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Effect of the addition of polypropylene fiber on concrete properties

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ABSTRACT

The random distribution of polypropylene fibers in concrete mixtures leads to an increase in abrasion and freeze-thaw resistance, a decrease in volume expansions formed as a result of sulfate attack and alkali silica reaction (ASR). Since the addition of polypropylene fiber in appropriate ratios to concrete mixtures improves the durability properties of the elements, the total cost decreases. The energy absorption capacity of concrete mixtures increases and their plastic shrinkage cracks significantly decrease by polypropylene fiber utilization. This study presents a comprehensive literature review related to history, advantages and disadvantages, workability, mechanical properties, durability performance and dimensional stability of polypropylene fiber-bearing concrete mixtures. For this aim, compressive, tensile and flexural strengths, modulus of elasticity, flexural crack and post-cracking behavior, the resistance of freeze-thaw, sulfate, high-temperature and abrasion as well as alkali-silica reactivity, drying shrinkage-based length change and impact strength of fibrous concrete mixture are thoroughly discussed.

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Fibrous concrete; polypropylene fiber; mechanical properties; durability performance; dimensional stability

1. Introduction

The main drawback of concrete is its low tensile strength. In this respect, it is known that conventional concrete has poor performance in terms of ductility, fatigue capacity, post-cracking load-bearing capacity, toughness, abrasion, and impact resistance. Use of randomly distributed fibers in concrete is one of the most effective methods used to improve compressive and tensile strength, energy absorption capacity, and the weak properties mentioned above. Another negative aspect of concrete samples is the cracks caused by poor dimensional stability. Researchers reported that the use of fiber in concrete reduces these cracks [1–5]. Fibrous concrete mixture was successfully used in different applications due to its superior performance compared to conventional concrete. In general, fibrous concrete production uses steel, polypropylene, glass, plastic, and carbon fibers with different aspect ratios [6–12].

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In this study, the properties of polypropylene fiber concrete are thoroughly discussed. In addition to its use in textile products, polypropylene is used as a fiber material in various civil engineering applications. Polypropylene fibers are chemically resistant to acids and alkalis and can be used with any type of portland cement. Polypropylene fiber is a 100% polypropylene-based artificial material that does not require much workmanship in its production, is easy to apply, improves some properties of concrete, and is added to the concrete during production [13]. Polypropylene fibers prevent the propagation of the micro cracks of the concrete [14] and thus, decreasing permeability and increasing the compression factor. According to the literature, the shrinkage-based crack in the concrete mixtures decreases by 90% with the use of polypropylene fiber [6]. Besides, the reports show that the addition of polypropylene fiber in appropriate proportions to concrete mixtures leads to an increase in the mechanical properties such as impact resistance [15,16] and abrasion resistance [17,18] and a decrease in the volume expansions resulting from freeze-thaw [19,20], sulfate attack [16,21] and ASR [17,22]. In this study, by taking into consideration the previous studies, the effects of the use of polypropylene fiber on the mechanical and durability properties of concrete mixtures are examined in detail. Accordingly, a comprehensive review publication was prepared on the effect of the use of polypropylene fibers on the mechanical and durability properties of concrete by addressing to the history of fiber, the importance of fibrous concretes, properties of polypropylene fibers, their applications in the field of civil engineering, the advantages and disadvantages of their use.

1.1. History of fibers in building materials

The most commonly used natural fibers that inspire fiber concretes are straw and horsehair. In ancient times, engineers and architects used straw, animal hair, and different natural fibers to protect structures against destructive effects [23]. As for Turkey, brick-dust which was used in the structures built by Mimar Sinan contained natural fibers as well. The known steel fibers started to be used in concrete production in the 1950s. In later years, concrete was tested by adding artificial fibers such as carbon [24–27], glass [28–31], asbestos, plastic [32–34], and natural fibers such as hemp [35–37], palm [38–40] and bamboo [41,42]. Since each fiber has different properties, its various functions and superiorities have come out. The use of polypropylene fibers in concrete began in the 1960s when a study which was conducted by the American Armed Forces Engineers Association proved that fibers resist abrasion and impacts. Furthermore, the development of synthetic fibers is very beneficial to the industry; and today, new types of synthetic fibers, especially polypropylene [43], polyolefin, and polyvinyl alcohol [44] are used in various projects [7].

1.2. The importance of fiber concrete

At the present time, with the development of concrete technology, different types of concrete mixtures are produced for various purposes [6]. While different chemical and mineral additives are used to improve the mechanical and durability properties of concrete, various types of fiber are used to increase ductility. Fibers distributed randomly within the concrete prevent the formation and growth of cracks that occur in concrete at different stages, thereby increasing the energy absorption capacity in concrete by dispersing internal stresses. The effectiveness of the fibers used in concrete varies in relation to the fiber's fineness ratio, geometry, tensile strength, type, and volume [45]. The ductility of fibrous concrete depends on the ability of the fibers that are dispersed randomly within the concrete to bridge the cracks. The propagation of the crack is prevented by either blocking up the stresses that occur during the crack formation by the fibers or transferring them to solid areas by means of the fiber [8]. Fibrous concrete was used for many years in various applications such as industrial buildings, water structures, shotcrete, slope stability and tunnel coatings, airport, and highway coating concrete. Specifically, fibrous concrete is preferred when the structures are exposed to heavy working conditions [7].

The advantages of fiber concrete are listed below:

- Increases impact stiffness or impact resistance in dynamic loads [6].
- The strength of the structural element against the severe cross-sectional effects due to the tension caused by the tensile and flexural force in the structure can be significantly increased with the use of steel reinforcement and fiber [7].
- The ductility of the fiber is high compared to normal concrete. In relation to that, it is more resistant to impact, vibrating load, and dynamic load effects than conventional concrete [46].
- Various structural behavior disorders can be prevented if fiber is used with steel reinforcement [6].
- Resistant to fatigue, torsional and shear strength [6].
- Besides its energy holding capacity, it has high elastic resistance, impact resistance and crack resistance [7].
- These superior qualities of fibrous concrete enable a reduction in cross-section depth, thus saving materials [7].

2. Polypropylene fibers

Polypropylene is an artificially produced lightweight polymer in the category of thermoplastic materials. Polypropylene is used in the production of many products in which durability and elasticity are expected in the form of raw materials. Polypropylene products have a wide range of uses both in terms of civil engineering and applications and in combination with general engineering materials [46].

2.1. Properties of polypropylene fibers

As it is emphasized earlier that polypropylene is used in the production of fibers which are added to concrete mixtures in various civil engineering applications as well as textile products. The reasons for the preference of polypropylene fibers can be listed as their low cost, easy workability, high strength, low density and immense chemical resistance [47]. Polypropylene fibers are added to the mixer during the production phase of concrete mixtures. Polypropylene fibers are the lightest reinforcement system compared to alternative reinforcement systems such as steel, metal fibers and poultry mesh. Also, compared to other reinforcement systems, polypropylene fibers do not provide dead weight reinforcement since they are used between 90 grams and 200 grams per square meter [13]. Polypropylene fibers positively affect the physical, mechanical and thermal properties of concrete [48].

