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PROPERTIES OF CEMENT MORTARS REINFORCED WITH POLYPROPYLENE FIBERS

Didem OKTAY, Büşra AKTÜRK[*], Nihat KABAY

Yildiz Technical University, Department of Civil Engineering, Construction Materials Division, ISTANBUL

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ABSTRACT

In this paper, the effect of polypropylene fibers (PF) on fresh and hardened properties of cement mortars produced with white cement is reported. Nine mixtures were prepared by using different volume fractions and different sizes of PF from 0 to 1.5% and 6 and 12 mm, respectively. Water to cement and sand to cement ratio by weight was kept constant as 0.4 and 3.0, respectively. PF with different length and amounts was introduced to mixtures and its effect on workability, density, water absorption, compressive strength, flexural strength and drying shrinkage were determined. Pore ratio at the cross-section of the specimens was calculated by image analysis. Test results showed that the addition of PF in higher amounts decreased workability, fresh and hardened density, compressive and flexural strength and increased water absorption and pore ratio of the mixtures. However when used in lower amounts, PF improved drying shrinkage and flexural strength.

Keywords: Polypropylene fiber, mechanical properties, workability, drying shrinkage, pore ratio.

POLİPROPİLEN LİF KATKILI ÇİMENTO HARÇLARININ ÖZELLİKLERİ

ÖZET

Bu çalışmada, polipropilen lifin (PF) beyaz çimento harcı ile üretilmiş çimento harcının taze ve sertleşmiş özelliklerine etkisi incelenmiştir. Farklı oranlarda (hacimce %0-%1,5) ve farklı uzunluklarda (6 ve 12mm) polipropilen lifler kullanılarak, toplam 9 seri üretilmiştir. Su/çimento oranı ve kum/çimento oranı, sırası ile 0,4 ve 3 olmak üzere sabit tutulmuştur. Farklı uzunluk ve miktardaki polipropilen lifler karışıma katılmış ve liflerin harcın, işlenebilirlik, yoğunluk, su emme, basınç dayanımı, eğilme dayanımı ve kuruma rötresine olan etkileri araştırılmıştır. Boşluk oranı, numune en kesitinden Image Analiz (Image Analysis) yöntemi ile belirlenmiştir. Deney sonuçlarına göre yüksek miktarda PP lif kullanımı, işlenebilirliğin, taze ve sertleşmiş yoğunluğun, basınç ve eğilme dayanımının azalmasına ve boşluk oranı ve su emme miktarının artmasına neden olmuştur. Düşük oranda PP kullanımı, kuruma rötresi ve eğilme dayanımını iyileştirmiştir.

Anahtar Sözcükler: Polipropilen lif, mekanik özellikler, işlenebilirlik, kuruma rötresi, boşluk oranı.

1. INTRODUCTION

Synthetic fibers, such as polypropylene, have primarily been used in concrete since late 1960s [1]. Polypropylene fibers (PF) have some unique properties that make them suitable for incorporation into concrete matrices; they are chemically inert and stable in the alkaline environment of concrete, they have a relatively high melting point with low cost raw materials and they have a hydrophobic surface so that they do not adsorb water [2,3]. PF is used in concrete in a wide

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[*] Corresponding Author/Sorumlu Yazar: e-mail/e-ileti: bucarkosar@gmail.com, tel: (212) 383 52 46

variety of applications; in general constructions and especially in ground-floor slabs where the constraint of the foundation or other parts of the structure produces tensile stresses when the concrete shrinks due to moisture loss. PF mitigates plastic and early drying shrinkage by increasing the tensile strength of concrete and by bridging cracks [4]. Specific uses include shotcreting, precast products and situations where fire resistance is of importance [5].

