PERFORMANCE OF STEEL MICRO FIBER REINFORCED MORTAR MIXTURES CONTAINING PLAIN, BINARY AND TERNARY CEMENTITIOUS SYSTEMS

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ABSTRACT

Steel micro fibers provide strengthening, toughening and durability improvement mechanisms in cementitious composites. However, there is not much data in the literature regarding how the extent of their effectiveness changes depending on the type of matrix being reinforced. For clarifying this point, the influence of a constant volumetric ratio (1%) of 6 mm long steel micro fibers on the performance of 5 mortar mixtures was investigated and were prepared using plain, binary and ternary cementitious systems. A total of 10 mixtures were cast. The mineral admixtures used in the study include silica fume (SF), metakaolin (MK) and a Class C fly ash (FA). While the replacement levels of SF and MK were 10% by weight of the total mass of the binder, this ratio was chosen as 30% for FA. In addition to the behavior of the mixtures under compressive, flexural and impact loads, abrasion, water absorption, chloride ion penetration, freezing-thawing resistance and drying shrinkage characteristics of the mixtures were determined. Test results indicate that generally the refinement in the pore structure of the matrix provided by mineral admixtures and the increase in resistance against growth and coalescence of micro-cracks provided by fibers produce a synergistic effect and improve the investigated performances of the mixtures.

KEYWORDS:

steel micro fiber, mineral admixtures, mechanical and transport properties, durability performance

1. INTRODUCTION

Low tensile strength and low strain capacity are among the most important characteristics of plain, unreinforced cementitious systems. Continuous reinforcing bars embedded in concrete at appropriate locations in order to withstand tensile and shear stresses have helped this quasi-brittle material to gain popularity. However, fiber-type materials are discontinuous; they are more closely and randomly distributed than reinforcing bars. This imparts more

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effective crack control ability, particularly when concrete is subjected to stresses that are generated due to humidity or temperature variations. Concrete components with a large surface area such as slabs and pavements have a high tendency for cracking and fibers act as secondary reinforcement (in addition to reinforcing bars) by providing post-cracking ductility. In thin sheet components in which there exists no possibility to use reinforcing bars, the role of fibers become the main reinforcement; therefore, they improve both the strength and toughness. Other examples for application areas of fibers include tunnel linings, blast resistant structures and precast piles [1].

Recent developments in concrete technology, including the use of highly effective chemical admixtures as indispensable ingredients have led to significant reductions (reaching even below 0.2) in water/cementitious material ratios. While low- and moderate-strength concrete have low post-peak ductility performance, the extremely high ultimate strength levels (i.e. >200 MPa for reactive powder concrete) lead to even more brittle failure. For this reason, fibers consistently remain attractive materials for the production of high strength cementitious composites with high ductility [2-4].

Fibers to be used for reinforcing cementitious matrices are expected to have some appropriate intrinsic material properties, such as far superior tensile strength compared to that of the matrix, resisting strains well in excess of the matrix cracking strain, a Poisson's ratio not significantly exceeding typical values applicable to cementitious matrices (0.20-0.25) and a low creep tendency. In this respect, steel fibers showing truly elastic behavior, high elastic modulus and compatibility with the matrix offer greater reinforcing effectiveness than polymeric fibers like polypropylene and nylon [5]. The ability of macro steel fibers in enhancing the post-peak response and hence the toughness of concrete has successfully been proved in many studies [6-10]. After the formation of the first cracking, which corresponds to the deviation from linearity in the stress-strain curve (bend over point), large fibers effectively bridge crack faces. This process prevents the widening and propagation of macro-cracks which in turn impart significant improvement to the toughness of the composite [11,12]. However, in most instances, large fibers fail to enhance the pre-peak response and tensile strength of the matrix. This is due to the spacing between large fibers being high which makes the bridging of the micro-level-cracks difficult. In contrast, for a given volumetric ratio, fibers with smaller size and higher specific surface area are expected to better arrest micro-cracks before they reach unstable dimensions. Thus, the use of micro-fibers offers the advantage of acquiring both a stronger and tougher composite at the same time [12,13].

Banthia and Sheng [12] investigated the performance of 3 mm long steel micro-fiber-incorporating cement paste and mortar beams. They found increasing bend over point load and peak load values along with reductions in crack tip opening displacements as the amount of volume fraction of steel micro-fiber in the composite increased from 1 to 3%. Improvements in strain hardening and multiple cracking behaviors gained through the addition of shorter fibers were reported in tension [14] and flexure [15] tests. Lange et al. [13] conducted "rule of mixtures" analysis and they differentiated the loads resisted by the matrix portion and fiber portion. The authors concluded that the presence of micro-fibers enhances the strength contribution of the matrix due to a synergistic effect. The images of the fracture surfaces in notched beams showed that the surface roughness, which is related to crack tortuosity and toughness, increased as the fiber content increased [13,16]. Ostertag and Yi showed that the dominant toughening mechanisms produced by the addition of steel micro-fibers were successive debonding at the fiber interface and multiple micro-cracking along the length of the fibers. The authors discussed the effect of fiber bridging and crack-aggregate interaction (aggregate bridging and aggregate pull-out) on the strain hardening behavior by conducting in-situ crack propagation measurements [17].

The behavior of steel micro-fiber-incorporating cement based composites in compression, direct tension and flexure has received great attention in the literature. However, little data exists regarding the influence of these fibers on the remaining properties of concrete and therefore there is still need for a more extensive study. This research paper presents the results on compressive and flexural strength, abrasion, impact resistance, water-related permeability, chloride ion penetrability, freeze-thaw resistance and drying shrinkage tests. It is expected that the effectiveness of the fibers depend not only on the fiber amount and properties, but it may also change with the type of the matrix being reinforced. In order to understand the influence of the matrix type, fly ash, silica fume and metakaolin were used as supplementary cementing materials and the tests were conducted on plain, binary and ternary cementitious systems.

2. EXPERIMENTAL STUDY

2.1. Materials and mix proportions

An ordinary Portland cement (PC) – CEM I 42.5R complying with EN 197-1 (similar to ASTM Type I) was used as the base binder. Mortar mixtures incorporating three different mineral admixtures, i.e., high-calcium Class C fly ash, silica fume and metakaolin which were delivered from the Soma Thermal Power Plant, Antalya Etibank Ferro-Chrome Factory and Mikron'S Micronised Mineral Industry Trade Co., respectively were prepared. The chemical compositions and some mechanical and physical properties of the cementitious materials are presented in Table 1. The fibers used in the study were 6 mm long brass-coated steel micro-fibers with a diameter of 0.2 mm, elastic modulus of 200 GPa and tensile strength of 2000 MPa. The other ingredients included natural, siliceous sand conforming to EN 196-1 and a polycarboxyclic ether-based superplasticizer (SP) for keeping the flow value of the mixtures constant.

TABLE 1. Some physical, chemical and mechanical properties of portland cement and mineral admixtures

Chemical Composition (%)				
Item (%)	**Cement**	**FA***	**SF***	**MK***
SiO_2	18.21	32.80	87.29	63.53
Al_2O_3	4.11	13.77	0.47	32.36
Fe_2O_3	3.07	4.78	0.63	0.54
CaO	64.70	39.69	0.81	0.29
MgO	1.28	2.05	4.47	0.18
Na_2O	0.42	0.40	1.25	0.33
K_2O	0.81	1.18	1.28	1.08
SO_3	3.64	4.22	0.22	0.01
Cl^-	0.005	-	-	-
LOI	2.5	-	-	-
Additive	3.92	-	-	-
Compressive Strength of Cement (MPa)				
2-day				28.6
7-day				43.5
28-day				55.2

Physical Properties of Cement			
Initial setting time (min)		110	
Final setting time (min)		166	
Le Chatelier expansion (mm)		1	
Specific gravity	Cement	3.11	
	Fly ash	2.29	
	Silica fume	2.10	
	Metakaolin	2.20	
Specific surface area (cm^2/g)			
Cement (Blaine)		3120	
Fly ash (Blaine)		4100	
Silica fume (BET)		20000	
Metakaolin (BET)		13500	
Pozzolanic activity index (%)		**7-Day**	**28-Day**
Fly ash		68	81
Silica fume		105	134
Metakaolin		103	112

* FA= Fly ash, SF= Silica fume and MK= Metakaolin

In addition to the control mixture including no mineral admixture (PC), silica fume- and metakaolin- incorporating binary systems (PC-SF and PC-MK) were prepared. Besides, two ternary systems, i.e., PC-SF-FA and PC-MK-FA were also designed. While the replacement levels of SF and MK were 10% by weight of the total mass of the binder, this ratio was chosen as 30% for fly ash. In order to see how fiber inclusion affects the investigated properties, these five cementitious systems were prepared with and without fiber reinforcement. A single volumetric inclusion level of fiber reinforcement was applied (Vf = 1%). The mixtures prepared in this study are designated as shown in Table 2. For the preparation of the control mixture designated as PC, the mixture proportion requirements given in ASTM C109/C109M [18] were followed. The water/binder ratio and standard sand/binder ratio were kept constant at 0.485 and 2.75, respectively. The proportions of the ingredients in ten mixtures are summarized in Table 3.