2.2. Classification and performance of polypropylene fibers

Polypropylene fibers are made from 100% homo-polypropylene in two types, namely F and M. The symbols F and M are used to represent fibrillated and multifilament fibers, respectively. Since M type fibers are not visible on the screed surface because of their thinness, appropriate results are obtained when they are used especially in indoor screeds. F type polypropylene fibers are more suitable for screed and concrete in heavy-duty industrial floors because of their durability and toughness properties. The types and technical properties of polypropylene fibers are shown in Table 1. Some Polypropylene fibers of different lengths and types are shown in Figure 1.

Polypropylene fibers are chemically resistant to acids and alkalis and can be used with all types of portland cement. Prolonged exposure to solar light damages the fiber. On the other hand, fiber is resistant to organic solvents, which makes its use in gas stations practical [46]. Its electrical conductivity and thermal transmittance are extremely low. Its thermal expansion is negligibly small. Since these fibers do not absorb water, they do not affect the water/cement ratio, they are nonreactive to acids and oxides, and they are resistant to corrosion and decomposition [13]. Polypropylene fibers are not effective in increasing the mechanical strength of concrete compared to steel fibers, but they provide an energy absorption property to concrete and decrease the plastic shrinkage. These fibers are preferred to prevent weak shrinkage [49]. When reinforced concrete structural elements are exposed to high-temperature effects, a decrease in the compressive strength of concrete, failure and crack formation occurs. Polypropylene fibers form channels by melting at 170 °C and gases come out thorough these channels; the pore pressure decreases and the degree of damage to concrete decreases accordingly [50].

Table 1. Types and technical properties of polypropylene fibers [13].

Type	Monofilament-1	Multifilament	Monofilament-2
Polypropylene (%)	100	100	92
Product type	Standard f	Standard M	Paint
Density (kg/L)	0.91	0.91	1.00
Cross-section	Quadratic	Round	Quadratic
Thickness (μ)	36	18	–
Color	Transparent	Transparent	Colorful
Appearance	Visible	Invisible	Visible
Tensile strength (N/mm^2)	500	700	500
Young's modulus (N/mm^2)	7116.20	7116.20	7161.20
Elongation (%)	Maximum 10	Minimum 100	–
Length (mm)	In all fiber types the length is variable as 3-6-9-12-15-19-25-31-37-46-51		

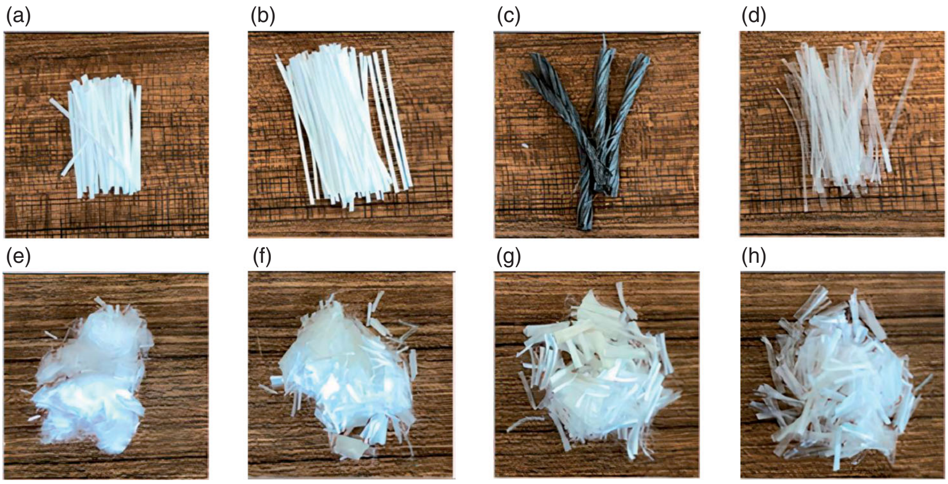

Figure 1. Polypropylene fibers a) 40 mm long monofilament type b) 54 mm long monofilament type c) 54 mm long multifilament type d) 50 mm long monofilament type e) 3 mm long multifilament type f) 6 mm long multifilament type g) 12 mm long multifilament type h) 12 mm long monofilament type.

2.3. Usage areas and ratios of polypropylene fibers

According to ASTM C1116 (2000) standard, fiber produced from 0.1% = 1 liter 100% pure polypropylene raw material is sufficient for 1 m^3 of concrete. Since the density of polypropylene raw material is 0.9 kg/liter, the amount of fiber is recommended to be at least 0.9 kg/liter. It can be used between 0.05% and 2%, and even up to 5%. Polypropylene fiber dosage can be increased up to 0.2% by volume, where micro reinforcement density and high abrasion resistance are required [13]. The amount of fiber required obtaining an optimum concrete mixture in terms of mechanical and durability performance is between 0.5% and 1.5% by volume. This rate can be increased up to 2%, depending on the properties of the produced concrete. However, if the rate is below 0.5%, the effect will be vague [6]. Polypropylene fibers are added 2 kg per ton for plaster and mortar concrete, up to 5 kg for repair mortars and grouts. It is evenly dispersed throughout the mixture and without flocculation. The fiber may vary in quantity and length characteristics depending on the need. Table 2 shows the recommended polypropylene fiber amount for preparing of 1 m^3 concrete mixture.

As pointed out above, polypropylene fibers which are artificially produced as textile industry products are widely used in concrete production as passive reinforcement [46].

Usage areas of polypropylene fibers in the construction industry are the following:

- Bituminous materials, spray plaster and concretes, structural reinforced concrete systems, screed works, field concrete and hydraulic structures [13].
- Industrial floors, garages, marine structures exposed to environmental attacks and mechanical stress, airports, structures exposed to vibration rotation, water tanks, swimming pools, and fine flooring [51].
- All precast elements, pipe manufacturing, flowerpot, curbstone, and tile production [52].

Table 2. Utilization amount of polypropylene fibers per 1 m^3 concrete production [13].

Polypropylene	Interior	Exterior	Heavy-duty
Fiber type	M	F	F
Minimum dosage (g/m^3)	600	900	1800
Optimum dosage (g/m^3)	1200	2700	3600
Length (mm)	6-9-12-15	6-9-12-15-19-25	

- Parks, warehouse areas, in the production of antibacterial concrete, against seismic movements, in mass and diaphragm concretes, in protection screeds, in the production of raft foundation and bond fillings, in ceiling panels, decorative concrete panels, and front facade panels [46].
- In cement-based mortars such as plaster, repair, insulation, fine and rough applications that will be exposed to external influences and highway barriers [50].

3. Properties of polypropylene fiber concrete

According to the ACI committee 544 [53], fibrous concrete aggregate is defined as a type of concrete which contains hydrate cement and discontinuous fibers in varying amounts. Many researchers have investigated the effect of different types of fiber on the mechanical properties of concrete. Nevertheless, research on polypropylene fiber concretes is relatively limited compared to the ones on other fiber types. The following is some research on the subject:

3.1. Workability feature

The effect of fly ash, silica fume, and polypropylene fiber usage on the behavior of fresh concrete under compression is examined within the scope of a doctoral thesis conducted by İnce [54]. It was reported that the addition of polypropylene fiber adversely affects the workability and pumpability of the mixtures, yet this reduces the risk of segregation.

