9.5, 5.0, 5.2 and 5.2 M40 9.0, 10.0, 5.0, 5.5 and 4.8
[69]	0, 0.25, 0.50 and 0.75	0.50	25 to 30	Fiber length = 30 mm 4.08, 4.32, 5.20 and 5.68 Fiber length = 25 mm 4.08, 4.72, 5.60 and 5.92
[71]	0, 0.5, 1.0, 1.5 and 2.0	-	24	28 Days 4.34, 5.21, 5.48, 5.72 and 4.82
[72]	0, 0.1, 0.2, 0.3, 0.4 and 0.5	0.034	12	28 Days 4.2, 5.0, 6.0, 7.0 and 5.5
[48]	0, 0.0625, 0.1250, 0.1875, 0.2500 and 0.3125	0.0115	27.1 to 32.6	7 Days 3.5, 3.7, 4.0, 4.2, 4.6 and 4.9 28 Days 4.9, 5.1, 5.3, 5.6, 5.9 and 6.2
[88]	0, 0.25, 0.50 and 0.75	0.01	3	1 Days 5.00, 6.03, 9.41 and 10.0 3 Days 5.51, 8.45, 7.50 and 9.41
[39]	0, 0.15, 0.30and 0.45	0.75 to 0.022	12	7 Days 6.94, 7.36, 7.52 and 7.75 14 Days 7.81, 8.50, 8.59 and 8.84 28 Days 8.45, 8.97, 8.91 and 9.12
[54]	0, 1, 2 and 3	0.018 to 0.040	6 to 19	28 Days 9.68, 9.78, 10.15 and 10.45
[55]	0, 0.2, 0.3 and 0.5	0.022	12	28 Days 4.45, 4.48, 5.17 and 5.58
[56]	0, 0.4, 0.8, 1.0 and 1.5	0.016	12	28 Days 4.05, 4.94, 5.91, 6.22 and 7.29

By preventing fractures from developing, fibers increase flexural capacity. Due to the interfacial between the fibers and the concrete components, the load is directly transmitted to the fibers. By enabling the crack to spread over them and transfer the weight, fibers stop fractures from breaking. The structure has greater flexural strength since the fibers and concrete matrix can sustain the force as a whole [49]. Short fibers added to cement concrete somewhat decreased its flexural strength. Longer fibers have a bigger bonding surface with the matrix, which results in a higher pull-out load and more effective fracture bridging [89].

According to research, fiber ends are pulled out during bending. The interfacial zone undergoes deformation at the start of bending. The deformations of the fibers and the surrounding cement matrix are incompatible because of the significant variation in young's modulus. The adhesive bonds tying fibers to cement mortar are broken off as a consequence.

One end of a fiber is kept securely fixed in the mortar by continued bending, while the other is pushed out of the cement matrix. This mechanism is shown in Figure 8.

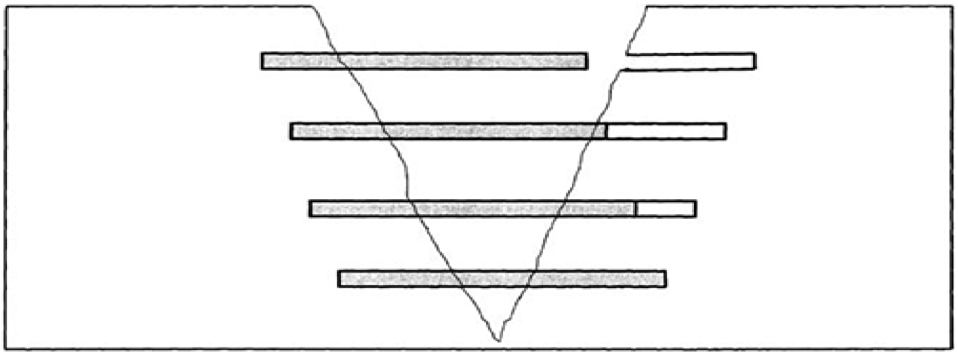


Figure 8. Mechanism of Fibers during Bending [40]; open access source.

A study shows that the presence of steel and polypropylene fibers affects concrete's flexural strength in very different ways. Due to its short length and lower tensile strength and elastic modulus than steel fibers, polypropylene fibers spanned only minor fractures and had little to no impact on flexural strength. Steel fibers, on the other hand, had a significant impact on the flexural strength of concrete due to their greater tensile strength and elastic modulus. Following testing, Figure 9 displays a flexural beam made from steel fiber-reinforced concrete. As seen in the image, some of the steel fibers with hooked ends became straight when put under strong weights during the pull-out step. Steel fibers were more successful at stopping concrete macro-cracks than polypropylene fibers because their tensile strength was around three times higher. Furthermore, compared to straight polypropylene fibers, the steel fibers employed in this investigation were able to achieve much greater maximum pull-out forces because of the anchoring mechanism provided by their hooked ends. Therefore, the flexural strength of hybrid fiber-reinforced concrete was decreased as a consequence of replacing steel fibers with polypropylene fibers [39].

Figure 9. Prevention of Cracks (bringing by fibers) [39] Used as per Elesivior Permissions.

The eventual failure of the concrete beams with various fiber dosages is shown in Figure 9. The 0 kg/m^3 beams behaved similarly after reaching the modulus of rupture (as shown in Figure 9a, which is the localized tensile stress along the height of the beam since the plain concrete beams fractured into two pieces in a brittle manner.