TABLE 2. Designations of the mixtures

Mixture	Mixture designation
1) 100% PC	PC
2) 90% PC + 10% SF	PC-SF
3) 90% PC + 10% MK	PC-MK
4) 60% PC + 10% SF + 30% FA	PC-SF-FA
5) 60% PC + 10% MK + 30% FA	PC-MK-FA
6) 100% PC + 1% Fiber reinforcement	PC+1FR
7) 90% PC + 10% SF + 1% Fiber reinforcement	PC-SF+1FR
8) 90% PC + 10% MK + 1% Fiber reinforcement	PC-MK+1FR
9) 60% PC + 10% SF + 30% FA + 1% Fiber reinforcement	PC-SF-FA+1FR
10) 60% PC + 10% MK + 30% FA + 1% Fiber reinforcement	PC-MK-FA+1FR

TABLE 3. Mixture proportions of mortars

Mix	Cement	Silica Fume	Metakaolin	Fly Ash	Water	Sand	Fiber (volumetric ratio)	SP (wt% of total binder)	Flow (mm)
PC	1	0	0	0	0.485	2.75	0	0	200±10
PC-SF	0.9	0.1	0	0	0.485	2.75	0	0.20	200±10
PC-MK	0.9	0	0.1	0	0.485	2.75	0	0.26	200±10
PC-SF-FA	0.6	0.1	0	0.3	0.485	2.75	0	0.22	200±10
PC-MK-FA	0.6	0	0.1	0.3	0.485	2.75	0	0.24	200±10
PC+1FR	1	0	0	0	0.485	2.75	1%	0.10	200±10
PC-SF+1FR	0.9	0.1	0	0	0.485	2.75	1%	0.32	200±10
PC-MK+1FR	0.9	0	0.1	0	0.485	2.75	1%	0.40	200±10
PC-SF-FA+1FR	0.6	0.1	0	0.3	0.485	2.75	1%	0.27	200±10
PC-MK-FA+1FR	0.6	0	0.1	0.3	0.485	2.75	1%	0.30	200±10

2.2. Test procedure

For compressive strength test 50 mm cubic specimens were prepared. Compressive strengths of the water-cured mortar mixtures were determined at 7, 28, 56 and 90-days according to ASTM C109/C109M [18] Standard. Also, 7, 28, 56 and 90-day flexural strength was determined on 40 x 40 x 160 mm water-cured prisms in accordance with the requirement of EN

196-1 [19]. The specimens were subjected to center-point loading over a span of 100 mm in a displacement controlled manner with a deflection rate of 0.15 mm/min until failure. The machine automatically recorded the mid-span deflection readings. The flexural toughness was determined by integrating the load-deflection curve up to 2.5 mm deflection.

The 90-day abrasion resistance test was performed on 71 mm cubic specimens. The specimens were dried in an oven at 50°C until achieving a constant weight and their initial weight was recorded. Bohme test apparatus consisted of a 750 mm diameter steel disc, rotating at a speed of 30 ± 1 rpm, a counter and a lever, which can apply a load level of 300 N on the specimens. At the beginning of the test, 20 ± 0.5 g of wear dust (corundum crystalline Al_2O_3) was spread on the disc, the specimens were placed, the load was applied to the specimen and the disc was rotated for 90 revolutions. Then, the surfaces of the disc and the sample were cleaned. The same procedure was repeated for 4 periods, where the specimen was rotated 90° at the beginning of each period. Finally, the weight loss due to exposure to 360 abrasion cycles in total was measured.

Impact resistance tests were performed on 150 mm diameter and 64 mm high discs that were cut from 150x300 mm cylindrical mortar samples at 90 days of age. In this test, a hammer weighing 4.5 kg (m) was dropped from a height of 450 mm (h) in accordance with ACI 544.2R-89 [20]. The load between the hammer and the sample was transferred via a 64 mm wide steel ball. The number of drops (N) required to fracture the specimens were observed and recorded. Besides, impact energy (E) was calculated in terms of joules by using Equation 1:

$$E = m.g.h.N \qquad \text{[Eq. 1]}$$

where g is acceleration due to gravity (9.81 m/s^2).

The 90-day water absorption and permeable void content of 50 mm cubic specimens were obtained in accordance with the ASTM C642 [21] Standard. Specimens were first kept in an oven maintained at 105°C until a constant mass (a) was attained. Then, they were brought into saturated surface dry condition by immersing in water for at least 48 h, and weighed (b) again. The specimens were placed in a suitable receptacle, covered with tap water, and boiled for 5 h. After they were allowed to cool to room temperature (22 ± 2 °C), the surface moisture was removed with a towel and the surface-dried mass of the boiled specimens (c) was determined. Finally, the immersed apparent mass (d) of boiled specimens was determined in water. Absorption after immersion (m_1), and absorption after immersion and boiling (m_2) as well as their permeable void content (B_0) were calculated according to Equations 2-4, respectively.

$$m_1 = [(b \quad a) / a] \quad 100 \qquad \text{[Eq. 2]}$$

$$m_2 = [(c \quad a) / a] \quad 100 \qquad \text{[Eq. 3]}$$

$$B_0 = [(c \quad a) / (c \quad d)] \quad 100 \qquad \text{[Eq. 4]}$$

Resistance of mortar mixtures to chloride ion penetration was determined on discs with a diameter of 100 mm and length of 50 mm in accordance with ASTM C1202 [22] at 90 days. The amount of electrical current passed through the specimens was measured for 6 hours. At the end of 6 hours, the total charge passed, which is a measure of the resistance to chloride ion penetration, was determined in coulombs.

The weight loss of hardened mortar mixtures upon exposure to freezing-thawing was determined in accordance with ASTM C 666/C666M [23] Standard. However, 50 mm cubic specimens were used and weighed in dry condition before and after frost exposure. The mortar specimens were frozen in air from 5±2°C to −18±2°C within 3 h, and they were thawed in water to 5±2°C within 1 h in a single cycle. Since the loss in weight upon scaling and gain of mass due to water uptake are not separable, at the end of specified cycles the specimens were dried before weighing. In this way, the effect of water uptake during freezing-thawing was discarded from the test results. The change in the initial weight of each specimen (W) was calculated at every 60 freeze–thaw cycles until 300 cycles are completed.

Unrestrained uniaxial drying shrinkage of mortar mixtures was determined on three 25 x 25 x 285 mm prisms in accordance with ASTM C157/C157M [24]. The standard and the average value was recorded. The test was conducted after a water-curing period of 90-days and then the specimens were kept at 50±5% RH and 23±2°C for air-drying.