Also, Sertbaş [55] reports similar results regarding polypropylene fiber use in self-compacting concrete (SCC) mixtures. According to the results, it is clearly seen that the workability of SCC incorporating fiber mixtures negatively affected by the increase in presence of fiber in the system.

Another study that investigates the effect of multifilament polypropylene fiber use on some mechanical and fresh state properties of SCC mixtures containing fly ash is Gencel et al. [56]. For this purpose, fiber was added to the control mixture in four different ratios: 3, 6, 9, and 12 kg/m^3 and it was observed that the fiber homogeneously distributed in all mixtures. As a result, it was found that the air content of the mixtures increases by fiber usage rate increases. Despite the observation that some mixtures do not meet the EFNARC criteria, it was pointed out that the fresh state properties of the mixtures are not severely affected.

Another study by Açı kgenç et al. [57] presents an experiment to investigate the effect of polypropylene fiber type and usage rate on some fresh and hardened state properties of concrete mixtures with different strength classes. For this purpose, a total of 21 concrete mixtures were prepared using two different polypropylene fibers which were in soft form and made up 1% and 2% of the total volume. The slump value of the mixtures decreased as with increase in the fiber usage rate and the addition of fiber regardless of the fiber type. This adverse effect was reported to be more evident in soft and agglomerated fibers compared to hard fibers.

A further study by Patel et al. [58] investigates the effect of 5 different polypropylene fibers on the properties of the SCC mixture. It was reported that the fluidity performance of the SCC mixtures containing fiber at a rate of 1% of the total volume, which is an acceptable level, is negatively affected by the addition of fiber beyond this rate.

Madhavi et al. [48] stated that the workability of the mixtures is negatively affected by the use of polypropylene fiber, yet this problem can be solved by addition of an appropriate type of high range water-reducing admixture to the mixture even in cases with very low water/cement ratio.

In another study, Guerini et al. [59] investigate the effect of using steel (high hardness) and macro synthetic (low hardness) fiber on some fresh and hardened state properties of concrete mixtures. For that purpose, a total of 16 concrete mixtures with two different strength classes were prepared by using different types of fiber at a rate of 0.5% and 1% by volume. Adding fiber to the mixture resulted in a meager increase in the air content of the mixtures regardless of fiber type. The workability of the mixtures was negatively affected by the addition of fiber. The increase in fiber content contributed to the prominence of the situation. The authors have reported that polypropylene fibers are more successful than steel fibers in terms of fluidity performance.

Matar and Assaad [60] studied the effect of the combination of recycled aggregates and polypropylene fibers on the workability of SCC mixtures. For this purpose, SCC mixtures were prepared using four different recycled aggregates ratio between 25% and 100% and seven different polypropylene ratios between 0.25% and 1.75% by volume. Fiber addition severely affected the transition ability and rheological property of the mixtures. This effect has become more evident with the increase in recycled aggregate usage rate. Combined use of polypropylene fiber and recycled aggregate was observed to reduce the risk of segregation of the mixtures. Furthermore, Karimipour et al. [15] report similar results.

Lastly, Leong et al. [1] observe some reductions in workability with the addition of polypropylene fiber to light cemented systems containing micro-perlite.

Cementitious systems are adversely affected with addition excessive amounts of fiber. This situation causes an increase in the void volume during the placement. Thus, the mechanical properties of the mixtures are negatively affected.

3.2. Mechanical properties (compressive, flexural, tensile strength and modulus of elasticity)

Tokyay et al. [61] investigate the relative effect of polypropylene and steel fiber usage on some mechanical properties of high strength concretes with a water/cement ratio of 0.25. For this purpose, a total of three series of concrete mixtures with a slump value of 2–3 cm were prepared using steel fiber 1.5% of the total volume and 1 kg/m^3 polypropylene in addition to fiber-free control mixture. The compressive strength of the mixtures was not significantly affected regardless of the fiber type. As compared with the control mixture, a 13% increase in the tensile strength of polypropylene fibrous concrete was observed. On the other hand, it was stated that this rate is 37% in steel fiber concretes. When it comes to energy absorption capacity, steel fiber concrete was reported to have the highest performance.

Qian and Stroeven [62] stated that the use of fine materials such as fly ash is required for a homogeneous distribution of fibers in the cementitious system. Fiber length was reported to have no similar effect on different mechanical properties of concrete mixtures. It was pointed out that the addition of short fiber to the mixture significantly affects the compressive strength while this effect is quite mild on the splitting-tensile strength. Also, the addition of long fiber to concrete mixtures was observed to affect the compressive strength of the mixtures in a negative way. In addition, it was stated that a synergy effect exists in hybrid fibrous cement systems.

In his doctoral dissertation, Yıldırım [63] studies the performance properties of polypropylene and steel fiber reinforced concrete. Steel fiber was added at 0.5%, 0.75%, and 1 by volume while polypropylene fiber was used at a rate of 0.1% in concrete mixtures. As a result, Yıldırım [63] reports that the strength of polypropylene fiber decreases as 'the' its amount increases and that the fibers do not distributed homogeneously. He points out that the addition of steel fibers by 0.5% increases the compressive strength of the mixtures; on the other hand, strength values decrease as the fiber usage rate increases.

In the study conducted by Aulia [64], polypropylene fiber which was 19 mm long and at rate of 0.20% was used in high strength concretes with silica fumes. According to the reports, there is an increase of 5.61% in the 28-day compressive strength and 5.20% in the modulus of elasticity of the fibrous concrete.

Alkan [65] investigates the effect of polypropylene fiber length on some fresh and hardened state properties of concrete mixtures. For this purpose, in addition to the control mixture, four series of concrete mixtures were prepared by using four different polypropylene fibers having length of between 12 and 51 mm as ratio of 0.50% and by addition of 10% silica fume (by volume) to the mixture. In all mixtures, the water/cement ratio was kept constant at 0.39. According to the reports, as polypropylene fiber length increases, fracture energy of concrete mixtures increases while compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity decrease.

Karahan [13] investigates the properties of fly ash added concrete and reinforced concrete with polypropylene and steel fiber. In the study, polypropylene fiber which was 19 mm long was added to the mixtures at ratios of 0.05%, 0.10% and 0.20% by volume. Steel fibers that were 35 mm long were used at ratios of 0.25%, 0.5%, 1.00% and 1.50% by volume. According to the results, the addition of polypropylene fibers to the concrete at a rate of 0.05% slightly increases the elasticity modulus of the mixtures while the elasticity modulus of the concrete decreases in cases where fiber is used above this ratio. The elasticity module values of the specimens decreased by the addition of 20% polypropylene fiber to the concrete mixtures. However, it was reported that the stress-strain curves are elongated and thus the samples behave ductile.

