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TECHNICAL PAPER

Effect of macro-synthetic fibers on the drying shrinkage performance of rigid pavement

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Abstract

Rigid pavement provides excellent advantages in terms of durability and economic efficiency. However, appropriate maintenance of this pavement is difficult in case of deterioration. Drying shrinkage cracking in the rigid pavement is the main reason of such disadvantages, and the need of maintenance on road sites is rising every day. For the aim of restricting drying shrinkage cracking, fibers are used in fresh concrete. Accordingly, this study evaluates the performance of using macro-synthetic fibers (MSF) in reducing the drying shrinkage strain in order to reduce cracking of the concrete pavement mix to restrict the deterioration of the pavement. The mechanical properties (compressive strength, splitting tensile strength, flexural strength) and the drying shrinkage of the plain concrete (PC) and macro-synthetic fiber-reinforced concrete (MSFRC) are evaluated. The results show that the effect of MSF on the compressive strength is minimal, while the splitting tensile strength and flexural strength of MSFRC are improved by 20 and 34%, respectively. Furthermore, the drying shrinkage strain of MSFRC can be significantly reduced by about 60% compared with that of PC.

Keywords Rigid pavement · Macro-synthetic fibers · Cracking · Drying shrinkage · Mechanical properties

Introduction

Two mechanisms are generally used for road pavement: the asphalt concrete pavement that is flexible pavement and the cement concrete pavement that is rigid pavement. Rigid pavement provides long-term service life and brilliant applicability for heavy traffic. However, appropriate maintenance of the rigid pavement is more difficult than the flexible pavement in case of deterioration [1, 2].

Shrinkage is a common phenomenon of concrete, which can induce tensile stress when the shrinkage is restricted, and may lead to cracking and finally decrease the service life of concrete structures [3]. Deformation due to shrinkage of concrete is one of the major causes for appearance of cracks, especially for concrete elements with large exposed surfaces such as pavements [4].

Drying shrinkage is one of the most important factors of pavement concrete durability [5]. It takes place because of humidity exchange arising from relative humidity changes between environment and concrete [6–8]. Drying shrinkage mechanism is complex which is not fully understood even nowadays [9]. The drying shrinkage is influenced by many factors such as water-to-cement ratio, reinforcement and fibers [10]. In restricting drying shrinkage cracks, an effective method was recommended: using synthetic fibers in fresh concrete [11–13]. The aim is to produce high early-age mechanical capacity for moderating the growth of crack in a way that the existence of fibers would cause more cracks but with small dimensions. It may transfer tensile stresses by reducing stress concentration [14].

Many studies have been carried out to examine the effect of using polypropylene (PP) fibers on drying shrinkage of concrete. The results stated that the PP fiber-reinforced specimens showed higher drying shrinkage strains compared with PC [15, 16]. However, these authors clarify that their conclusions are in inconsistency with those of several

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other researchers. In contrast, other study showed that the drying shrinkage of PP fiber-reinforced concrete was about 75% less than that of a plain concrete without fibers [17]. Additionally, adding 0.5% of polyvinyl alcohol (PVA) fibers had a slight impact on reducing the drying shrinkage [18]. A recent review article regarding the performance of the macro-synthetic fibers indicates that there is currently no definite conclusion on this issue [19]. There are many studies on the effect of fibers on drying shrinkage; however, there is not a strong agreement among the researchers [20].

Structural macro-synthetic polypropylene fiber as an innovative solution to enhance the engineering properties of concrete has been expected to be one of the fastest growing sectors of the synthetic fibers industry. Furthermore, the effect of adding structural macro-synthetic polypropylene fiber on reducing the drying shrinkage strain has not been investigated. As a result, this study was designed to evaluate the drying shrinkage strain with respect to the fiber reinforcement in order to restrict cracking of rigid pavement, besides improving other mechanical properties. Mechanical properties of specimens are characterized by using compressive, flexural and tensile strengths.

Objective of study

Drying shrinkage can contribute significantly to the cracking observed in cement concrete pavement that can lead to degradation or damage. By controlling the drying shrinkage in concrete, cracking will be reduced and that will enhance the durability of rigid pavement for longer service life. So, the aim of this study is to examine the effect of structural macro-synthetic fiber on the drying shrinkage behavior to control cracking of concrete pavement.