3. RESULTS AND DISCUSSION

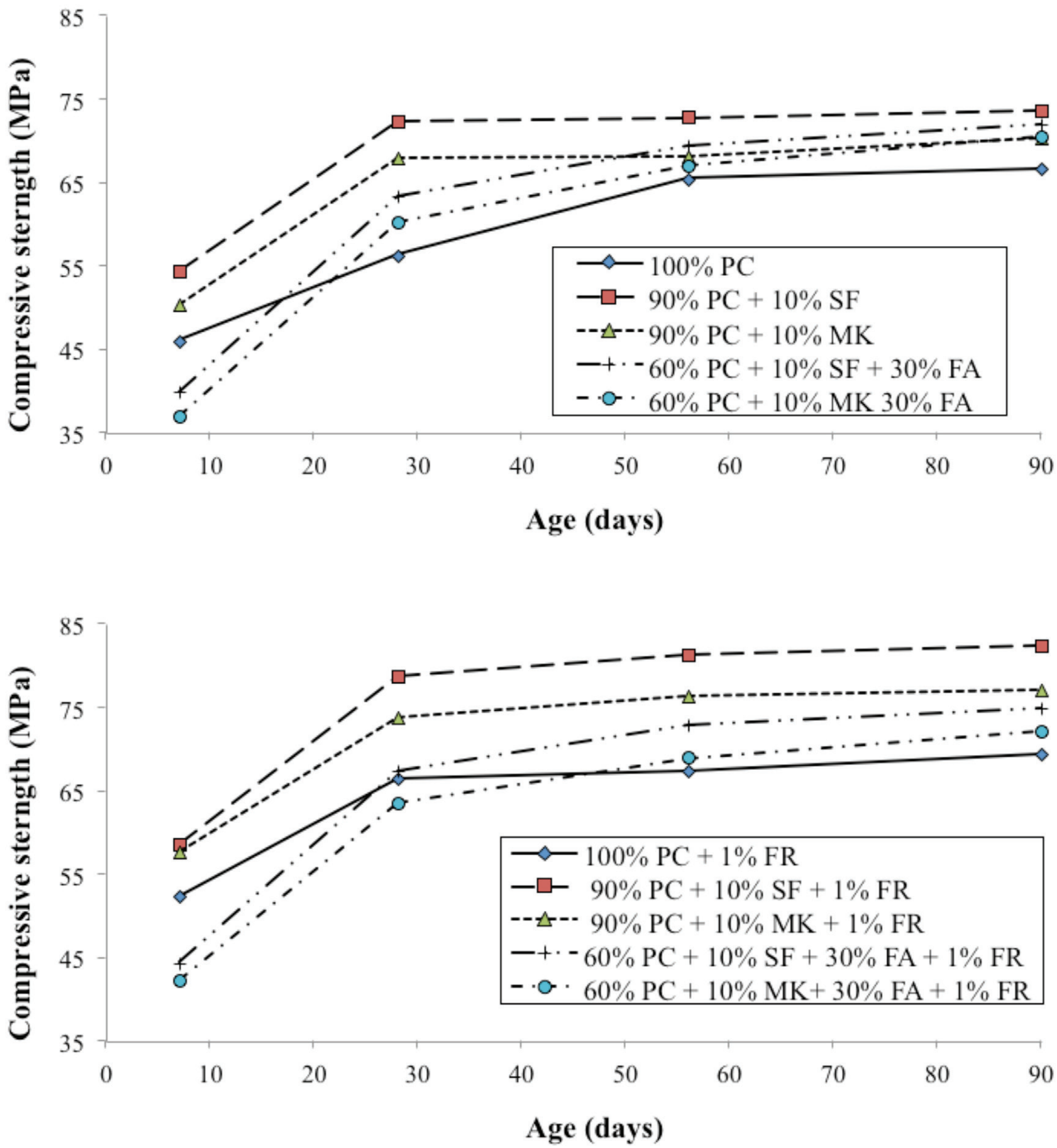
3.1. Compressive and flexural behavior

Compressive strength developments of mixtures with and without micro-fibers are shown in Figure 1a and b, respectively. According to both figures, binary systems incorporating only silica fume or metakaolin as mineral admixture led to higher strength levels with respect to control (PC) mixture at all ages. Due to its higher pozzolanic activity, silica fume showed superior performance in terms of compressive strength. At all ages, the binary system including silica fume resulted in the highest strength among the mixtures. On the other hand, ternary systems prepared by the addition of fly ash reduced the 7-day strength values by 15-19%. Nonetheless, compressive strength test results showed that all mixtures with pozzolans led to improvement in strength at 56 and 90 days.

Steel micro-fiber reinforcement at a volumetric ratio of 1% resulted in 2-14% improvements in compressive strength values. In previous studies [25,26], this behavior was attributed to the ability of micro-fibers to delay micro-crack formation and arrest them before they propagate and coalesce to form macro-cracks. Compressive strength enhancement due to fibers was more evident in binary systems than in ternary ones at 28, 56 and 90 days. As expected, improvement in compressive strength was not so significant when compared with the contribution of fibers to flexural performances of the mixtures.

Some selected examples showing the load-deflection behaviors of the mixtures at 56 and 90-days age are presented in Figures 2, 3 and 4. As can be seen from these graphs, micro-reinforcement resulted in dramatic changes in post-peak responses irrespective of the mixture type and age. The load-deflection curves of plain mixtures without fibers were characterized by an ascending portion up to peak load followed by a sudden drop with no increase in displacement till reaching zero-stress level. These mixtures fractured due to the development of a single crack and its rapid propagation towards the neutral axis. The use of fibers had no significant influence on the initial slope and shape of the load-deflection curves up to peak load; however, increments in peak load values ranging from 2% to 30% were observed as a consequence of the ability of micro-fibers to bridge the micro-cracks effectively. This finding was in close agreement with the previous studies finding similar positive influences of micro-fibers on tensile and flexural performances of the cementitious systems [14,16,17,27,28].

FIGURE 1: Compressive strength of mortar mixtures a: mixtures without fiber reinforcement, b: mixtures incorporating 1% fiber reinforcement



It is worthwhile to note that strain hardening response was not evident in the load-deflection curves obtained in the current study. It is well-known that strain (or deflection) hardening behavior is not an expected outcome unless hybridization of short fibers with longer ones is applied. Park et al. [14] summarized existing data in the literature regarding ultra-high performance concrete reinforced with short steel fibers and stated that in some cases a fiber volumetric ratio of as much as 4~6% is needed for strain hardening if only micro-fibers are to be used. By taking into account the adverse effects of very high fiber content on cost and workability (fiber balling, poor fiber dispersion, etc.), such a high content was not chosen in our study.

Test results given in Figures 2-4 and Table 4 indicate that the main contribution of micro-fibers was towards enhancement in the energy absorption capacities of the mixtures. The flexural

FIGURE 2: Flexural load-deflection curves of mortar mixture having plain cementitious system (without any mineral admixture).

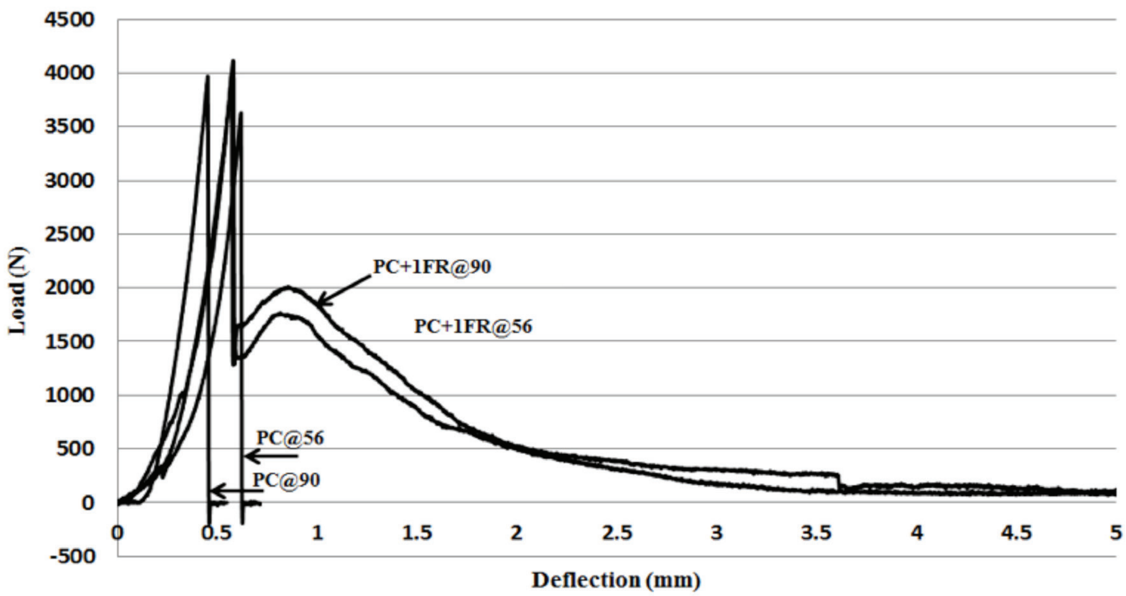
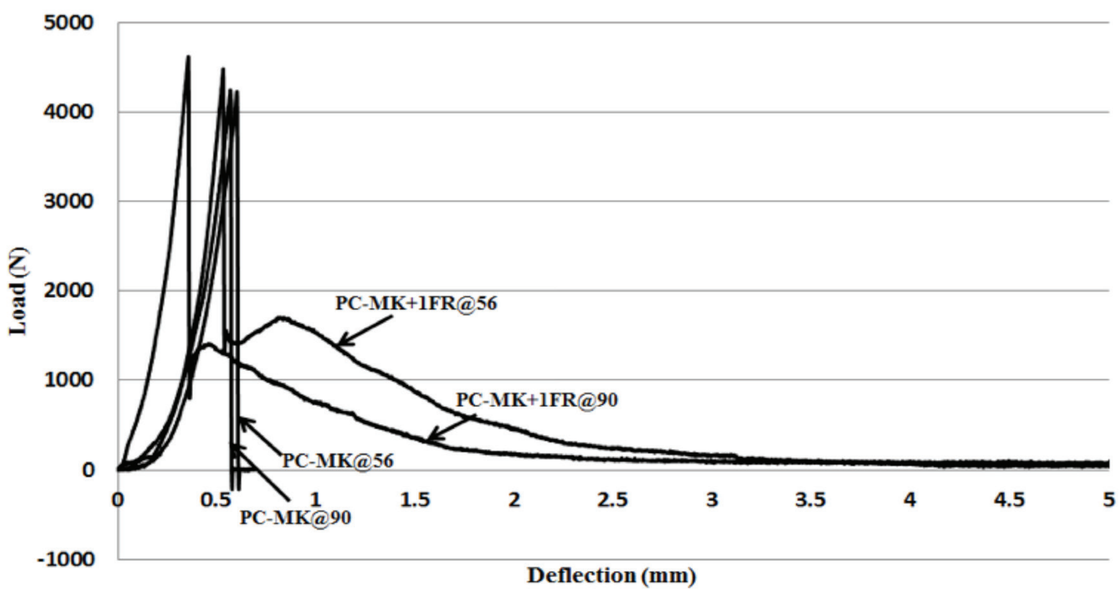
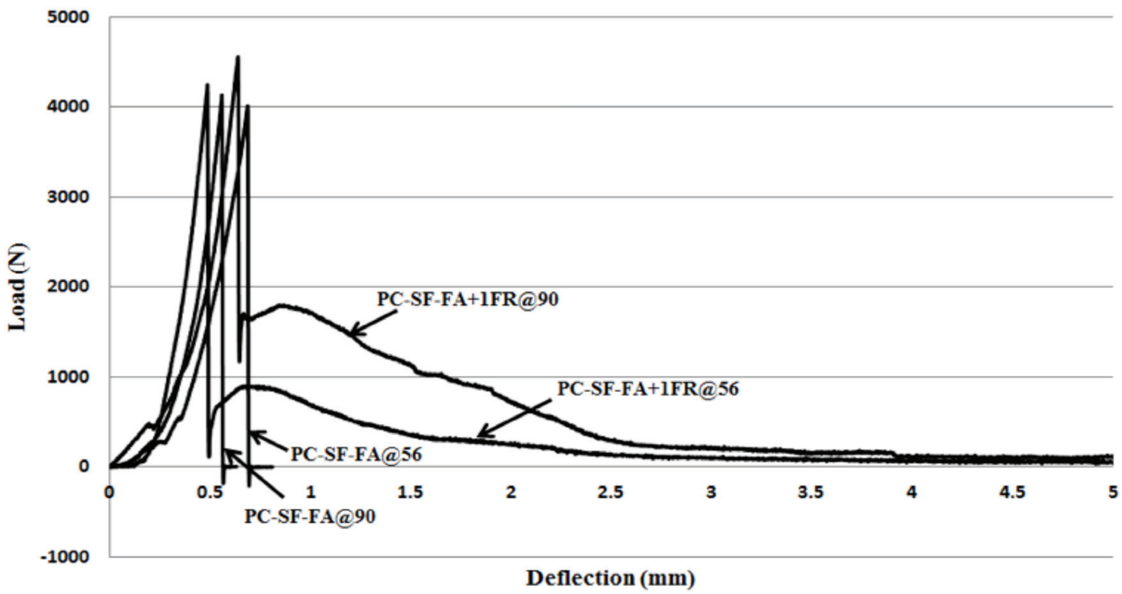