Özcan [66] investigates the effect of polypropylene fiber usage on some mechanical and durability properties of two different series of concrete mixtures which are prepared by boiler ash of fine aggregate (five different rates ranging from 10% to %50) and granulated blast furnace slag respectively. For this purpose, the rate of use of polypropylene fiber was kept constant at 0.02% by volume in all mixtures. In both cases, no significant effect was observed on the strength properties of the mixtures by substitution of fine aggregates. However, it was reported that the durability performance of the mixtures such as freezing-thawing, abrasion, resistance to sulfate and permeability have been improved with the addition of polypropylene fiber in concrete mixtures with fine aggregate substitution up to 30%.

In another study, Topçu and Canbaz [67] analyze the effect of the use of 0.65% steel fiber, 0.05% and 0.08% polypropylene fiber on mechanical properties of concrete mixtures which contain silica fume. It is seen that fiber addition positively affects the mechanical properties of the mixtures and that this increase is more evident in flexural strength. The authors point out that steel fiber is more effective compared to polypropylene.

Moreover, Subaşı [68] argues that the use of steel and polypropylene fibers has a positive effect on the compressive strength of SCC mixtures.

In another study by Sun and Xu [69], the effect of polypropylene fiber used on the physical, mechanical and microstructural properties of concrete mixtures was investigated. Microstructural analysis has clearly shown the network structure which is formed by polypropylene fibers in the matrix. The authors state that the use of fiber prevents capillary cracks in the concrete and breaks that may occur between cement paste and aggregate. According to the reports, the formation of $Ca(OH)_2$ in the system has decreased thus the structure of the pore has improved as a result of the use of fiber. It was reported that the segregation risk is reduced in mixtures with fiber use. Considering all of these, the authors suggest that the optimum fiber content should not exceed 0.9–1 kg/m^3.

Bahadir [50] prepares mixtures containing 0.9 and 1.8 kg/m^3 fiber to examine the effect of polypropylene fiber type on the mechanical properties of concrete mixtures. The author reports that monofilament polypropylene fibers significantly increase the tensile strength of concrete while multifilament fibers reduce the void ratio of the concrete, thus contributing to the strength of the concrete.

Celep [46] states that the use of polypropylene fiber positively affects the mechanical properties of the concrete mixtures, it increases the tensile and flexural strengths by acting as auxiliary reinforcement, and it improves the durability performance of the concrete.

Sümer and Sarıbıyık [70] study the effect of silica fume and polypropylene fiber usage on the properties of concrete mixtures. For this purpose, concrete mixtures were prepared by adding 5%, 10%, 15% silica fume of cement weight and 0.10%, 0.50%, 1.00% polypropylene fiber by volume. In the experiment, the compressive and flexural strength of concrete increased in 1.00% and 0.50% fiber-reinforced concretes while the compressive and flexural strength of concrete decreased in 0.10% fiber-reinforced concretes.

In their study, Fathima and Varghese [71] state that the optimum polypropylene fiber usage rate in terms of compressive, splitting tensile strength and flexural strength of concrete mixtures is 0.5% by volume.

Memon et al. [72] investigate the effect of polypropylene fiber length on the mechanical properties of concrete mixtures. For this purpose, concrete mixtures were prepared by using polypropylene fiber which was 12.25 mm and 25.4 mm long at the ratios of 0.20%, 0.25% and 0.30% by volume. It was seen that the compressive strength increases with fiber addition to the mixtures while this effect decreases with an increase in the fiber length. An increase in flexural strength was observed with the increase in fiber length. It was reported that as the usage rate of short fibers increases, compressive strength is not severely affected while flexural strength decreases. When it comes to the increase in the long fiber content, the compressive strength decreases while the flexural strength increases.

Altalabani et al. [73] investigate the mechanical properties of self-compacting light concrete containing polypropylene fiber. It was observed that the addition of polypropylene fiber does not affect the compressive strength but increases the elasticity modulus and splitting tensile strength. It was stated that the impact resistance and flexural strength of the mixtures increase significantly by the combined use of micro and macro polypropylene fibers.

In another study, the effect of polypropylene fiber utilization on the mechanical properties of light weight cementitious systems containing micro-perlite was investigated by Leong et al. [1]. For this purpose, concrete mixtures were prepared by adding polypropylene fiber at the rates of 0.15%, 0.30% and 0.50%. It was reported that the addition of polypropylene fiber to the mixture had no significant effect on the compressive strength of the mixture. However, in the case of presence low amount of fiber in the systems flexural strength increased by 27%. The flow ability of the mixtures negatively affected by the utilization of fiber. This effect was more pronounced by increasing fiber addition level.

3.3. Flexible resistance and post-crack behavior

In their study, Qian and Stroeven [62] investigate the effect of fiber type and length on the properties of concrete mixtures. They state that micro polypropylene fibers are effective in preventing minor cracks caused by dynamic loads. Also, they report that it will be more appropriate to use steel fibers or polypropylene fibers if the concrete fractures or it breaks under heavy loads.

Akkaş et al. [74] examine the effect of polypropylene fiber usage on the properties of semi-lightweight concrete. It was reported that the fibers prevent cracks which occur in samples under a compressive load and that the samples do not break into pieces in cases where fracture occurs.

In their study, Hüsem and Demir [75] investigate the effects of steel and polypropylene fiber use on some mechanical properties of conventional and high strength concrete mixture. It was reported that the compressive and tensile strengths of conventional and high strength concrete with steel and polypropylene fibers are higher than the control mixture. It is noted that the fracture is more ductile in high-strength samples with polypropylene fibers compared to the fiber-free mixture.

Zhang and Li [76] study the effect of polypropylene fiber used on the fracture properties of concrete mixtures containing silica fume and fly ash. For this purpose, concrete mixtures were prepared using 0.04%, 0.06%, 0.08%, 0.10% and 0.12% fiber by volume, 15% fly ash and 6% silica fume. Beam samples were subjected to a three-point flexure test. By adding fiber to the mixture, the fracture parameters of concrete mixtures such as fracture toughness, fracture energy, effective crack length and maximum aperture deviation were substantially positively affected. This event became more evident with the increase in fiber use rate.

Madhavi et al. [48] report that the use of polypropylene fibers prevents the cracks which are spontaneously formed in mixtures and it increases cohesion; therefore, fracture is ductile and gradual.

In another study, Wang et al. [17] investigate the effect of the use of macro polypropylene fiber and processed rubber on the mechanical properties of concrete mixtures. For this purpose, a total of four series of concrete mixtures were prepared using 0.5% fiber and 10–15% rubber by volume. The compressive and tensile strength of the mixtures decreased as the ratio of rubber aggregates increased. However, the combined use of macro polypropylene and rubber aggregate significantly improved the post-fracture behavior of the mixtures. This effect was more evident with the increase of the rubber ratio.

As it can be seen from the results, in general, fiber addition to the mixture negatively affected the compressive strength. However, it was found that there are studies in which the compressive strength of fiber-containing mixtures is higher than that of fiberless concrete. It is thought that the decreases in compressive strength with the use of fibers are caused by the increased void amount as a result of the non-homogeneous distribution of the fiber in the matrix. When the fiber is homogeneously distributed in the mixtures, it can prevent lateral deformations caused by loading and increase the compressive strength. It is known that the bridging effect of the fibers transports the load from the weak area to the stronger areas, preventing the advancement of micro-cracks in the matrix. Thus, it causes an increase in the tensile and flexural strength of the mixtures. However, as a result of the formation of flocculation in the mixture due to the excess amount of fiber, the flexural strength decreases with the increase of the void volume.