Experimental program

Materials

Cement

The cement used in this study was ordinary Portland cement type I (CEM-I 42.5 N) in compliance with the EN 197-1 standard [21]. The physical and mechanical properties of the cement and the Egyptian standard specifications [22] are listed in Table 1.

Table 1 Physical and mechanical properties of the cement

Property		Value	Specification limits
Soundness (mm)		1.0	≤ 10
Initial setting time (min)		150	≥ 60
Final setting time (min)		195	–
Specific gravity (g/cm^3		3.05	–
Specific surface (cm^2/g)		3850	–
Flexural strength (MPa)	2 days	4.6	–
	28 days	7.3	–
Compressive strength (MPa)	2 days	19.2	≥ 10
	28 days	47.9	42.5 ≤ X ≤ 62.5

Aggregate

Locally available crushed stone from Suez Attaka quarry of sizes 20 and 10 mm in 50:50 proportion was used as coarse aggregate, and natural sand was used as fine aggregate. The physical properties of aggregate and the Egyptian standard specifications [23] are presented in Table 2.

Table 2 Aggregate properties

Property	Value	Specification limits
Bulk specific gravity (g/cm^3)	1.65	–
Fine particles (%)	1.1	≤ 2.5%
Water absorption (%)	1.7	≤ 2.5%
Los Angeles abrasion loss (%)	23.8	≤ 30%
Shape index (%)	8.5	≤ 25%
Flakiness index (%)	12.5	≤ 25%

Water and superplasticizer (SP)

Potable water was used in all concrete mixtures for casting and curing purposes. The superplasticizer used in this study was polycarboxylic ether (PCE) provided by BASF and complies with the ASTM C494 standard [24]. The superplasticizer was used to facilitate the dispersion of fibers throughout the concrete mixture and to achieve an appropriate workability for concrete [25].

Fibers

The selection of synthetic fibers was done as per the current market trend and the conclusions of a literature survey. The structural macro-synthetic polypropylene fibers were found to be the most sustainable and desirable. The fibers were extruded from a natural polypropylene (PP) homo-polymer in compliance with ASTM C1116 [26] and EN 14889-2 [27]. The macro-synthetic fibers (MSF) were manufactured by BASF Construction Chemicals, Dubai, with a trade name Master fiber 249. Material properties and dosage of the MSF were supplied by the fiber manufacturer and can be found in the data sheet published at the BASF Web site [28]. Typically, MSF have been used in rigid pavement to protect plain concrete against drying

Table 3 Properties of the structural macro-synthetic polypropylene fibers

Properties	Value
Material	Polyolefin 100%
Design	Monofilament
Specific gravity	0.91
Equivalent diameter	0.85 mm
Length	48 mm
Aspect ratio	56.6
Tensile strength	400 MPa
Modulus of elasticity	4.7 GPa
Water absorption	Nil
Shape	Elliptical
Melting point	160 °C
Ignition point	350 °C

Fig. 1 Structural macro-synthetic polypropylene fibers

shrinkage [28]. These PP fibers were straight strips that had a continuously embossed surface texture to improve adherence and were highly resistant to chemicals and alkali. Further details about the characteristics of the MSF, as specified by the manufacturer [28], are given in Table 3. Figure 1 shows the shape of the fibers used in this study.

Mix design

Mixing was performed using a pan mixer of 0.1 m^3 capacity. Two batches with the same mix proportion were required to cast all the specimens. The first batch was used to cast all specimens of PC and the second one to cast all specimens of MSFRC. The ratio of water/cement (w/c) used in both mixtures was 0.45. A mixture without any MSF was prepared as a control. To produce PC, the process of mixing started with the dry mixing of the coarse and fine aggregates for 30 s. Subsequently, the cement was added to the mixture and blended for 1 min. Then, a liquid mixture consisting of water and SP was slowly poured into the mixture for 30 s, and then, the resulting mixture was stirred for 2 min to achieve a good concrete workability.