The concrete beams with a fiber dosage of 4 kg/m^3, in comparison, had a little fracture along the length of the beam where the crack mouth opening was connected at the time. As seen in Figure 9b, the detected fracture continued to grow until it almost reached the top of the beam, when the ultimate collapse took place. A snipping sound that may have been caused by the fibers breaking in during the test was audible. Similar findings were observed with the 6 kg/m^3 macro poly fiber-reinforced beams (Figure 10c). Even after the ultimate breakdown, both fibrous concrete beams exhibited gradual failure without separation. This was caused by the presence of macro poly fibers, which attenuated the spread of cracks by resisting and distributing the tensile pressures brought on by bending.

Figure 10. Flexural Failure modes: (**a**) 0%, (**b**) 4 kg/m^3 and (**c**) 6 kg/m^3 [82]; open access source.

Figure 11 shows how fiber reinforcing affects the crack pattern. The greatest fracture widths seen in these tests are shown against the crack areas indicated in the numerous individual tests in Figure 11a. The number of cracks found in each test is displayed against the largest fracture width in Figure 11b. Both Figure 11a,b show the centroids of the families of data points for plain overlays and fiber-reinforced overlays. Observe how the reductions in fracture area, maximum crack width, and number demonstrate the effect of fiber reinforcing. According to one study, when the volume percent of the fiber in the concrete mixture increases, fracture breadth reduces, perhaps due to a stronger "fiber bridge effect" in the concrete matrix [65].

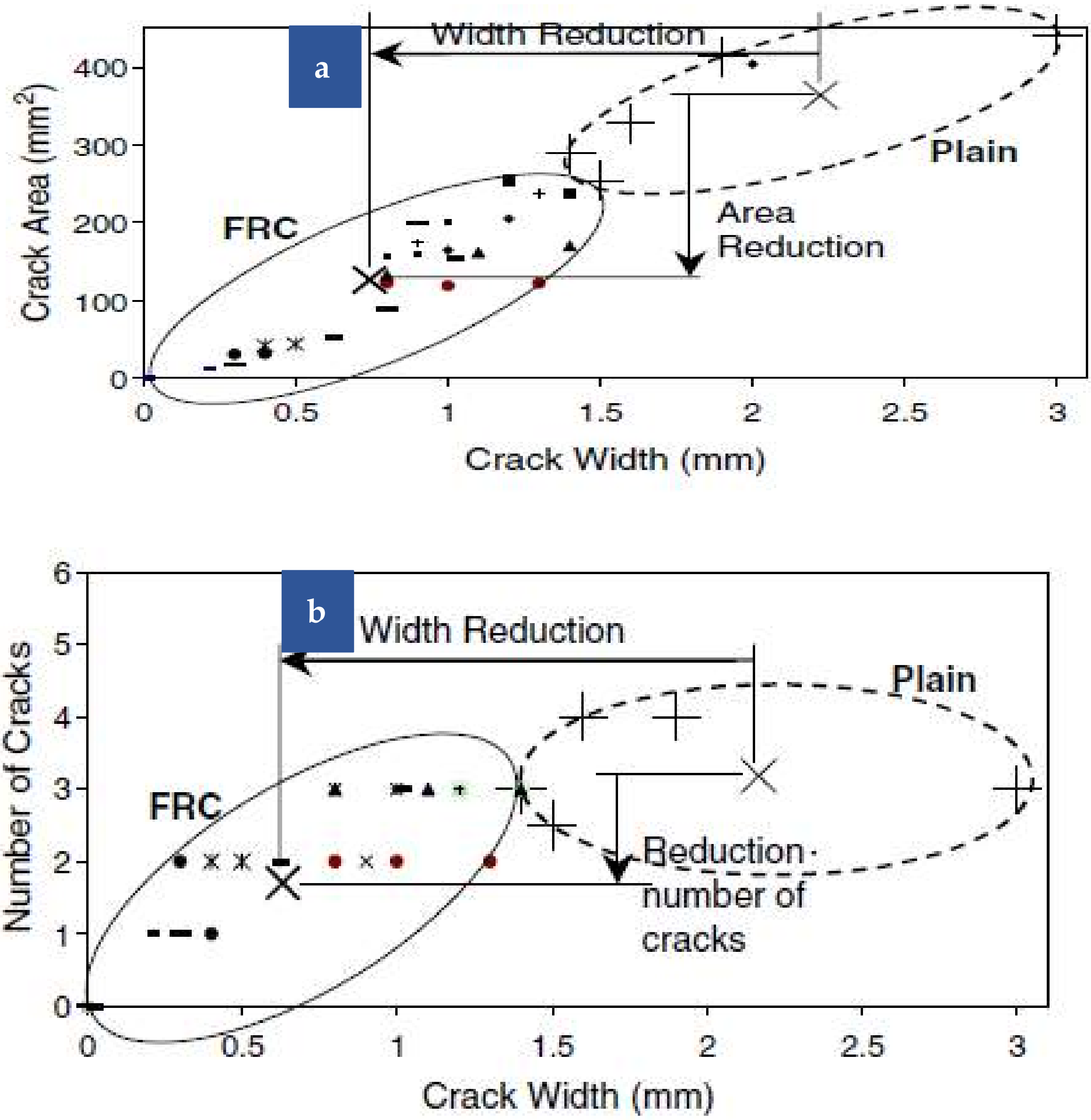


Figure 11. (**a**): Crack Area and Crack Width and (**b**): Crack No and Crack Width of Polypropylene Fibers [90]; used as per Elsevier Permissions.