It is known that fiber length is one of the other important parameters affecting the mechanical properties of cementitious systems. The use of microfibers positively affects the flexural and tensile strength of the mixtures by preventing micro-cracks that occur during loading. However, it was emphasized that the use of macro fiber does not have a significant effect on the strength properties. It was declared that the energy absorption capacity of the mixtures increases due to the bridging effect that occurs with the use of these fibers.

3.4. Abrasion and impact resistance

Can et al. [77] investigate the effect of steel and polypropylene fiber usage on the abrasion resistance of concrete mixtures. For this purpose, in addition to the control mixture, three series of mixtures were prepared by using steel and polypropylene fiber at ratios of 0.1%, 0.3%, and 0.5% by volume. In terms of wear resistance, it was reported that steel fiber, polypropylene fiber, and fiber-free mixtures are the best mixtures, respectively.

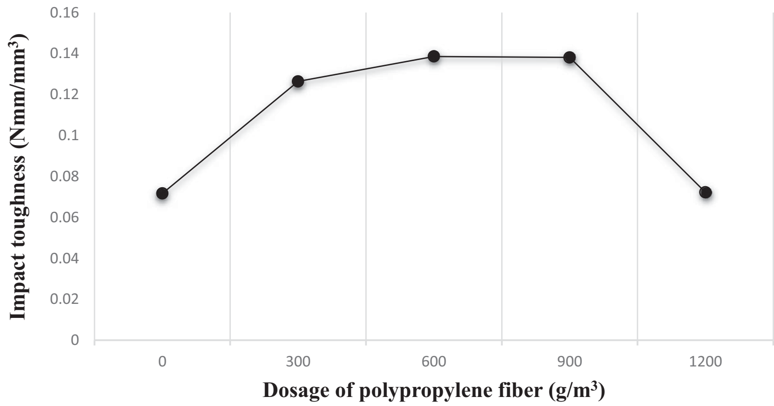

Figure 2. The relationship between the amount of polypropylene fiber and impact strength [79].

Nili and Afroughsabet [78] investigate the effect of using different amounts of polypropylene fiber on compressive strength and impact performance of concrete mixtures which contain 8% silica fume with 0.36 and 0.46 water/cement ratios. For this purpose, a total of five series concrete mixtures were prepared by adding 12 mm polypropylene fiber in four different proportions between 0.2% and 0.5% to the fiber-free control mixture. As a result of adding fiber to the mixtures, an increase in compressive, splitting tensile strength, flexural strengths, and impact performance was observed. This increase has become more evident by the increase in the rate of fiber use. In addition, the authors report that the presence of silica fume in the system causes polypropylene fiber to be more homogeneously distributed in the matrix.

Caf [79] studies the effect of polypropylene fiber usage rate on the impact performance of concrete mixtures. For this purpose, in addition to the control mixture, four series of concrete mixtures containing 300, 600, 900 and 1200 g/m^3 polypropylene fiber were prepared. Figure 2 shows the results of the impact toughness of the mixtures. The impact toughness of the mixtures increased with use of fiber as shown in Figure 2. While the impact toughness of the mixtures increased as the fiber content increased up to 600 g/m^3, it was not severely affected by the addition of fiber above this amount. Furthermore, the impact toughness value decreased as the fiber content increased to 1200 g/m^3. This phenomenon is thought to have been caused by the increase in pore volume as a result of agglomeration in the mixture which occurs with an increase in fiber content by greater than a certain ratio.

In another study, Mardani-Aghabaglou et al. [18] investigate the durability performance and dimensional stability of polypropylene fiber concrete mixture. For this purpose, in addition to the control mixture, 0.40%, 0.80% and 1% ratio by volume of polypropylene fiber was control mixtures four series of concrete mixtures were prepared. In all mixtures, water/cement ratio, cement dosage, and slump value were kept constant at 0.45, 350 kg/m^3, and 130 ± 10 mm respectively. Figure 3 shows the weight loss of concrete mixtures after exposure up to 360 cycles. As expected, the weight loss of concrete mixtures increased as the number of abrasion cycles increased. The loss in question decreased as the fiber ratio increased. As seen in Figure 4, the abrasion resistance of fiber-containing mixtures is 12–22% higher compared to the control mixture.

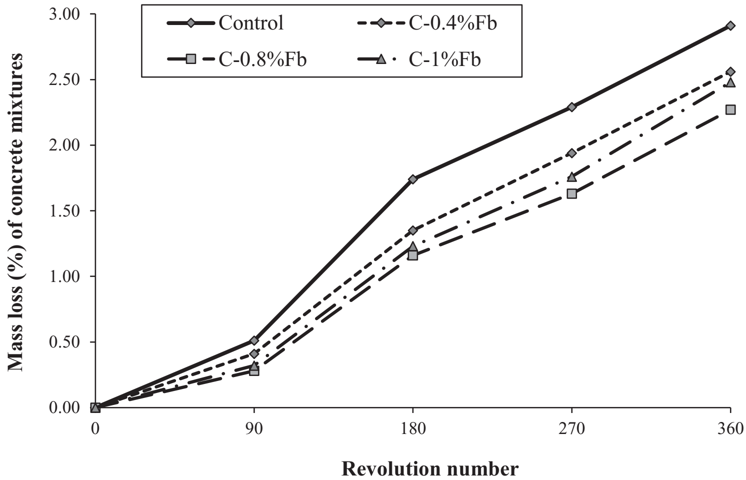

Figure 3. Weight loss in concrete mixtures exposed to 360 abrasion cycles (%) [18].

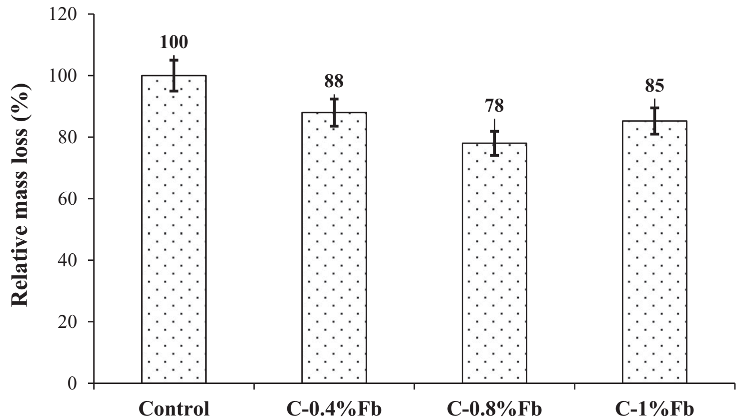

Figure 4. Relative weight loss in concrete mixtures exposed to 360 abrasion cycles (%) [18].

Besides, it was reported that the mixture which contains 0.80% fiber performs best in terms of abrasion resistance.

3.5. Shrinking

Aulia [64] investigates the effect of fiber usage in high strength concrete which contains silica fume. For this purpose, 0.20% fiber with a length of 19 mm was used. It was reported that the fibers in question do not affect the compressive strength and elasticity modulus but they reduce early shrinkage cracks.