FIGURE 3: Flexural load-deflection curves of mortar mixture having binary cementitious system and incorporating metakaolin as mineral admixture.



strength values of the mixtures were comparatively close to each other; however, toughness values were subject to a much greater variation. Incorporation of micro-fibers as reinforcement in mortar mixtures led to 1.8-4.9 fold increases in flexural toughness. Although the embedment lengths of the micro-fibers were limited, the descending portions of the load-deflection curves of fiber-incorporating mixtures showed a steadier drop compared to plain mixtures. Besides, two-stage softening phase was observed; in other words, after a rapid drop following the first peak, a smaller second peak occurred.

FIGURE 4: Flexural load-deflection curves of mortar mixture having ternary cementitious system and incorporating silica fume and fly ash as mineral admixtures.



By using 3 mm long fibers, Lange et al. [13], concluded that the matrix with silica fume outperformed the plain matrix in terms of strength and toughness. The authors attributed this result to the densification of the matrix and thus improvement in the fiber-matrix bond. Similarly, Yang et al. [29] emphasized the importance of the homogeneity and porosity of the concrete matrix on the fiber debonding effect which in turn imparts the flexural behavior significantly. In contrast to these findings, the rule of thumb which is stated as *the brittleness of concrete increases with its strength* was valid according to the results obtained at 90-days age. Among the five fiber-incorporating mixtures, the binary matrices incorporating silica fume or metakaolin had the highest compressive and flexural strength values. While the flexural toughness values of these mixtures were at the order of ~1700 N.mm, the calculated energy absorption capacities of the other three mixtures were all higher with falling in the range between 2000 and 3000 N.mm.

3.2. Abrasion and impact resistances

Results of the abrasion test after 90, 180, 270 and 360 revolutions in the Bohme apparatus are presented in Table 5. It was proved in many previous studies [30-34] that abrasion resistance of concrete is greatly influenced by its compressive strength. Similarly, in this study, plain mixture including neither mineral admixture nor fiber and having the lowest compressive strength at 90-days suffered the highest mass loss upon abrasion. The ultimate mass loss values of the mortar mixtures are compared with respect to PC mixture and the results are shown in percentage in Figure 5. As the results indicate, concrete mixture with the highest strength value (PC-SF+1FR) had the highest resistance to abrasion.

According to the findings of Sonebi and Khayat [35], the incorporation of 50 mm-long steel fibers did not improve the mechanical and hydraulic abrasion resistance of high-strength concrete. Nanni [36] conducted ball bearings abrasion tests, and he similarly found no evidence of improvement in abrasion resistance of roller compacted concrete by using steel and

TABLE 4. Flexural properties of mixtures based on load-deflection curves

Age	Mixture	Ultimate load (N)	Deflection at ultimate load (mm)	Flexural strength (MPa)	Flexural toughness (N.mm)
at 56 days	PC	3628.1	0.618	8.50	582.9
	PC+1FR	3987.5	0.571	9.35	2457.5
	PC-MK	4218.8	0.601	9.89	660.7
	PC-MK+1FR	4475.0	0.532	10.49	2409.7
	PC-SF	4480.0	0.654	10.50	646.2
	PC-SF+1FR	4575.0	0.598	10.72	1256.7
	PC-MK-FA	3965.6	0.351	9.29	510.0
	PC-MK-FA+1FR	4103.1	0.276	9.62	2503.7
	PC-SF-FA	4012.5	0.688	9.40	746.2
	PC-SF-FA+1FR	4246.9	0.487	9.95	1369.5
at 90 days	PC	3965.6	0.451	9.29	510.0
	PC+1FR	4115.6	0.578	9.65	2454.4
	PC-MK	4240.6	0.567	9.94	661.9
	PC-MK+1FR	4612.5	0.356	10.81	1760.7
	PC-SF	4625.0	0.692	10.84	861.8
	PC-SF+1FR	4712.5	0.806	11.04	1781.4
	PC-MK-FA	4012.5	0.709	9.40	746.2
	PC-MK-FA+1FR	4278.1	0.886	10.03	2227.2
	PC-SF-FA	4131.3	0.559	9.68	579.6
	PC-SF-FA+1FR	4562.5	0.640	10.69	2864.1

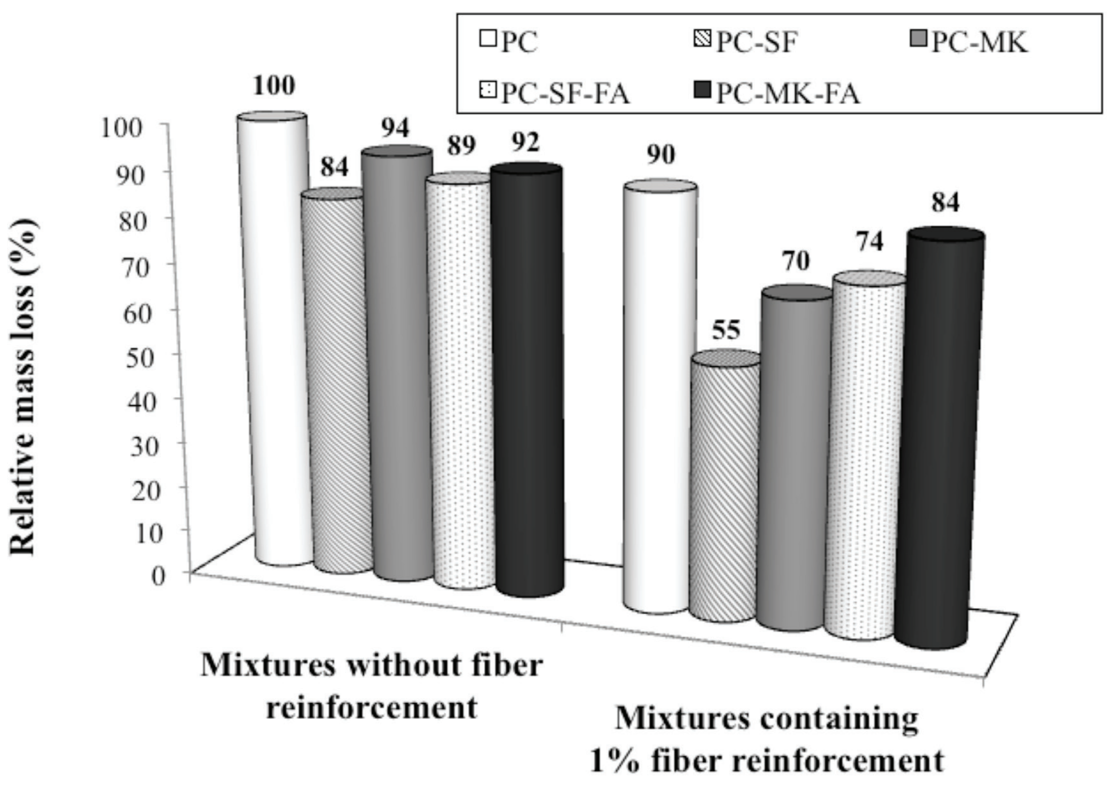
TABLE 5. Mass loss (%) of mortar mixtures after being exposed to abrasion cycles

Mixture	Revolution number				
	0	90	180	270	360
PC	0	1.1	2.4	3.1	4.21
PC-SF	0	0.81	1.68	2.59	3.54
PC-MK	0	0.95	1.99	2.84	3.96
PC-SF-FA	0	0.88	1.8	2.49	3.74
PC-MK-FA	0	0.95	2.12	2.87	3.88
PC+1FR	0	1	1.81	2.66	3.81
PC-SF+1FR	0	0.5	1	1.89	2.33
PC-MK+1FR	0	0.66	1.23	2.26	2.95
PC-SF-FA+1FR	0	0.76	1.66	2.51	3.12
PC-MK-FA+1FR	0	0.89	1.88	2.84	3.54

polypropylene fibers. However, there are many other studies that report a noticeable increase in the resistance of cementitious systems to abrasion by using steel [37,38,39,40], polypropylene [38,40,41,42], polyester [30], carbon [43], basalt [44]and glass [40] fibers. For instance, Felekoğlu et al. [38] found that when used at a dosage of 156 kg/m^3, steel fibers with 5 mm length decreased weight loss due to abrasion by 42% in self-compacting repair mortars. In the study conducted by Vassou and Kettle [40], the optimum volumetric amount of 45 mm long steel fibers was found to be 0.51% from the abrasion view point, and these fibers reduced the abrasion depth in the range of 8-79% depending on the w/c ratio of the mixture and curing regime. Grdic et al. [41] carried out an accelerated test by applying a high-velocity jet of water/sand mixture on concrete surfaces. The authors reported a 6-16% improvement in abrasive erosion resistance of the mixtures due to 0.91 kg/m3polypropylene fiber addition. In the current study, reductions in the ultimate mass loss values of PC, PC-SF, PC-MK, PC-SF-FA and PC-MK-FA mixtures provided by steel micro-fibers were found as 9.5, 34.2, 25.5, 16.6 and 8.8%, respectively. It seems that the effectiveness of fibers depends on the matrix strength, and they reduced the mass loss to a greater extent in the two binary mixtures which had the highest compressive strength (as discussed in the previous part).