3.4. Fracture Toughness

Figure 12 shows the differences in fracture toughness of polypropylene fiber-reinforced concrete as a function of fiber volume fraction for a three-point bending beam specimen after 28 days of curing, with a fly ash content of 15% and a silica fume concentration of 6%. In general, the use of polypropylene fiber can make fly ash and silica fume-containing concrete more resilient. The improvement in toughness for the concrete with 0.12% fiber was 6.4 percent, as compared to the concrete without polypropylene fiber. Toughness progressively increases with an increase in fiber volume fraction. However, the fiber volume fraction does not exceed 0.12% due to a lack of flowability, which adversely affects the strength of concrete. Furthermore, when the fiber volume fraction is less than 0.06 percent, the influence of polypropylene fiber on toughness is less noticeable [91]. The increased energy required to propagate the crack along the zigzag crack route was thought to be the cause of the increase in the load needed for full fracture.

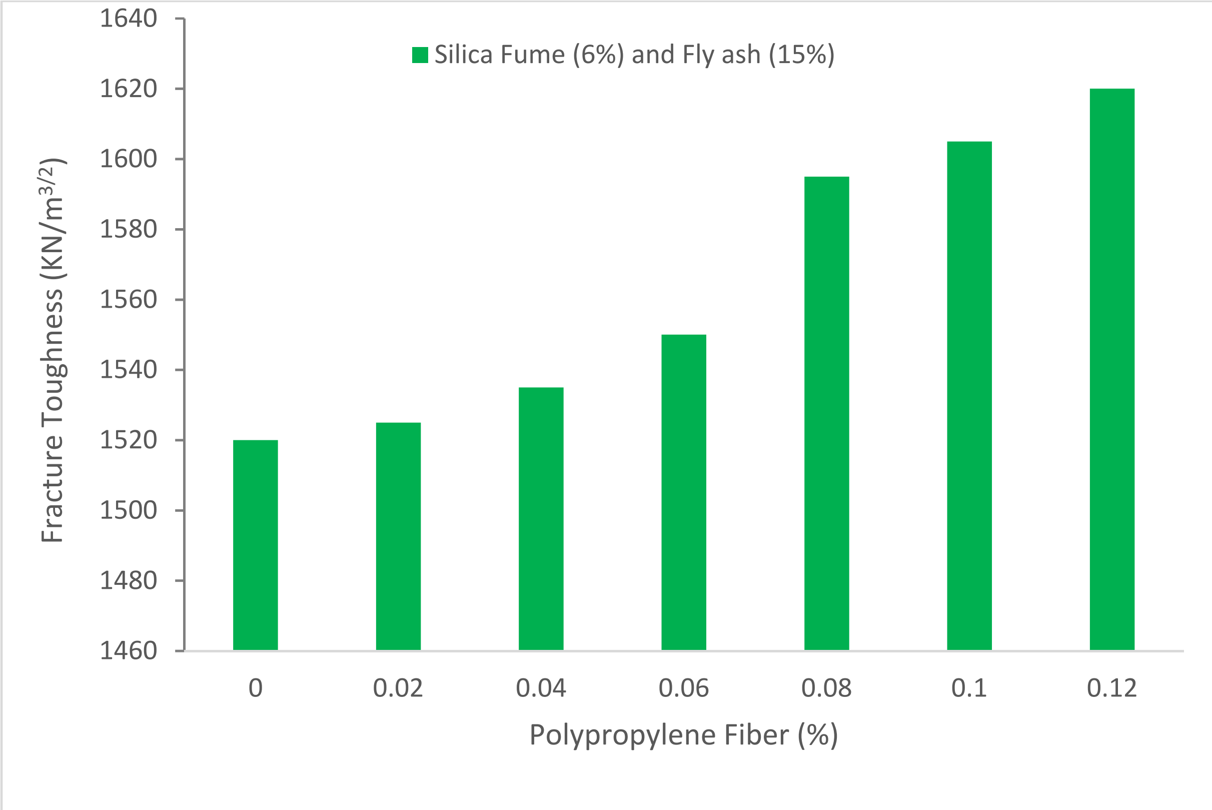


Figure 12. Fracture Toughness [91].

A polypropylene fiber's greater diameter has little impact on the microcracks and has a negligible impact on the stress concentration at the prefabricated crack growth of the concrete [92]. Thus, compared to basalt fiber, polypropylene fiber generates a comparatively lesser improvement in concrete's initial fracture toughness. The load capacity of a single fiber in polypropylene is large, while the aspect ratio is quite low. When the load approaches the instability load and the microcracks partially stretch, it can endure the stress and energy generated and won't break suddenly. In addition, it can reduce the stress after the matrix is penetrated by microcracks, raise the zone's fracture process cohesiveness, and postpone the period when microcracks become macrocracks [93].

However, according to a study, the majority of polypropylene composites break brittlely and have low fracture toughness, which significantly reduces their performance, especially in demanding and long-term applications. The majority of research on polypropylene-based composites is concentrated on creating high-strength composites that incorporate various types of reinforcements and fillers [94].

4. Durability

4.1. Water Absorption

The capacity of concrete to withstand the entry of harmful ions is another important component that influences concrete durability. Concrete's absorption properties serve as an indirect indicator of its porosity while also providing important details regarding the amount of permeable pores within the concrete and the connection between those pores. Figure 13 shows how various fiber-reinforced concretes used in this investigation absorbed water.