In their study, Kirca and Şahin [80] investigate the effect of polypropylene fiber use on some properties of concrete mixtures which contain white cement. For this purpose, concrete mixtures containing 600 g/m^3 fiber with a 0.49 water/cement ratio were prepared. With the use of polypropylene fiber, a 25% reduction in the drying-shrinkage deformations of the mixtures was observed.

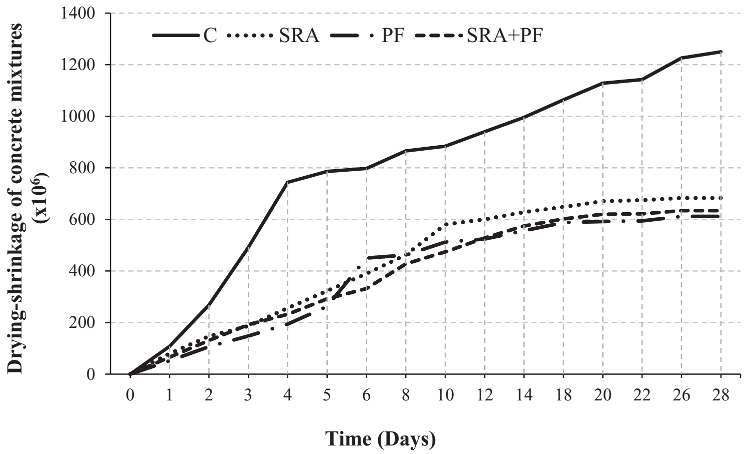

Figure 5. 28-day drying shrinkage values of concrete mixtures [3].

Song et al. [81] investigate the effect of using polypropylene and plastic nylon fiber on some mechanical and durability properties of concrete mixtures. For this purpose, the rate of nylon and polypropylene fiber usage in all mixtures was kept constant at 0.60 kg/m^3. It was reported that plastic nylon fibers perform better in preventing shrinkage cracks compared to polypropylene fibers.

Banthia and Gupta [5] investigate the effect of polypropylene fiber geometry on cracks caused by plastic shrinkage. In this regard, concrete samples were prepared using Monofilament and Multifilament polypropylene fibers of different lengths and diameters at the rates of 0.1%, 0.2% and 0.3%. It was seen that the use of polypropylene fiber is effective in preventing cracks. Thin fiber compared to thick one, long fiber compared to short one, and fibrillated fiber compared to Multifilament fiber have been reported to be more effective in controlling cracks.

Aly et al. [4] investigate the effect of polypropylene fiber usage on the shrinkage behavior of concrete mixtures which contain blast furnace slag. For this purpose, concrete mixtures were prepared using different proportions of polypropylene fiber in the range of 0.05% to 0.5% by volume. According to the results of early age-restricted shrinkage in slag concretes, it was reported that polypropylene fibrous concretes tend to crack more than non-fibrous concretes since they have higher shrinkage and modulus of elasticity.

Ilhan [3] investigates the effect of polypropylene fiber and shrinkage reducing admixture (SRA) utilization on fresh and hardened state properties of cementitious systems. For this purpose, three series of concrete mixtures whose water/cement ratio was kept constant at 0.4, cement dosage at 450 kg/m^3, and a slump value at 210 ± 20 mm were prepared. In the first series of mixtures, SRA up to 2% of the cement weight was used. In the second series, polypropylene fiber was used at a rate of 1% of the total volume. In the third series, fibrous mixtures containing SRA were prepared using both 2% SRA and 1% polypropylene Figures 5 and 6 show the drying-shrinkage and relative shrinkage results of the mixtures respectively. According to the experimental results, the use of polypropylene fiber showed better results than the use of shrinkage reducing admixture in terms of drying shrinkage. The combined use of polypropylene fiber and

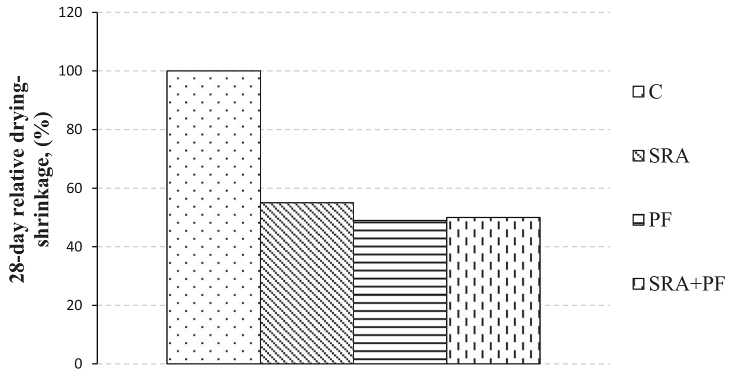

Figure 6. 28-day relative drying shrinkage values of concrete mixtures [3].

shrinkage reducing admixture did not show any positive effect in terms of drying shrinkage.

Wang et al. [17] report that the drying-shrinkage of mortar samples becomes limited and that the length change which is caused by the alkali-silica reaction decreases thanks to the combined use of rubber and polypropylene fiber together.

Mardani-Aghabaglou et al. [82] examine the effect of shrinkage reducing admixture and polypropylene fiber usage on the shrinkage behavior of concrete mixtures. They report that shrinkage formation decreases with the use of shrinkage reducing admixtures and fiber. However, it is noted that fiber use is more effective than shrinkage reducing admixtures in terms of shrinkage. Leong et al. [57] investigate the effect of polypropylene fiber use on drying shrinkage of lightly cemented systems that contain micro-perlite. It was reported that the addition of polypropylene fiber has a positive effect on drying shrinkage behavior.

The use of fiber increases the tensile strength of concrete mixtures and reduces the formation of cracks due to shrinkage. In addition, the fibers in the matrix prevent crack expansion by distributing the stresses caused by shrinkage. Thus, the dimensional stability of concrete mixtures is positively affected.

3.6. Resistance to high temperature

Aulia [64] and Varghese et al. [83] observe that when the high strength fibrous concrete exposed to high temperatures, the resistance to fire increases as a result of melting of polypropylene fibers at 160 °C.

Noumowe [84] examines the change in mechanical properties of high-strength concrete samples which contain polypropylene fiber after their exposure to 200 °C. It was observed that polypropylene fibers melt at 170 °C and cause air channels in concrete. The canals formed by melting of polypropylene fibers have been observed as a result of DSC (Differential Scanning Calorimetry) and TG (Thermogravimetric) analyses. The pores formed as a consequence of melting polypropylene fibers have been clearly seen by microscopic examination. Compressive strength, flexural strength, and elasticity modulus of concrete samples which have porous structure have decreased. However, the negative impact of these mechanical properties in question was slightly more obvious in fiber-free mixtures compared to fibrous mixtures.

Xiao and Felkner [85] investigate the high-temperature resistance of high-strength concrete mixtures which contain polypropylene fiber. Explosion and cracking which occur in fiber-free samples have not been observed in samples containing polypropylene fiber. It was observed that a temperature up to 400 °C positively affects the strength of the samples while a temperature above this causes a decrease in strength. It was observed that the flexural strength decreases as the temperature increases regardless of fiber use.