In the other mixture, the MSF were added into the PC mixture at a constant dosage of 6 kg/m^3 corresponding to a volume fraction (V_f) of 0.66%. The concrete mixture proportions are reported in Table 4: The same proportions were retained for the concrete matrix in MSFRC mixture realized as part of this research. To evaluate the effect of MSF on concrete mixture workability, the amount of SP was remained constant for both mixtures at 1.0% of the cement weight. MSF are usually added to the ready-mix concrete in the batch plant, and the produced concrete is not difficult for either pumping or implementation [29]. In this research, the MSF were added after mixing aggregates, cement and water, and the mixture was thoroughly mixed in the mixer for 2 min to achieve a uniform distribution. Two minutes of further mixing was considered adequate for the appropriate dispersion of the MSF in the mixture without causing a "balling" effect [30].

After the mixing procedure, the fresh properties of concrete, including slump, air content and fresh density, were then evaluated for each mixture. Before casting directly, the interior surfaces of the assembled mold shall be thinly coated with mold oil to prevent concrete adhesion. The concrete specimens were cast into cubes (100 mm), cylindrical molds (150 × 300 mm), prismatic molds (100 × 100 × 500 mm) and prismatic molds (75 × 75 × 258 mm). The specimens were cast in two layers and vibrated (25 s per layer) on a vibrating table. Then, a smooth steel trowel was used to finish the surface of fresh concrete.

After casting, specimens were covered with plastic sheets to prevent the loss of moisture and kept under standard laboratory conditions for 24 ± 2 h until demolding. The specimens were then placed in a curing tank (23 ± 2 °C and 95 ± 5% relative

Table 4 Concrete mix proportions (unit: kg/cm^3)

Type of mixture	Cement	Coarse aggregate		Fine aggregate	Water	SP	Fibers
		20 mm	10 mm				
PC	400	540	540	730	180	5.8	–
MSFRC	400	540	540	730	180	5.8	6

humidity (RH)) until they were tested, except for the prisms used for the measurements of shrinkage that were removed after 24 h, and initial values of test specimens were measured. Then, the specimens were kept under standard laboratory conditions of 23 ± 2 °C and 50 ± 5% RH until testing.

Test procedures

Fresh property

The fresh properties were measured immediately after the mixing procedure, and the slump, air content and fresh density were obtained by following the ASTM C143 [31], ASTM C231 [32] and ASTM C138 standard [33], respectively.

Compressive strength test

Compressive strength tests were conducted on three 100 × 100 × 100 mm cubic concrete specimens of every mixture according to EN 12390-3 [34] at the age of 3, 7, 14 and 28 days. The compression testing machine used was an ELE (Engineering Laboratory Equipment) with a load capacity of 2000 KN. The average of three compressive strength values was taken for each mixture.

Splitting tensile strength test

The splitting tensile strength test is well known as one of the simplest and most dependable tests for indirect assessment of concrete tensile strength [35]. The splitting tensile strength tests of the concrete specimens were conducted on the cylindrical 150 × 300 mm at 28 days in accordance with ASTM C496 standard [36]. Figure 2 shows the splitting tensile test setup. In this test, the load is applied continuously at a constant rate up to failure using a universal testing Shimadzu machine of capacity 500 KN. The maximum load at failure point was reported to determine the splitting tensile strength by Eq. (1), and the average strength was based on three samples.

$$f_{sp} = 2P/(\Pi DL) \tag{1}$$

where f_{sp} = splitting tensile strength (MPa), P = failure load (N), D = cylinder diameter (mm) and L = cylinder height (mm).

Flexural strength test

Flexural strength, sometimes also called as modulus of rupture (MOR), is like an evaluation of tensile strength in bending. Flexural strength tests were conducted on 100 × 100 × 500 mm prism test specimens at 28 days in accordance with ASTM C293 standard [37]. Three specimens were made for each mixture, and the average values were recorded. The adopted flexural test setup is shown in Fig. 3. The setup consists of two supporting rollers, 400 mm apart and one loading roller located at center. A universal testing machine used in flexural test is Shimadzu AG-500KN. The flexural strength of the concrete specimens was determined using Eq. (2):

Fig. 2 Splitting tensile test setup

Fig. 3 Flexural test setup

$$f_b = \frac{3\,P\,.\,L}{2\,b\,.\,h^2} \tag{2}$$

where f_b = flexural strength (MPa), P = peak load at failure point (N), L = specimen span (mm), b = width of specimen's cross section (mm) and h = height of specimen's cross section (mm).