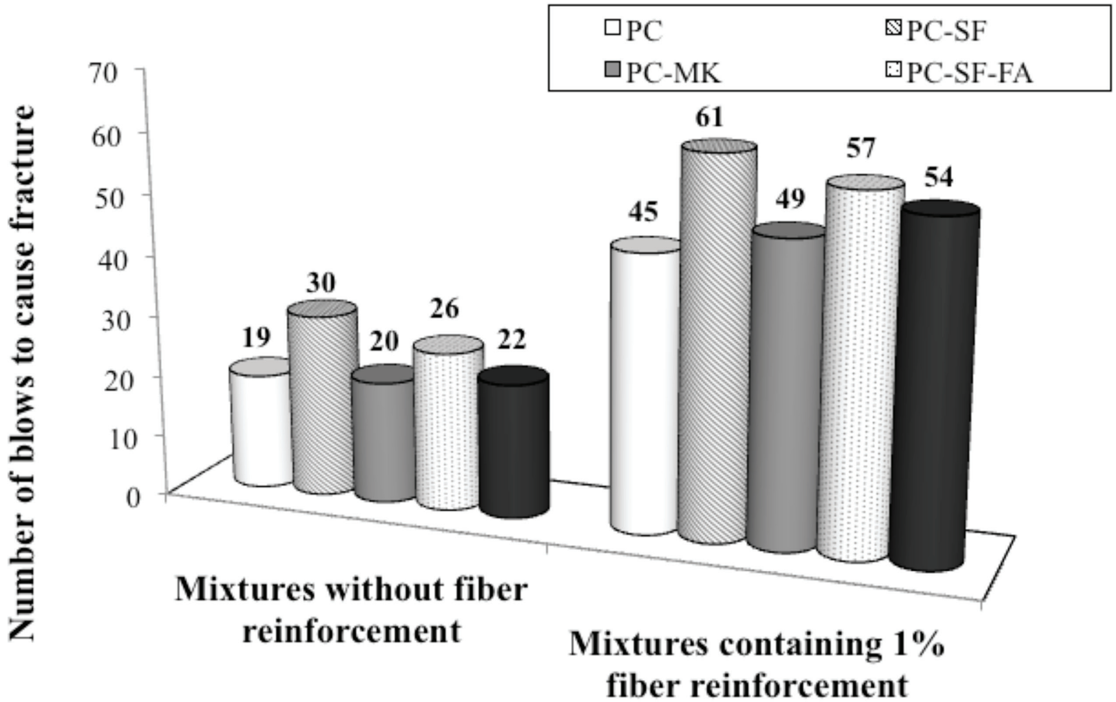
The effect of steel micro-fibers on the number of drops required to fracture each mixture for an impact test is presented in Figure 6. It should be remembered that tests were conducted on mortar specimens and the absence of coarse aggregate resulted in ultimate drop numbers that were considerably lower compared to the results existing in the literature [45-47]. Besides, it was not possible to observe the first crack particularly in non-reinforced mixtures and thus only the ultimate drop values are presented.

FIGURE 5: Relative mass loss of abraded mortar mixtures compared to the control mixture (%).



Test results demonstrated that the plain mixtures had lower resistance against repeated drops in the impact test than their fiber reinforced counterparts. In the previous studies [45,46] a strong correlation between compressive toughness and the impact energy of fiber-incorporating concrete was reported. Therefore, it can be stated that the ability of fibers in delaying the growth and propagation of micro-cracks leads to a higher energy absorption

FIGURE 6: Required blow numbers to reach specimen failure in impact test.



capacity in both static and dynamic tests. Nevertheless, it should be remembered that the fibers used in this study are of micro-type and the resistance offered by these fibers against impact is limited compared to longer fibers [48-50]. This behavior apparently results from the lower bond strength and easier pull out process of smaller fibers from the matrix during repeated impact load.

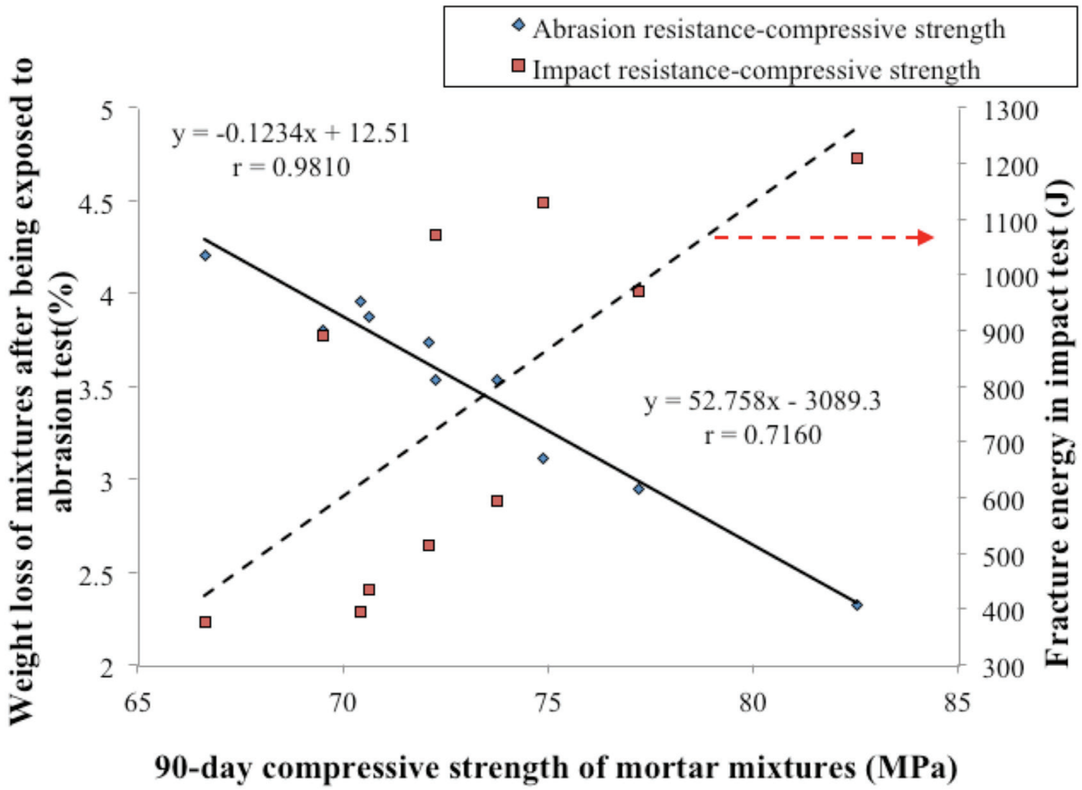
According to the results given in Figure 6, the addition of mineral admixtures and steel fibers at the same time led to higher impact resistance levels and among all mixtures, and the PC-SF+1FR mixture had the highest impact resistance performance. This can be attributed to the pore refinement as well as grain refinement effects of mineral admixtures which enhanced the bond between matrix and fibers by reducing the pre-loading cracks in the interfacial transition zone and by densifying the matrix [47]. Nonetheless, the improvement obtained by the addition of mineral admixtures was comparatively lower than the positive influence of fibers on the impact performance.

The compressive strength results obtained for each mixture at 90-days age were plotted against their mass loss values after the abrasion test and also against strength reduction values after the impact test (Figure 7). The abrasion resistance of the mixtures was found to be very highly correlated with the compressive strength. Although the relationship between compressive strength and impact energy was not so strong, in general, as the strength of the mixture increases, the impact energy also tends to increase.