PF is known to reinforce against the formation of plastic shrinkage cracks in mortar and concrete and that a finer and longer fiber is more effective than a coarser and short fiber in controlling plastic shrinkage cracking in concrete [1]. PF therefore has a low Young's modulus; as a consequence, it can neither prevent the formation and propagation of cracks at high stress levels nor bridge large cracks [6]. The effect of PF on shrinkage of cementitious materials has been studied by several researchers. Filho et al. [7] reported that the addition of small quantities of fibers such as steel, polypropylene and cellulose can reduce the plastic shrinkage cracking of cement based materials. Grdic et al. [8] reported that the addition of fibers contribute to reduction of both size and frequency of the cracks in concrete in the early phase. According to Aly et al. [1], increasing dosages of PF in concrete caused small but consistent increases of the overall total shrinkage strain of concrete. They also noted that concrete mixtures that incorporated PF were more permeable and hence more vulnerable to drying, as evidenced by more moisture lost during the period of drying than companion mixtures without fibers. They also found that addition of PF increased the nano-porosity and provided a more refined micro-pore structure that was more influential on the rate of drying shrinkage and concluded that the high porosity was likely due to the increase in mesopores zone at the vicinity of PF. Mesbah and Bodin [9] observed a 6% reduction in the drying shrinkage of mortars with 0.25% PF ratio. For higher PF contents, they found that PF had an unfavorable effect.

PF is also used to enhance the mechanical properties of cement based materials. Nili and Afroughsabet [10] indicated that the increase of PF ratio in the mixtures from 0.2% to 0.5% generally increased the compressive strength of concrete and that splitting tensile and flexural strength of 0.5% fibrous silica fume concretes was enhanced considerably. They also noted that silica fume improved the fiber dispersion in the mixtures. Grdic et al. [8] found that PF improved tensile strength and abrasion resistance of concrete. Sun and Xu [11] similarly, reported that using 0.9 kg/m^3 PF improved the compressive and flexural strength and toughness up to 7%, 14%, 152% respectively, compared to reference concrete. However, when PF content was 1.35 kg/m^3 this trend reversed and there occurred a decrease in mechanical and physical properties such as compressive strength, flexural strength, brittleness, bonding strength, toughness and water penetration depth. Similar findings were reported by several researchers. Karahan and Atis [12] reported that adding PF 0.05%, 0.10%, 0.20% by volume reduced unit weight, compressive strength and modulus of elasticity, and increased porosity and sorptivity. Shekarchi et al. [13] found that fibers seemed to have no effect on compressive strength of mortars, but excessive fibers content such as 0.7% caused a considerable decrease in strength which they attributed to the fact that sample compaction and homogeneity were influential in the final strength of the samples. Puertas et.al [14] incorporated PF in various types of mortars and found that PF induced a slight decrease in the mechanical strengths.

The use of PF also has a significant effect on workability. The most important disadvantage of incorporating a fiber is the loss of workability thus, increasing the difficulty of casting. This situation mostly results with inadequate workability and high volumes of entrapped air in mortar [15]. Chen and Liu [16] reported that at %1 volume content, PF reduced slump values of concrete by about 21%. They also noted that slump flow property of concrete was more significantly affected than the slump which they attributed to the holding effect of fibers distributed uniformly in concrete, which as they stated reduced the surface bleeding of concrete and the sedimentation of the aggregates, and improved the viscosity of the concrete. Puertas et.al [14] found that the presence of the fibers reduced workability and affected the compaction of the mortar. Shekarchi et.al [13] reported that in constant water to cement ratio, the use of PF decreased workability and that an increase of fibers volume led to an increase in the rheological properties of mortar, namely viscosity and yield stress. They also found that doubling the length of fibers in the same fiber content ratio did not affect workability and that mixes with low fiber content (0.1%) did not make considerable changes in workability. Karahan and Atis [12] reported that inclusion of PF in fresh concrete increased vebe time and reduced slump values and that the increase in fiber content caused additional increase in these properties. Topcu and Canbaz [17] reported that fiber addition decreased slump values of fresh concrete and that addition of fibers into concrete might cause a decrease in workability.

According to the above literature survey, it can be noticed that the effect of PF on fresh and hardened properties of mortar and concrete is not quite clear. Some of the works show in some cases no effect, a modest improvement or a negative effect in these properties and some, however, show the opposite. Kang et.al [18] reported that non-uniform fiber distribution decreased the strengthening effect of fiber and that fiber distribution is strongly influenced by various factors such as fiber size, fiber ratio and workability of the matrix. The improved fiber distribution is reported to be responsible for the enhanced mechanical properties of hardened engineered cementitious composites [19].