Drying shrinkage test

The drying shrinkage tests were conducted to evaluate the drying shrinkage of concrete mixtures in accordance with ASTM C157 standard [38]. Four test specimens with dimensions of 75 × 75 × 285 mm were prepared for each mixture. Drying shrinkage measurements were taken using a digital dial gauge length comparator with 285 mm gauge length and a reading accuracy of 0.001 mm. The length comparator reading of each specimen was taken following the procedures described in the ASTM C596 standard [39].

Figure 4 shows the test setup used to measure the length changes of specimens. At the age of 24 ± 1 h, the specimens were demolded and the initial measurement for the length was conducted for all specimens. This measurement was used as the reference or 0-day measurement. Afterward, the length changes were measured at 2, 3, 7, 14, 21, 28 and 56 days for the all specimens after the initial measurement. The drying shrinkage value of each mixture at each period of curing was the average drying shrinkage value of the four specimens. At each measurement age, drying shrinkage of a specimen was determined for the same side and direction as the other ages to reduce the error of warping. Equation (3) was used to calculate the drying shrinkage strain at a particular time. Consider

Fig. 4 Drying shrinkage test setup

$$\varepsilon_{s,t} = \frac{L_t - L_0}{L_g} \tag{3}$$

where $\varepsilon_{s,t}$ = drying shrinkage strain at time t, L_t = specimen length measured at time t (mm), L_0 = specimen initial length (mm) and L_g = original gauge length (mm).

Results and discussion

Fresh concrete properties

The fresh properties of PC and MSFRC mixtures were studied, and the results are summarized in Table 5. The addition of fibers is well known to affect PC workability substantially [40]. In this research, the amount of water and SP was kept constant for both mixtures in order to assess the influence of MSF on MSFRC workability. From Table 5, it can be noted that the slump of 110 mm was obtained for the PC, and once the MSF were introduced, the slump decreased by 32% compared with that of control mixture. This slump reduction can be attributed to the fact that the use of fibers can form a network structure in the concrete matrix, consequently restraining mixture from segregation and flow [19]. Moreover, due to large surface area of the fibers, the fibers can easily absorb cement paste to wrap around, which in turn leads to an increase in the viscosity and a decrease in the workability of a concrete mixture [41].

In the case of air content as reported in Table 5, the introduced MSF contribute to the air content increase. The PC mixture showed air content of 2.7%, and the MSFRC mixture showed higher air content of 2.9%. The fibers can entrap more air during the process of mixing [42]. The large specific surface area of the fibers and their tendency to occasionally agglomerate can also contribute to air entrapment increase [43].

The densities of PC and MSFRC are 2344 and 2286 kg/m^3, respectively, as shown in Table 5. The density of MSFRC is reduced by 58 kg/m^3T than that of PC. Consequently, the density of MSFRC is reduced by 2.5% as compared with that of PC. The less density of MSFRC than that of PC is due to the existence of less density of MSF [44]. Furthermore, the aforementioned air content increase can slightly influence the density [42].

Table 5 Fresh concrete properties

Mixture ID	Slump (mm)	Air content (%)	Density (kg/m^3)
PC	110	2.7	2344
MSFRC	75	2.9	2286

Compressive strength

Figure 5 represents the results of compressive strength of the control and fiber-reinforced specimens at ages of 3, 7, 14 and 28 days. These results corresponded to the average of three specimens tested for each mixture at every age. Each mixture satisfied the target compressive strength of 30 MPa at age of 28 days. The compressive strength of samples containing MSF was less than that of the control mixture. The 28-day mean strength of PC was 34.7 MPa. The addition of MSF decreased the compressive strength by 9% in comparison with that of control mixture specimens. This decrease could be attributed to the existence of voids due to the addition of MSF and the presence of a weak interfacial bonds among the MSF and cement particles [45]. Furthermore, this decrease may be caused due to the negative influence of MSF on decreasing the density of mixture [29].