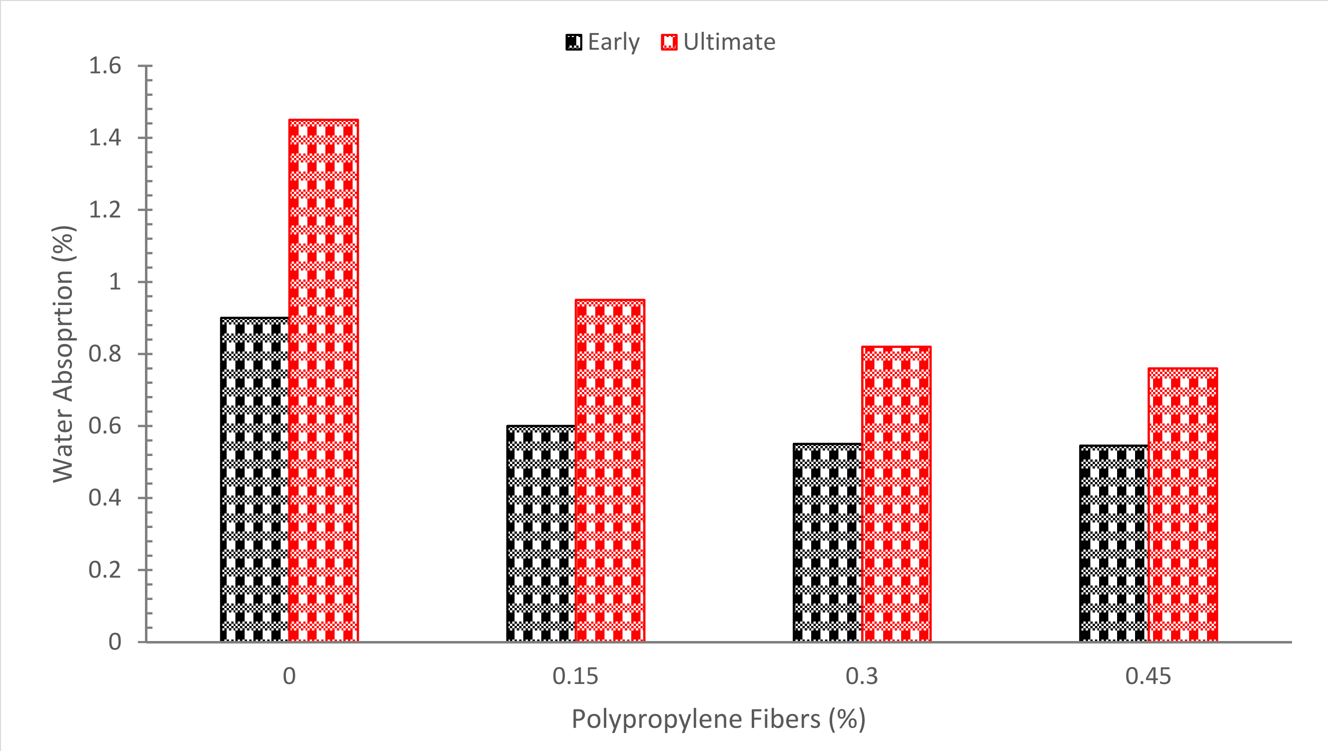


Figure 13. Water Absorptions [39].

The outcomes of polypropylene fiber-reinforced concrete show that polypropylene fibers have a beneficial impact on reducing the water absorption of concrete. Fiber content rose, which reduced water absorption even more. As a result, among all polypropylene fiber-reinforced concretes, the combination containing 0.45 percent polypropylene fiber had the lowest water absorption [39]. Additionally, it has been said that adding steel fibers at a rate of 2.0 percent resulted in the least amount of water absorption possible [12]. Studies stated that favorable results were attained at 0.6% addition of fiber [95,96]. The elastic modules of conventional concrete are less than those of fiber-reinforced concrete because of this. The addition of fibers would improve the concrete's ability to withstand the tensile strain, which would prevent the formation of cracks in the concrete at an early stage [97]. In other words, decreasing water absorption lowers the density of concrete. Greater doses (over 2.0 percent) produced less thick concrete because they lacked workability. One study found that fiber-reinforced concrete absorbed more water than control mortar due to the higher porosity of the fibers fraction mortar compared to the control mortar. The most significant factors affecting water absorption are the cement blocks' porous nature and the existence of an interfacial zone around the particles. The results show that the fiber mortar experienced much more water absorption than the control mortar [98].

The material reinforced with polypropylene fibers and fly ash, in contrast, exhibited the maximum level of porosity and water absorption. For all concrete combinations, as indicated in Figure 14, the fly ash and fiber contents rose along with the porosity and water absorption values. When polypropylene fiber was added to a fibrous mixture, the quantity of big holes rose, according to a researcher who investigated the subject [99].