Celep [46] investigates the change of the mechanical properties of polypropylene fiber concrete mixtures which are exposed to high temperature. In addition to the fiber-free control mixture, concrete samples containing two different rates of polypropylene fiber and at different water/cement ratios were produced. The samples were left at 20, 200, 400 and 600 °C temperature effect after curing for 28 days. Explosion and cracking occurred at 600 °C in non-fiber concrete exposed to high temperatures. However, such phenomena were not observed in concretes containing polypropylene fiber. It was observed that the ducts which are formed by the melting of polypropylene fibers exposed to high temperature help release the internal pressure of the concrete and increase its resistance against fire.

Atashafrazeh [86] studies the compressive strengths of polypropylene fiber concrete after its exposure to high temperature. For this purpose, in addition to the fiber-free control mixture, concrete samples which contain 300, 600, 900 and 1200 g/m^3 polypropylene fiber and fiber rod were produced. The produced samples were exposed to 23, 150, 300, 450, 600 and 750 °C temperatures at the end of the 28th day. The highest compressive strength was found in samples containing 300 g polypropylene fiber. Rod polypropylene fibers have been reported to be more successful in terms of high temperature performance compared to fiber polypropylene ones.

Abaeian et al. [87] investigate the effect of polypropylene fiber use on resistance of high-strength concrete mixtures to high temperature. For this purpose, high-strength concrete mixtures were prepared using macro synthetic polypropylene fiber at the rates of 1, 2 and 3 kg/m^3. In terms of strength, a 1 kg/m^3 fiber usage rate was reported as an optimum rate. Compressive, tensile and flexural strength of samples have increased by 14%, 7% and 15%, respectively.

Aygörmez et al. [88] investigate the effect of geopolymer composites on high temperature resistance. For this purpose, 0.8% polypropylene fiber by volume was added to the mixture. In the study, it is pointed out that the use of fiber does not have a significant effect on resistance of the mixtures to high temperature.

Due to the evaporation of the water in the concrete due to the effect of high temperature, the osmotic pressure increases and cracks occur in the mixtures. Thus, the strength of the mixtures is negatively affected. In systems containing polypropylene fiber exposed to high temperatures, two different mechanisms occur. First, extra pores are formed in the matrix as a result of the fiber melting under the effect of temperature. These pores minimize the negative effect of osmatic pressure. Thus, the resistance of the mixtures to high temperature increases. As the second mechanism, the increase in the pore volume caused by the melting of the fiber negatively affects the compressive strength of the concrete mixtures. It is understood that the first mechanism is more dominant in fibrous samples exposed to high temperature.

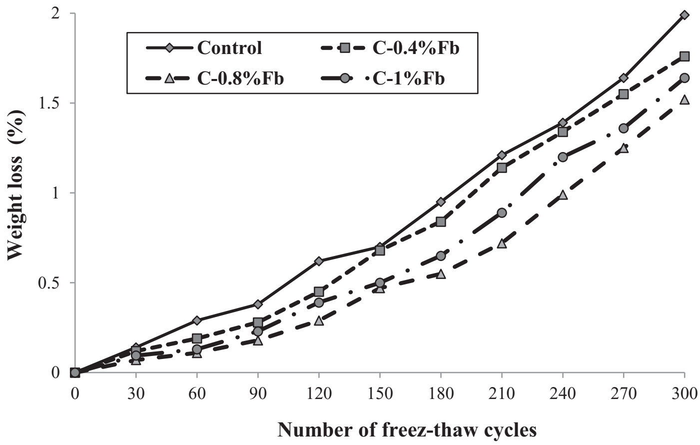

Figure 7. Relative weight loss in concrete mixtures exposed to freeze-thaw cycles (%) [18].

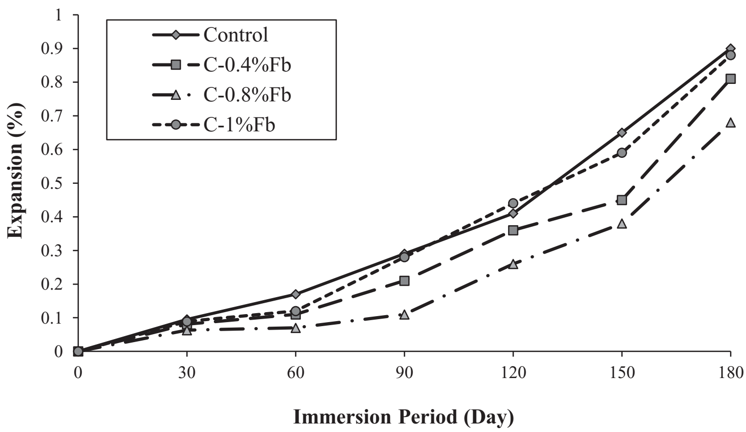

Figure 8. Expansion in concrete mixtures exposed to sodium sulfate solution (%) [18].

3.7. Freeze-thaw and sulfate resistance

Mardani-Aghabaglou et al. [18] investigate the effect of polypropylene fiber usage on the freeze-thaw and sulfate resistance of concrete mixtures. For this purpose, in addition to the fiber-free control mixture, three different concrete mixtures were prepared by adding polypropylene fiber at a rate of 0.4%, 0.8%, and 1% of the total concrete volume. Figures 7 and 8 show the weight loss caused by freeze-thaw cycles of the mixtures and the length change due to sulfate attack respectively. As seen in Figure 8, after 300 cycles, the mixture which contains 0.8% fiber by volume is superior in terms of freeze-thaw performance with 24% less weight loss compared to the control mixture. This ratio was measured as 0.4% and as 12% and 18% for fiber mixtures respectively. It was reported that the permeability property of the mixtures is an important feature that determines the freeze-thaw resistance and the use of fiber to a certain extent reduces the permeability. The authors report that the permeability of the mixture increases when the fiber content exceeds 0.8% thus, the water entering the capillary pores damages the structure of the concrete by internal expansion during freezing. Similar results have been observed in the sulfate resistance performance of the mixtures as well.

Wang et al. [17] investigate the effect of the use of macro polypropylene fiber and rubber on freeze-thaw resistance of concrete mixtures. For this purpose, they have prepared three additional mixtures to the control mixture using 0.5% fiber by volume and 10% to 15% rubber. According to the results, the mixture which contains 0.5% microfiber and 10% rubber has the most outstanding result in terms of freeze-thaw performance.

In another study, Yuan et al. [89] examine the effect of fiber type and usage rate on the freeze-thaw resistance of slag and class F fly ash-based geopolymer concrete mixtures. For this purpose, they used polypropylene, polyvinyl alcohol and steel fiber in 3 different ratios, 0.15%, 0.30% and 0.45% by volume. They report that adding fiber to the mixture does not prevent the formation of micro cracks, yet it prevents the propagation of the formed cracks regardless of the type of fiber. Optimum fiber usage rate was obtained as 0.30% in terms of freeze-thaw resistance in all mixtures. The authors state that mixtures which contain steel fiber have the lowest performance in terms of freeze-thaw resistance in all usage rates compared to the other two types of fiber.