Splitting tensile strength

The results of the splitting tensile strength at 28 days are presented in Table 6. As can be noted from results, the splitting tensile strength of fiber-reinforced specimens was increased when compared with that of control specimens. The results clarified that the incorporation of MSF enhanced the splitting tensile strength of MSFRC mixture specimens by about 20% in comparison with that of control mixture specimens.

Even if the MSF have considerable tensile strength, the brittle concrete is not designed to withstand the tensile force and therein the cracks initiation is still restricted by the cement matrix quality, and the peak load normally occurred when the main crack happened in the concrete. However, after the crack occurred, the influence of fiber bridging could provide an important role in restricting the fast growth of the crack. Consequently, the MSF did not clearly enhance the splitting tensile strength of the control concrete, but it obviously participated to the crack restricting [42].

Table 6 Splitting tensile strength and flexural strength of concrete mixtures

Mixture ID	Splitting tensile strength (MPa)	Flexural strength (MPa)
PC	3.5	8.6
MSFRC	4.4	13.1

Behaviors of distinct failure of concrete specimens were noticed after the test of splitting tensile. As shown in Fig. 6, the control specimen displayed the apparent brittle failure. However, after the addition of MSF, the failure behavior of fiber-reinforced sample was changed, failure is gradual and less brittle and the two parts are not completely separated. The fracture morphology supported that the MSF can bridge the crack and keep the concrete specimen to sustain considerable load after the occurrence of first crack.

Flexural strength

Table 6 presents the results of 28-day flexural strength test of PC and MSFRC specimens. The results show that adding MSF increases the flexural strength of PC. The flexural strength of PC was 8.6 MPa, and the addition of MSF appeared to increase it by about 34%. It could be due to bridging mechanism of MSF which prevent cracks development and decrease the width of crack. Figure 7 displays the cracking mechanism of concrete specimens under flexural test.

It is obvious to observe that the control concrete specimens broke at the peak load into two parts exhibiting the brittle behavior. Brittle behavior is always related to PC [46].

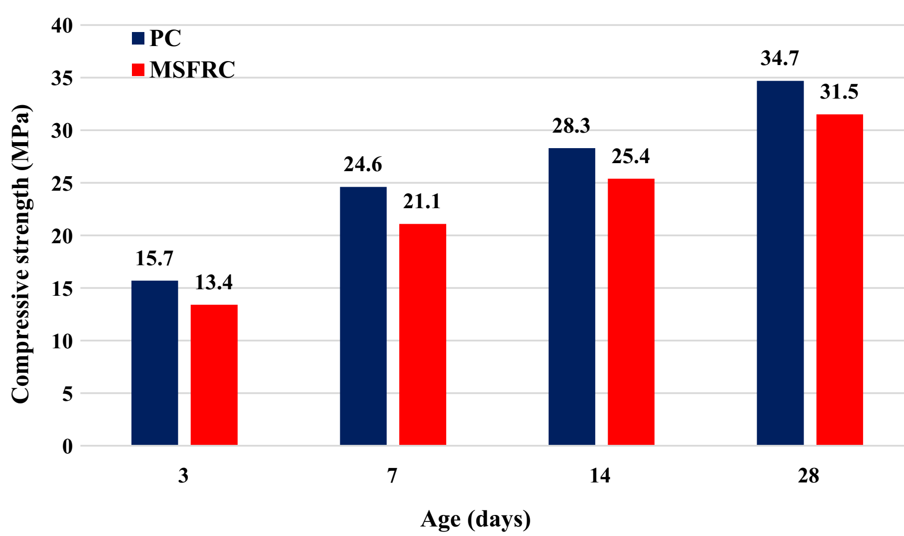

Fig. 5 Compressive strength of concrete mixtures

Fig. 6 The fracture sample morphology: **a** failed PC specimen; **b** failed MSFRC

When the first crack is occurred, the specimen cracks and collapses almost suddenly, with very small deformation and no prior warning. However, in FRC specimens, the failure progresses with bending, but without any sudden collapse as observed in plain concrete. When the concrete fails, the load is transmitted to the MSF. The MSF prevent cracks spread and hence delay the collapse [47].