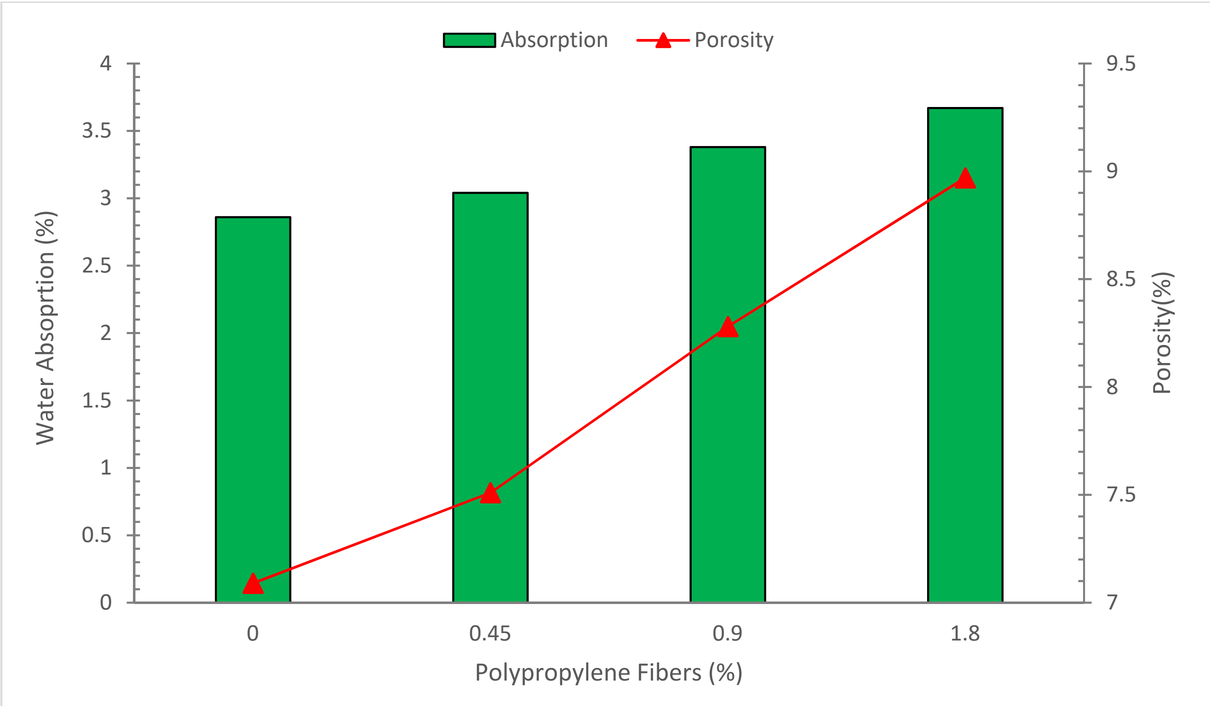


Figure 14. Porosity and Water Absorptions [73].

4.2. Shrinkage

The prepared specimens were put in the controlled temperature and humidity room and monitored throughout time. For control concrete, a thin hairline fracture was seen spanning the length of the slab after 150 min (since water was injected). Further drying revealed that this little break, which may have been caused by settling, widened. For specimens of fiber-reinforced concrete, it took up to 7 h before the first fracture appeared. Thus, fiber reinforced concrete had an appearance duration that was three times longer than that of ordinary concrete. Figure 15 displays examples of concrete with shrinkage cracks. These events may be explained by the presence of bleed water on the top surface, which postpones the drying of the top layer and might prevent polypropylene fiber reinforcement of the concrete. No break could be seen in the case of 0.3% addition of polypropylene fibers.

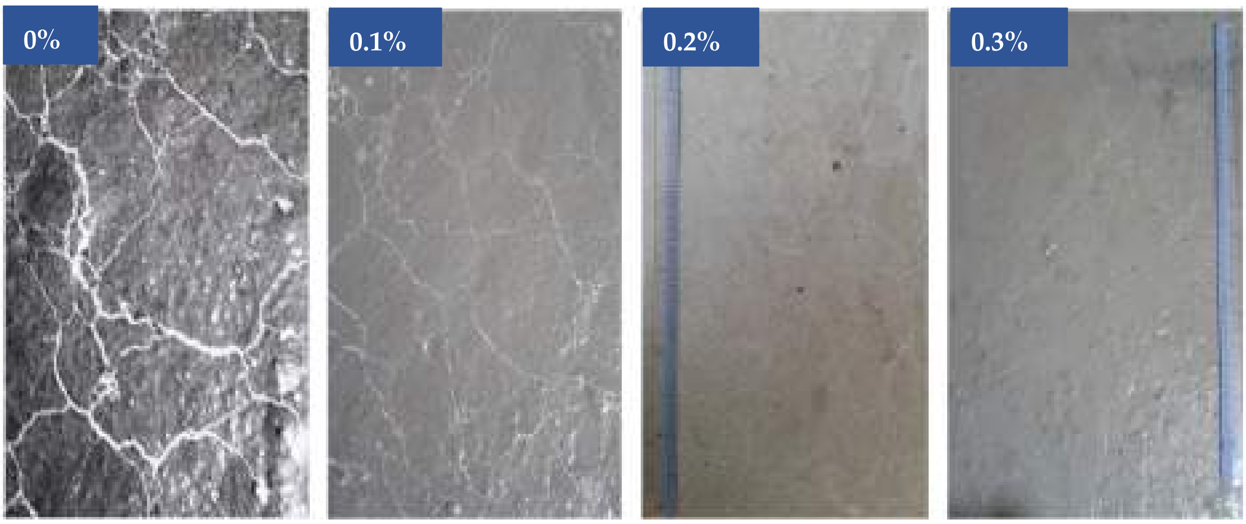


Figure 15. Shrinkage Cracks in Slab with different Doses of Polypropylene Fiber [76].