3.3. Transport properties

The water absorption test on concrete determines permeable void content which is one of the basic indicators of its resistance to the transport of aggressive ions. Both the water absorption (Figure 8a and 8b) and permeable void (PV) content (Figure 9) values obtained in the

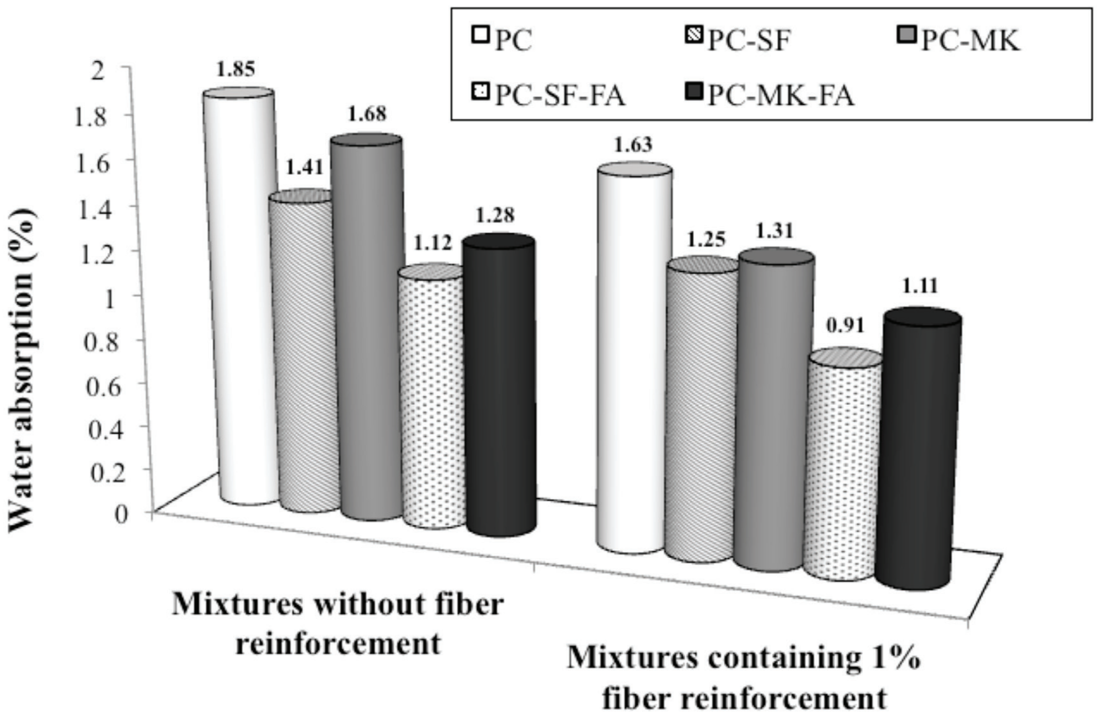
FIGURE 7: Relationship between compressive strength- abrasion resistance and -impact resistance



tests indicate that there is a substantial improvement in the pore system of concrete mixtures through the addition of mineral admixtures and steel fibers. The highest water absorption and PV content values belong to the control mixture. The reduction in permeable porosities of the mixtures with the addition of mineral admixtures and steel fibers were found to lie between 6.7-30.6% and 9.0-43.0%, respectively. It is worthwhile to note that the best performance was obtained in the fiber reinforced ternary mixture of PC-SF-FA.

The beneficial effect of mineral admixtures in promoting the pore structure can be attributed to a combined action of filler effect and pozzolanic reaction. However, fibers restrict crack growth and reduce the pore connectivity by effective bridging. Besides, as cited by Nili and Afroughsabet [51], some mineral admixtures such as silica fume may play an additional positive role by improving the dispersion of fibers throughout the cementitious matrix which may further increase the effectiveness of steel fibers [52]. The improvements obtained in the current experimental study agree well with those in the literature [51,53] obtained by incorporating macro (60 mm length and an aspect ratio of 80) steel fibers into concrete. Some other researchers [54-56] applied different testing procedures and measured the permeability values of cracked specimens. In these studies, the emphasis was laid on the reduction in crack width and generation of multiple cracking by the use of fibers. The authors indicated that since the permeability is related to the cube of the crack width, smaller multiple cracks reduce the permeability significantly.

FIGURE 8: Water absorption values of mortar mixtures a: after immersion (m1) b: after immersion & boiling (m_2).



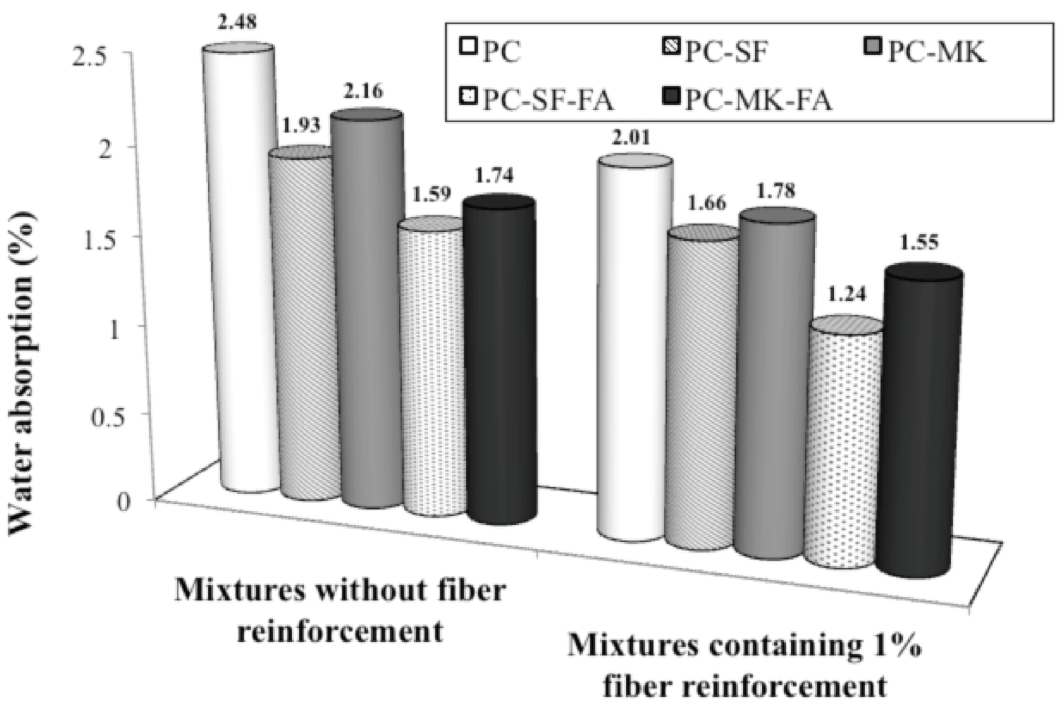
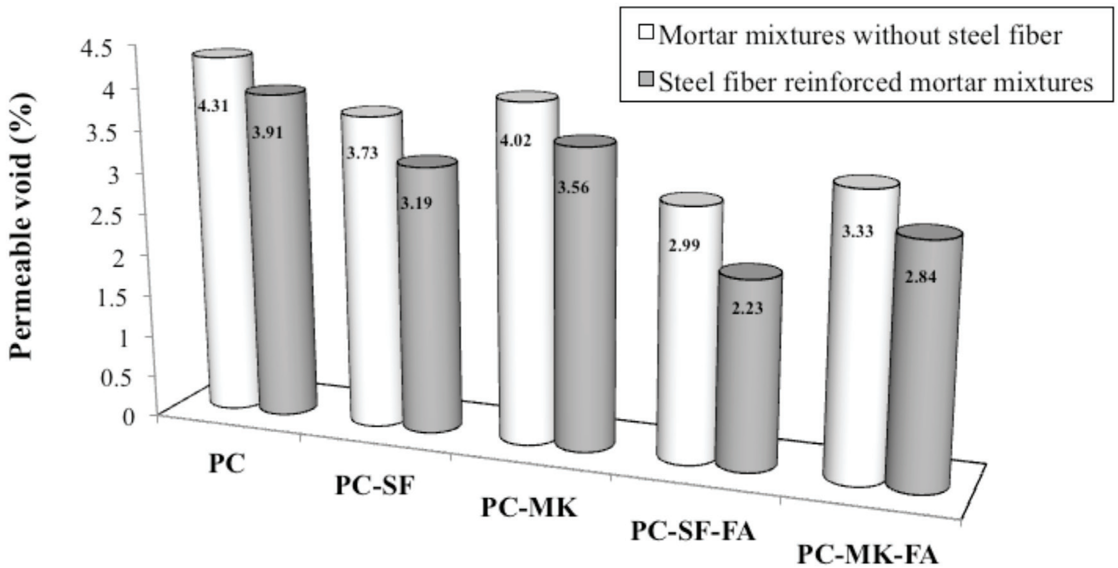
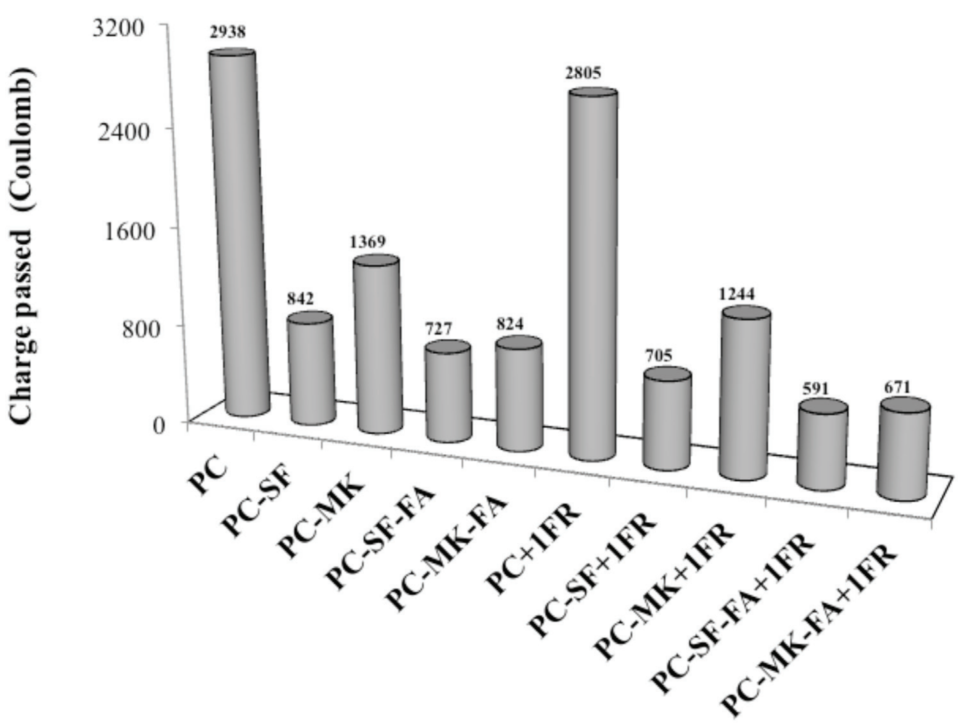