In this study it is aimed to evaluate the effects of admixed PF content of 0%, 0.25%, 0.5%, 1% and 1.5% on the fresh and hardened properties of mortars. This objective is supported by various tests such as fresh density, workability, hardened density, water absorption, compressive strength, flexural strength, drying shrinkage and pore structure analysis.

2. EXPERIMENTAL STUDY

2.1. Materials and Mixing Procedure

The materials used in this research include sand as fine aggregate, cement, chemical admixture and PF. Siliceous standardized sand with a maximum particle size of 2 mm was in saturated surface dry conditions and its bulk unit weight and particle density were 1540 and 2610 kg/m^3, respectively.

The cement used in all mixes was a white Portland cement, from one source and its physical properties and chemical composition is given in Table 1. A commercially available policarboxylic ether based superplasticizer was also used.

Table 1. Chemical, physical and mechanical properties of cement

Chemical Properties (%)		Physical Properties	
Insoluble residue	0.16	Specific gravity (g/cm^3)	3.1
SiO_2	23.46	Volume expansion (mm)	2
Al_2O_3	3.57	Specific surface (cm^2/g)	3975
Fe_2O_3	0.22	Compressive Strength	
CaO	66.48	28 days (MPa)	56.0
MgO	1.51		
SO_3	2.35		
K_2O	0.42		
Na_2O	0.39		
Cl^-	0.0065		
Loss of ignition	2.6		

A PF with a density of 0.91 g/cm^3 and a length of 6 and 12 mm was used throughout the study and PF content varied between 0 to 1.5% by volume of mortar. Physical and mechanical properties of PF, provided by the manufacturer, are presented in Table 2.

Table 2. Properties of PF

Length (mm)	Density (g/cm^3)	Tensile Strength (MPa)	Young's Modulus (MPa)	Elongation (%)
6 and 12	0.91	350-700	3000-3500	20-25

The mixing procedure for fresh mortar mixtures was as follows: cement, mixing water and plasticizer were mixed initially for 1 min. Fine aggregate was added and mixed for 1.5 min and finally PF was added and mixed for another 1 min. Fresh properties were determined immediately after the mixing and six 40x40x160 mm prismatic specimens for each series were cast to perform mechanical and physical tests. Mix proportions and designation codes of the mixtures are provided in Table 3.

Table 3. Mix proportions

Mix	Water (g)	Cement (g)	Sand (g)	Plasticizer (g)	PF (%)	PF(g)	Fiber length (mm)
R	180	450	1350	4.2	0	0	-
M6-0.25	180	450	1350	4.2	0.25	1.74	6
M6-0.5	180	450	1350	4.2	0.5	3.49	6
M6-1.0	180	450	1350	4.2	1.0	6.99	6
M6-1.5	180	450	1350	4.2	1.5	10.48	6
M12-0.25	180	450	1350	4.2	0.25	1.74	12
M12-0.5	180	450	1350	4.2	0.5	3.49	12
M12-1.0	180	450	1350	4.2	1.0	6.99	12
M12-1.5	180	450	1350	4.2	1.5	10.48	12

2.2. Specimen Preparation and Curing

Nine different mortar mixes with a constant aggregate gradation and content, cement content and water content were prepared. Each mortar mixes consisted of four different PF ratio as 0.25, 0.5, 1.0 and 1.5% and two different PF length as 6 and 12 mm. All mixes had 0.93% of superplasticizer by weight of cement. Mortars without fibers were named as reference (R) throughout the paper.

The specimens were demoulded 24 h after the production and stored in a controlled humidity cabinet at a temperature and relative humidity of 20±5°C and 55±10%, respectively. Physical and mechanical tests were performed at 90 days.

2.3. Test Procedure

The performance of mortars incorporating different amounts and length of PF was evaluated by determining the following properties; workability, fresh density, water absorption, density, drying shrinkage, pore ratio, compressive strength and flexural strength.

2.3.1. Tests on Fresh Mortar

Workability of fresh mortar was determined by means of flow values immediately after the mixing according to EN 1015-3. In each series, fresh density was also determined. Table 4 summarizes the test results of fresh mortar.