Wongprachum et al. [16] investigate the effect of fiber type length and usage rate on the sulfate resistance of mortar mixtures. In their study, the authors have prepared a total of eight different combinations of fiber mixtures by using polypropylene and steel fiber separately and combined, in different proportions, and macro and micro sizes. According to the results, the sample which contains 1% macro polypropylene fiber has the best result among all the weight losses of the samples exposed to sulfate attack for 8 months. The use of macro fibers in combination with microfibers shows the highest performance in terms of sulfate resistance.

Algin and Gerginci [90] investigate the effect of the use of macro synthetic fiber on the freeze-thaw resistance and permeability properties of roller-compacted concrete mixtures. In their experiment, the authors prepare four different concrete mixtures by adding macro synthetics which are 0%, 0.2%, 0.4%, and 0.6% by volume and have an aspect ratio of 80 to the mixture. It was observed that the freeze-thaw resistance of the mixtures increases with the use of fiber. However, the 0.4% fiber use rate is indicated as optimum in terms of freeze-thaw performance. The authors report that fiber use positively affects the freeze-thaw resistance by preventing cracking which occurs on the surface of the mixtures.

In another study, Nguyen et al. [19] investigate the effect of polypropylene fiber usage on the durability properties of ettringite-based composites exposed to both freeze-thaw and sulfate chlorine solution. For this purpose, the researchers used the multifilament type polypropylene fiber with an aspect ratio of 833 and a ratio of 2% by volume. Samples were exposed to freeze-thaw cycles after being saturated in a solution containing 5% $NaSO_4$ and 3% NaCl. Thawing was carried out by immersion in the solution in question. Figure 9 shows the appearance of surface damages of fibrous and fiber-free samples exposed to both solution and freeze-thaw. As seen in Figure 9, the researchers did not observe macro cracks in polypropylene fibrous samples because of the ability to manipulate the crack propagation of the fibers despite some micro-cracks. Contrary to this, the non-reinforced sample exhibited very poor freeze-thaw resistance

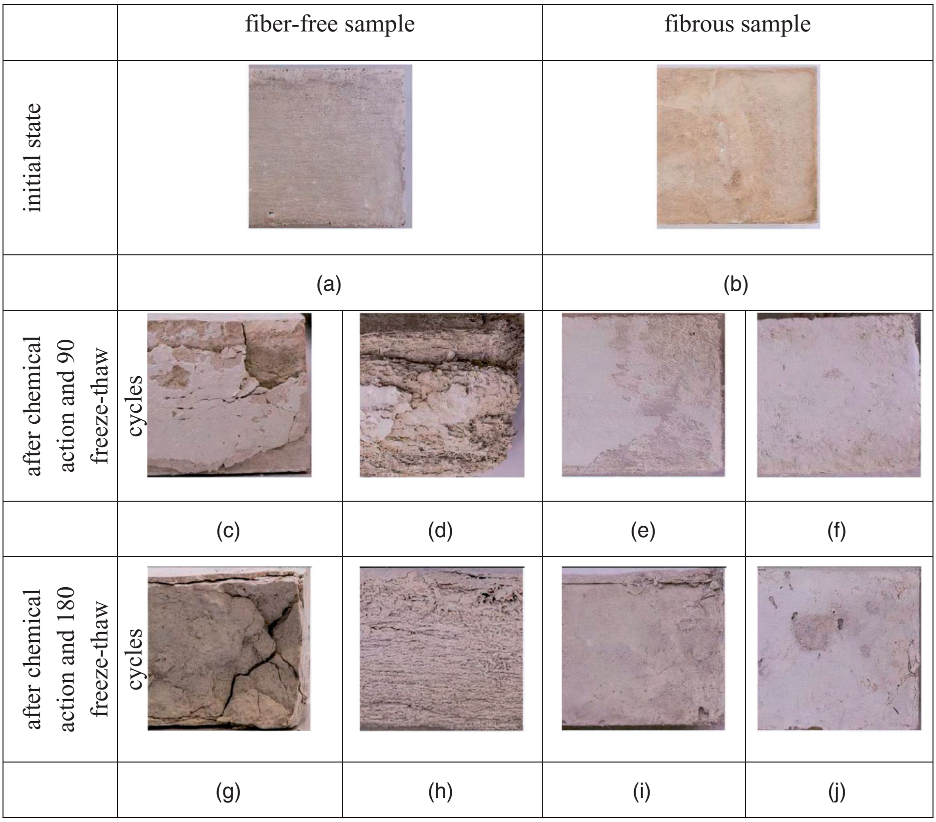

Figure 9. Appearances of fiber-free and fibrous samples exposed to chemical action and freeze-thaw [19].

and sulfate-chloride resistance and macro cracks were observed in its structure. In conclusion, researchers measured weight loss in fiber-free mixtures seven times more than fibrous mixtures.

According to XRD analysis results in the study, $C_{12}A_7$ crystals were observed on the fibrous sample while they were undetectable on the non-fibrous sample due to their reaction with the sulfate ion to form secondary ettringite. The authors state that secondary ettringite in fibrous samples is lower because of the fact that fibers' bridging action reduces the infiltration of sulfate ions *via* delaying crack propagation.

4. Conclusion

- The addition of polypropylene fiber to concrete mixtures negatively affects the workability of the mixtures. This effect is due to the fact that polypropylene fiber is not distributed homogeneously in cementitious systems and increases the risk of flocculation.
- The compressive strength of the mixtures was not severely affected. However, significant increases in tensile and flexural strengths were detected. In addition, the flexural toughness and ductility of the mixtures increased. This situation arises

from the prevention of crack development in concrete due to the bridging ability of the fiber.

- It is pointed out that while the addition of short polypropylene fiber has a serious effect on compressive strength, it slightly affects splitting tensile strength. Compressive strength is negatively affected by adding long fibers to concrete mixtures.
- With the use of fiber, the resistance of the mixtures against high temperatures increases. Cracks occur in samples exposed to high temperatures due to the increase in osmatic pressure. The pore volume in the mixture increases as a result of the melting of the fiber under the effect of temperature. Thus, the negative effect of osmatic pressure is reduced. On the other hand, the compressive strength of the mixtures is adversely affected due to the increased pore volume as a result of the melting of the fiber. It was found that the first effect is more dominant in mixtures containing PP fiber.
- Durability and dimensional stability of the mixtures were positively affected. Specifically, shrinkage-induced length changes significantly decreased.
- The elasticity modulus, abrasion and impact resistance of the mixtures were positively affected.
- In addition to these, microstructure studies show that the fibers are distributed more homogeneously in the matrix with the addition of mineral additives in mixtures that contain fiber.
- It is pointed out that both the sulfate and freeze-thaw resistance of the mixtures increases with fiber use. Thanks to the presence of fiber prevention of propagation of the micro-cracks formed in the matrix reduce the degree of damage. Samples that contain macro-fiber and micro-fiber combined are seen to perform superior in terms of freeze-thaw and sulfate resistance.
- The bridging effect of the fibers was observed to reduce the development of expansion due to freeze-thaw, sulfate attack and alkali-silica reaction.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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