FIGURE 9: Wermeable void contents of mortar mixtures



As can be seen in Figure 10, the incorporation of mineral admixtures and steel micro-fibers provided reductions in the total charge passed through concrete specimens during the rapid chloride permeability test. Among the mixtures tested in this study, the PC-SF-FA+1FR mixture had the highest resistance to the penetration of chloride ions. The ratio of the charge passed through the mixtures with mineral admixtures to that of the charge passed through the control mixture ranged from 1/2.1 to 1/4.8. The high effectiveness of silica fume in improving

FIGURE 10: Chloride ion penetration test results of mortar mixtures.



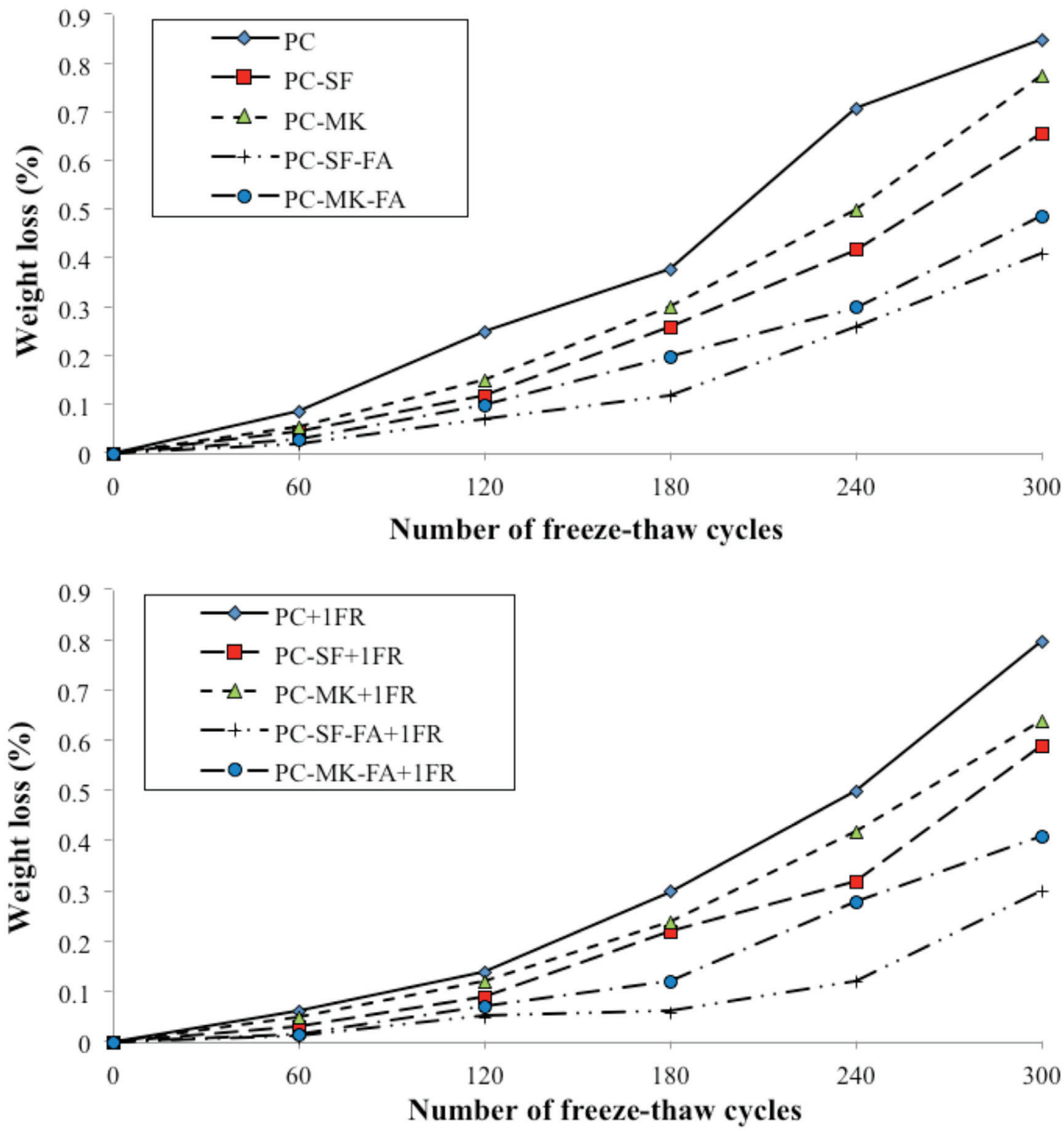
the resistance to chloride ion penetration can be attributed mainly to its very high pozzolanic activity and thus to refinement in pore structure. Particularly in the case of metakaolin utilization an additional mechanism exists. Reactive $Al_2O_3^{-2}$ in its structure reacts with some of the chloride ions and binds them which may otherwise remain free and create a great risk of steel reinforcement corrosion [57]. While the presence of either silica fume or metakaolin with/without fly ash caused great reductions in the charge values, the influence of steel micro fibers was comparatively minimal and only slight improvements were observed. Contradictory results can be found in the literature regarding the performance of steel fibers in ASTM C1202 (rapid chloride permeability) test. For instance, similar to this study, Abbas et al. [15] found reductions in penetrability of chloride ions with increasing steel fiber dosages and confirmed their findings with mercury intrusion porosimetry analysis. However, El-Dieb [58] reported increments in total charge values when the steel fiber volume increased and this behavior was attributed to the high electrical conductivity of the fibers themselves.

3.4. Freezing-thawing resistance
Weight measurements at each 60 cycles in freezing-thawing tests (Figure 11) and also residual compressive strength percentages obtained after the completion of 300 cycles (Figure 12) showed that mineral admixtures reduced the deterioration. Since the freezable water exists in capillary pores in concrete, the role of the mineral admixtures in improving the frost resistance may be considered as an expected consequence of reduced permeability (or refinement in pore system) as discussed in the previous section. This positive effect became more apparent especially at later cycles. The weight loss values obtained after exposing the ternary mixtures to 300 cycles reached even below half of the relevant values belonging to plain mixture. Similar but somewhat lower improvements were observed also in binary mixtures.

Figure 11 indicates that the incorporation of micro-steel fibers at 1% volumetric fraction into plain, PC-MK, PC-SF, PC-MK-FA and PC-SF-FA mixtures reduced the ultimate weight loss values by 6.1, 17.5, 10.4, 16.0 and 26.8%, respectively. Besides, according to Figure 12, compressive strength reductions of fiber-incorporating mixtures were always lower than their plain counterparts. It can be stated that PC-SF-FA+1FR mixture showed the best performance in terms of both weight loss and compressive strength reduction. Early study conducted by Pigeon et al. [59] showed that steel fibers 3 mm in length led to lower air void spacing factors with respect to the control mixture. Consequently, the authors related the improvement in frost and deicer salt scaling resistance of mortar mixtures partly to the air entrainment properties resulting from fibers. Another study conducted by Pigeon et al. [60] showed that similar reductions in the rate of deterioration can be gained by using the same fibers in pastes and mortars batched under vacuum. Therefore, the authors concluded that after the tensile stresses due to ice formation exceeds the tensile strength and thus cracks occur, fibers reduce the rate of crack propagation and thus a better performance is obtained. It was proved by investigating the pore structure parameters in a more recent study that steel fibers reduced both the total porosity and average pore size which contribute to enhance the frost resistance [61].