Overall, through evaluating the mechanical characteristics of PC reinforced with MSF, it can be observed that the incorporation of MSF caused a decrease in compressive strength of PC; however, this decrease is negligible. Tensile strength and flexural strength of concrete increased by incorporation of MSF.

Drying shrinkage

Figure 8 presents the drying shrinkage strain under the time for control and fiber-reinforced specimens. As shown in Fig. 8, MSF have greatly restricted the drying shrinkage of PC. The comparison between the performance of the PC and MSFRC mixtures displays the highest contribution of MSF in decreasing the drying shrinkage strain by 60% at the age of 56 days. The results display that the shrinkage happened at a rapid rate for early ages, and then, the rate tended to stabilize after 25 days.

This may occur because the existence of MSF could adjust the internal water movements within the concrete [18]. Shrinkage reduction property of MSF can be applied in the area where concrete shrinkage is a concern (i.e., large floors, road pavements).

Fig. 7 Cracking mechanism of concrete specimens under flexural strength test: **a** PC; **b** MSFRC

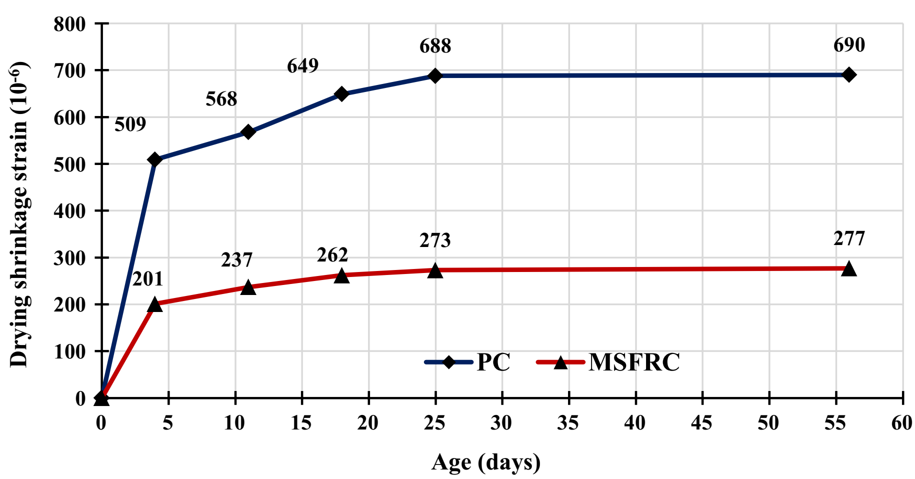

Fig. 8 Drying shrinkage of concrete mixtures

Conclusions

Based on the results of this study, the following conclusions can be drawn:

1. Using MSF in PC decreases fresh concrete workability.
2. Adding MSF led to a slight increase in air content of MSFRC compared with that of PC.
3. The density of fresh concrete is not mainly influenced by the incorporation of MSF due to their lower specific gravity.
4. The incorporation of MSF had no significant influence on compressive strength of MSFRC; 9% decrease in compressive strength was observed.
5. The incorporation of MSF increases the 28-day splitting tensile strength of MSFRC by about 20% compared with that of PC.
6. The 28-day flexural strength of MSFRC increased by about 34% compared with that of PC.
7. The influence of adding MSF in enhancing the flexural strength of PC is more pronounced compared with its effect on splitting tensile strength.
8. Incorporating MSF has much greater influence on decreasing the drying shrinkage strain in MSFRC compared with PC.
9. The 56-day drying shrinkage strain of MSFRC reduces by 60% compared with that of PC, and it was confirmed that the drying shrinkage strain decreasing performance was the best.
10. Adding MSF has an effect on restrained drying shrinkage in concrete, as well as on the control of cracking.
11. Incorporation of 0.66% MSF was found to be effective for concrete considering compressive (9% decrease), tensile (20% increase) and flexural (34% increase) strengths and shrinkage (60% decrease) properties of concrete under this study.
12. In general, the results obtained and the observation made in this study propose that concrete incorporating MSF can be used with satisfactory engineering properties in the construction of concrete pavement.

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Declaration

Conflicts of interest The authors declare that they have no conflict of interest.

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