According to Figure 16, the proportion of cracks reduces when the fiber is added. It was absolutely impossible to see any plastic shrinkage fractures while using 0.30 percent fiber (by volume). In comparison to the control sample, the inclusion of 0.10–0.25 percent fibers significantly reduced the crack width (shown in Figure 16). With the inclusion of fiber up to 0.25 percent, the crack width decreased by 72–93 percent. By adding fibers up to 0.30 percent, shrinkage cracking is decreased by 50–99 percent.

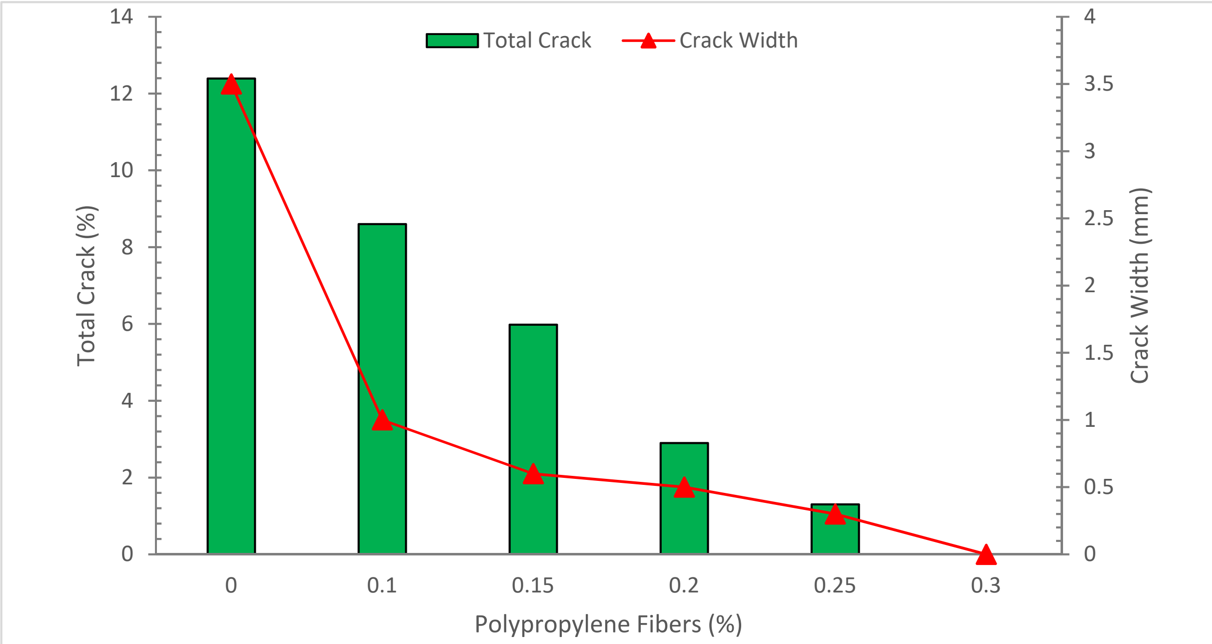


Figure 16. Shrinkage Total and Crack Width [76].

The ACI [100] recommends that the plastic shrinkage crack width be kept to within 3 mm. Although this wasn't met for the control concrete, these conditions were met with the inclusion of fiber. Generally speaking, fiber might serve as a crack bridge and help prevent the onset of shrinkage cracking. The decrease in plastic shrinkage crack was found to range between 49 percent and 99 percent when a researcher examined the shrinkage properties of concrete reinforced with 0.5 percent fiber (a mix of steel and polypropylene). Additionally, it was shown that adding polypropylene fiber was more effective than adding steel fiber in preventing shrinkage cracking. With 0.5 percent polypropylene fibers, the cracking area in the concrete was reduced by 99 percent [80]. The development of cracks is prevented by a large number of uniformly spaced polypropylene fibers by significantly limiting their breadth by two orders of magnitude [15]. Polypropylene fibers prevent cracks from forming both during drying shrinkage and plastic shrinkage [101]. The research found that strong glass fiber cementitious matrix bonding was responsible for the significant reduction in free early age shrinkage. Additionally, compared to mortar without fibers, shrinkage in glass fiber-reinforced mortar was more uniform. Finally, it was determined that glass fibers had a positive effect on preventing fractures from developing and restricting them [16].

4.3. Electric Resistivity and Thermal Conductivity

Electric resistivity is among the most significant properties of concrete longevity because it significantly affects corrosion in reinforced concrete. It has been shown that the limit for internal steel reinforcing bar corrosion propagation is 120-ohm meters of electrical resistance, beyond which corrosion of concrete reinforcement is unlikely to occur [102]. The ions' passage through the concrete is halted by the rise in electrical resistance. Therefore, greater electrical resistance causes concrete reinforcing bars to corrode at a slower pace [103].

In Figure 17, the results of electrical resistivity testing for the polypropylene fiber-reinforced concrete used in this investigation are shown.