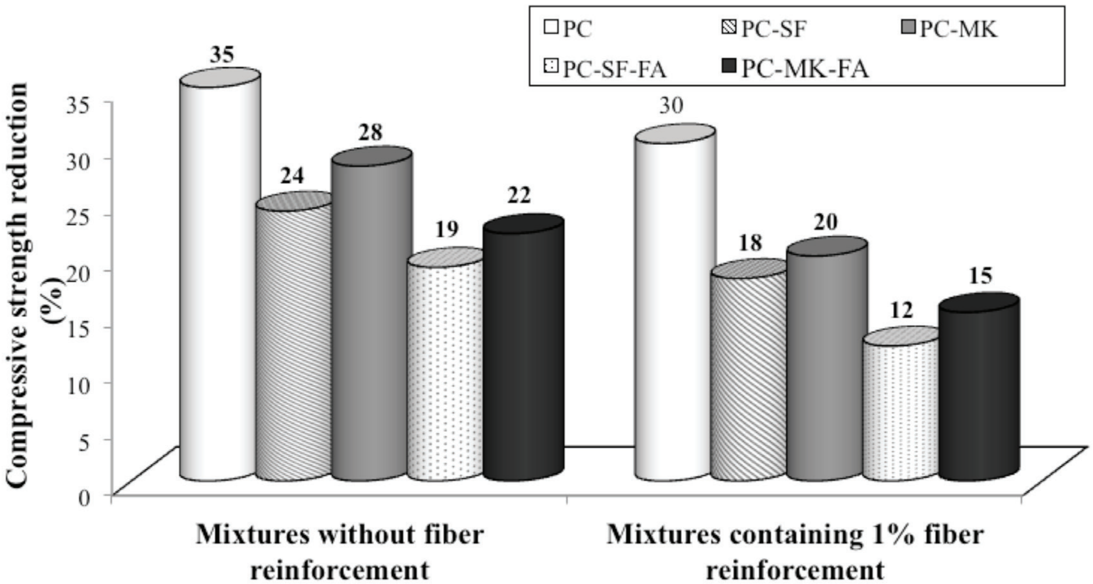
3.5. Drying shrinkage
According to the unrestrained shrinkage measurements taken on hardened mortar specimens up to 90 days (Figure 13), a great portion of the length change occurred during the first 20 to 30 days and then the graphs tended to level out. By comparing Figure 13a and 13b, it can be indicated that the reductions in shrinkage values gained by the addition of fibers reached

FIGURE 11: Weight loss of mortar mixtures during 300 freezing-thawing cycles: a) mixtures without fiber reinforcement, b) mixtures incorporating 1% fiber reinforcement.



even up to 25% in PC-SF and PC-SF-FA mixtures. When the matrix shrinks, shear stresses are transmitted between the fibers and the surrounding matrix. Therefore, the development of a strong interfacial bond between the fibers and the matrix is the key parameter regarding shrinkage behavior of hardened concrete [16, 62-64]. Moreover, as the results of the other tests conducted in the experimental study suggest, the densifications in binary and ternary matrices compared to plain matrix made the evaporation of the internal moisture more difficult [65,66]. The ternary mixtures showed the best performance since the ultimate shrinkage values of PC-SF-FA and PC-MK-FA mixtures were 33.7% and 28.3% lower than PC mixture, respectively. All of the mineral admixture-incorporating mixtures showed improved performance and the lowest shrinkage was obtained in the ternary mixture of portland cement, silica fume and fly ash.

FIGURE 12: Reduction in compressive strength of mortar mixtures after 300 freeze-thaw cycles.



4. CONCLUSION

According to the results of the tests conducted in this study, the refinement in the pore structure of the matrix provided by mineral admixtures and the increase in resistance against growth and coalescence of micro-cracks provided by fibers generally produce a synergistic effect and improve the investigated performances of the mixtures. Based on the tests conducted for investigating the influence of steel micro fibers on some mechanical, transport and durability properties of 5 different mortar mixtures with plain, binary and ternary cementitious systems, the following conclusions were drawn:

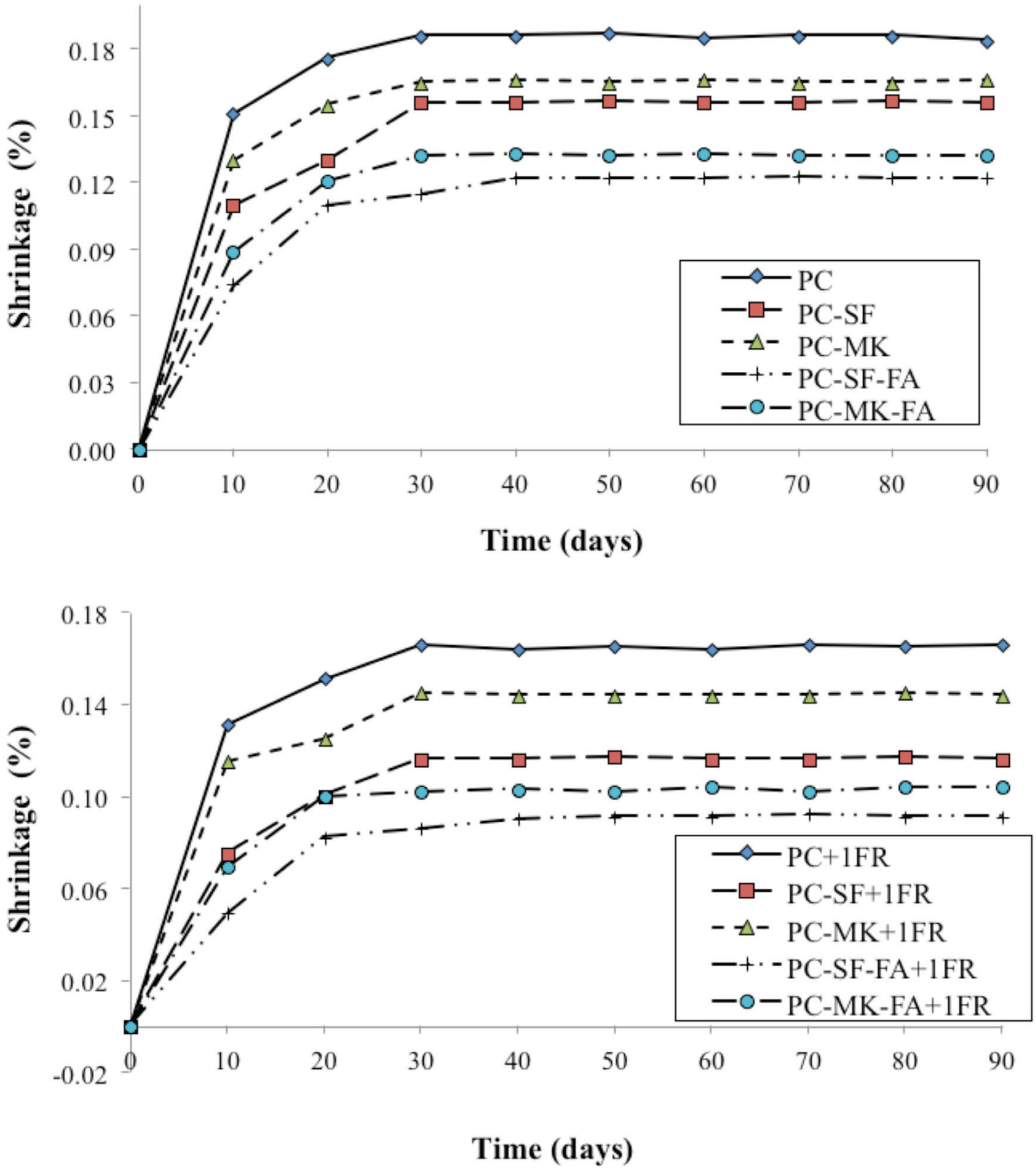
(1) According to the compressive strength test results, only ternary systems (PC-SF-FA and PC-MK-FA) led to lower 7-day strength values compared to plain mixture. However, at 56 and 90-day, binary and ternary mixtures showed superior strength than the plain mixture. Among all mixtures, the highest strength values were recorded in PC-SF binary mixture.

(2) Incorporation of steel fibers having 6 mm length increased both compressive and flexural strength. The effects of fibers are more pronounced on the shape of the stress-strain curves and calculated energy absorption values of the mixtures. 1.8-4.9 fold increase was gained in flexural toughness through the addition of fibers. Besides, at 90 days age, the binary systems (PC-SF and PC-MK mixtures) had the highest flexural strength and lowest toughness among the mixtures.

(3) A very strong correlation was found to exist between abrasion resistance and compressive strength values of the mixtures. The plain mixture showed the poorest performance from abrasion and impact view points. Inclusion of the mineral admixtures improved the behavior and a further improvement was gained through the addition of fibers.

(4) The pore structure enhancement of the matrix by mineral admixtures and effective inhibition of crack growth by fibers both helped to reduce either water absorption or chloride permeability of the mixtures. The inclusion of mineral admixtures had the major effect on chloride ion permeability and the role of fibers was rather minimal.

FIGURE 13: Shrinkage values of mortar mixtures exposed to drying: a) mixtures without fiber reinforcement, b) mixtures incorporating 1% fiber reinforcement.



This was not the case in water absorption characteristics because reduction in permeable void contents with the addition of mineral admixtures and steel fibers reached up to 30.6% and 43.0%, respectively.

(5) The mortar mixture containing micro fibers and a ternary system of portland cement, silica fume and fly ash showed the highest freezing-thawing resistance. As the results of permeability tests suggest, this fact arises from the reduced amount of freezable water in capillary pores.

(6) Since the fiber-matrix bond is the key parameter in determining the level of restrain provided by fibers, the formation of a more densified matrix in PC-SF-FA ternary system led this mixture to undergo the lowest amount of length change upon drying.

(7) In order to gain the best performance through the use of fibers, the engineer should pay attention while choosing the matrix type for design. Mineral admixtures clearly improve the mechanical, transport and durability characteristics of concrete and create a synergistic effect with micro fibers. The influence of the volumetric fraction of fiber and different replacement levels of mineral admixtures can be investigated in the future studies.

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