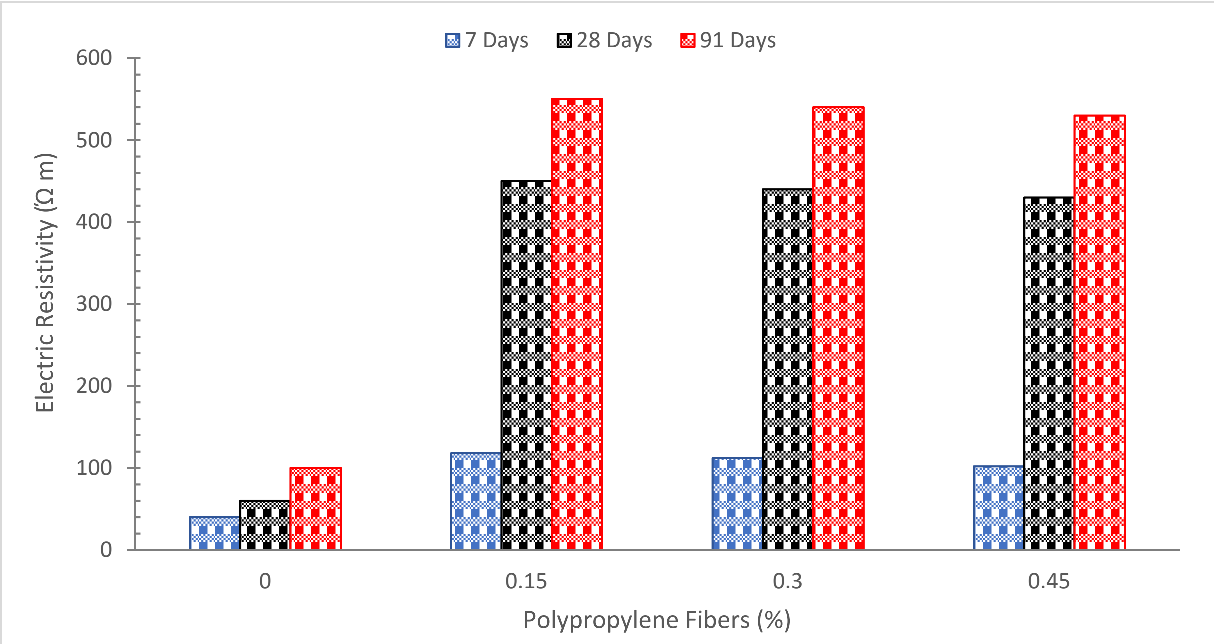


Figure 17. Electric Resistivity [39].

The findings of polypropylene fiber-reinforced concrete show that the fibers' integration led to a modest decrease in the electrical resistance of the concrete, the amount of which rose with an increase in fiber content. This may be a result of fiber inclusion increasing the porosity of the mixture [104]. Concrete transport qualities are significantly influenced by the connection and size of pores. Therefore, electrical current may be transmitted by ions through the pore network of concrete much more readily in concretes with increased porosity, which results in reduced electrical resistance [105] and increased thermal conductivity.

Conversely, the findings demonstrate that polypropylene fiber reinforcing enhances resistance or decreases conductivity. The resistivity increases seem to be more apparent at later ages while being substantial at an early age. Because steel fibers have high electrical conductivity, as predicted, their presence drastically reduced resistance. Due to glass and polypropylene fibers' lower conductivity compared to steel fiber, concrete's electrical resistance increases [106]. It was noted that the conductivity value decreased when the concrete was supplemented with PP fibers. The heat flow in concrete reinforced with 0.30 percent PP fibers was reduced by 2.94 percent. This is because PP fibers have hydrophobic properties, which keep water in concrete. As a result, air holes (voids) were created as the water dried. The concrete's heat conductivity decreases when there are more air spaces present [107]. However, a study claimed that the thermal conductivity of the polypropylene is increased from 0.27 up to 2.5 W/(m K) with 30 vol% in the polypropylene matrix [108]. The increase in thermal conductivity of addition PP is due to the restriction of cracks which increased the density and reduced the matrix porosity. The decrease in porosity results in more conductivity.

5. Scanning Electronic Microscopy

The ability to assess the microstructure of cement and concrete is enhanced by the use of scanning electron microscopy (SEM). It will also help in examining the effects of additional cementing components or fibers and in assessing problems with concrete durability. Figure 18 shows SEM microphotographs of sample fractures after mechanical testing. The ends of the fibers, which emerge from the cement matrix in various orientations and have varying lengths, are apparent in the images (Figure 18a). Specific fibers are clearly differentiated from one another and dispersed uniformly across the sample's volume. The projecting ends are securely fastened to the mortar and cannot be removed by hand. The hole in the matrix that is left after the fibers are pulled out is seen in the second microphotograph (Figure 18b). The network structure of the fibrillated fibers is partially opened in the concrete, as can be seen. Further splitting into smaller specific fibrils is seen simultaneously (Figure 18c). These processes increase the fibers' specific surface area, which greatly improves their capacity for adhesion.

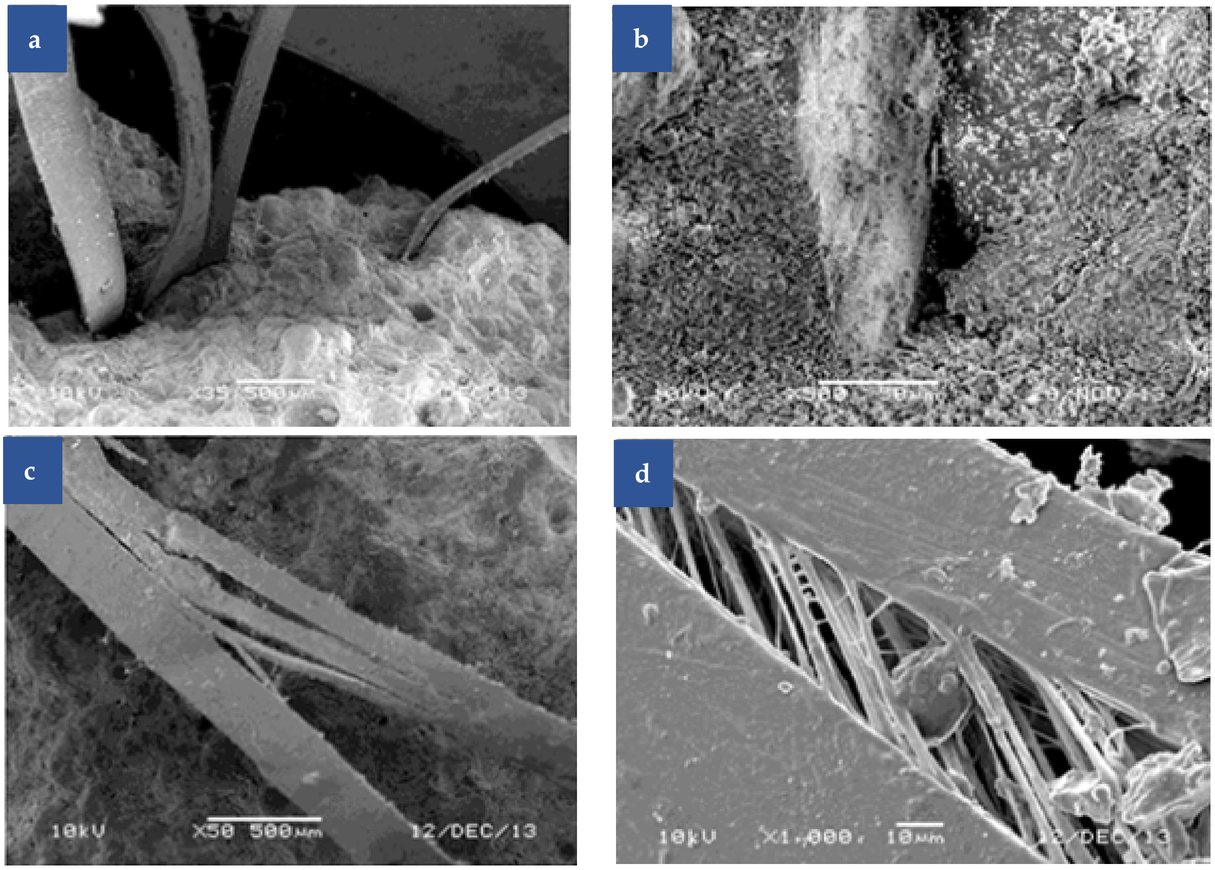


Figure 18. (**a**): Fiber anchored, (**b**): Pulling out Fiber, (**c**) Splitting Fiber, and (**d**): Fibrillation Fiber [40]; used as per Elsevier Permissions.

Previous studies have shown that the network structure's opening and splitting assist the mechanical anchoring of the fibers in the matrix and contribute to the interaction between the fibers and the matrix [109]. According to Bentur et al. [110], the utilization of fibrillated fibers produces two effects that interact with the fiber matrix: interfacial adhesion and mechanical anchoring. The dense matrix that formed in the transition zone and the close contact at the interface is thought to be responsible for the first. The second is linked to a combination of fibril branching, which occurs when fibers divide into multifilament strands, filamenting, and the development of small fibrillations on the surface of the fibers.

6. Conclusions

Fiber made of polypropylene is a kind of polymer material that is lightweight, very durable, and resistant to corrosion. Polypropylene fiber may be added to concrete to increase its fracture resistance. Concrete distribution of pore sizes may be improved via polypropylene fibers. Because polypropylene fiber may limit fractures and prevent water or harmful ions from penetrating concrete, the mechanical and durability of concrete are thus greatly improved. This study provides an overview of the impact of polypropylene fiber on the initial strength, long-term durability, and microstructure of concrete. The conclusion in full is provided below.

- The workability of concrete decreased with the addition of polypropylene fiber due to the larger surface area of the fiber. Additionally, fiber increased the friction among concrete ingredients which results in less workable concrete.
- The mechanical strength of concrete improved with the addition of polypropylene fiber. However, the effect of polypropylene fiber compressive strength is less or little compared to the tensile or flexural strength. Furthermore, the optimum is important for better performance. Higher amounts of polypropylene fiber (beyond 2%) decreased the mechanical strength and durability of concrete. The typical optimum dose of polypropylene fiber ranges from 1 to 2% depending on the length, diameter, and mix design of the concrete.
- Polypropylene fiber also shows crack prevention or, even if a crack appeared, polypropylene fiber restricts its propagation. Furthermore, polypropylene fiber also changes the undesirable brittle failure of concrete into ductile failure.
- The addition of polypropylene fiber decreased the water absorption and dry shrinkage cracks which adversely affect the durability of the concrete.
- Scanning electronic microscopy also shows that strength and durability improved with the addition of polypropylene fiber.

7. Future Research Recommendations

- Polypropylene fiber has little or no effect on the compressive strength of concrete. Therefore, further research was recommended to investigate the improved compressive strength of polypropylene fiber reinforced concrete. The review suggests detailed studies on the addition of different secondary cementitious materials, such as fly ash or silica fume, into polypropylene fiber reinforced concrete.
- Treatments of polypropylene fiber should be investigated to further improve its performance.
- The thermal properties of polypropylene fiber reinforced concrete should be explored.

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