Table 4. Fresh and hardened properties

Series	Flow value (mm)	Density (kg/m^3)		Comp. strength (MPa)	Flexural strength (MPa)	Water absorption (%)	Pore ratio (%)	Drying shrinkage at 90 days (microstrain)
		Fresh	Hardened					
R	170	2344	2208	56.8	8.5	10.0	0.86	625
M6-0.25	155	2305	2133	45.7	8.3	10.3	0.87	500
M6-0.5	125	2148	2071	44.3	8.2	10.4	1.06	600
M6-1.0	115	2062	2018	39.8	7.9	10.9	1.25	631
M6-1.5	110	2018	1968	35.5	6.8	12.2	1.27	656
M12-0.25	130	2279	2159	52.9	9.1	10.2	0.93	550
M12-0.5	120	2214	2135	50.8	7.8	10.5	0.94	648
M12-1.0	110	2181	2077	37.3	6.5	12.9	2.04	667
M12-1.5	110	2083	2035	36.1	6.5	14.0	1.74	688

2.3.2. Tests on Hardened Mortar

In each mix density, water absorption, pore ratio, compressive and flexural strength were determined on 40x40x160 mm specimens at 90 days and drying shrinkage of each mix was calculated at 1, 7 and 90 days. Test results of hardened mortar mixes are presented in Table 4.

3. RESULTS AND DISCUSSIONS

3.1. Workability and Density

The flow value and fresh density of the mortars varied between 110-170 mm and 2018-2344 kg/m^3 respectively. As seen in Fig. 1, the increase in fiber ratio resulted in a decrease in flow values.

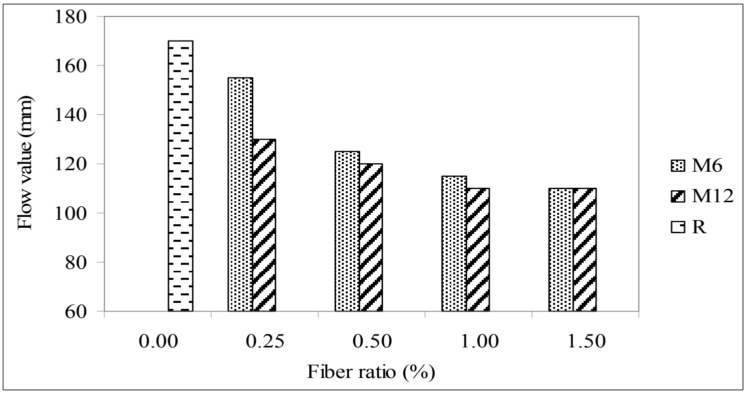


Figure 1. Relationship between fiber ratio and flow value

Karahan and Atis [12] and Shekarchi et.al [13] reported that inclusion of PF reduced workability and increase in fiber content caused additional reductions in workability. Among all series reference mortar without fiber (R) had the highest and M6-1.5, M12-1.0 and M12-1.5 had the lowest flow values as 170, 110 and 110 mm, respectively. The use of longer fiber (12 mm) resulted in a further decrease in flow values. The same trend was also observed in the fresh and hardened density values. Increase in fiber ratio resulted in a decrease in the density of the samples (Table 4). These reductions in the density values can be attributed to the difference between the specific gravity of PF and the other ingredients. Since PF is lighter than cement and sand, mortars with fibers had lower densities when compared to the reference mortar without fiber.

3.2. Water Absorption

To determine water absorption, specimens were initially oven dried at 100±5°C until constant weight (W_d, g) was achieved and then immersed in water for 24 h to obtain saturated weight (W_s, g). Water absorption was then calculated using Eq. (1) as

$$\%WA = \frac{(W_s - W_d)}{V} \times 100 \qquad (1)$$

where W_A indicates the water absorption by volume (%) and V the volume (cm^3) of the specimen.

According to the test results, water absorption of the mortars varied between 10-14% (Fig. 2). The increase in fiber ratio resulted in an increase in absorption values. The reason for that can be attributed to the poor workability that resulted in a more porous structure. Aly et.al [1] reported that the pore system arising from the addition of PF into the concrete is more permeable. The higher the permeability therefore would result in higher absorption values. This increase in water absorption was notable especially for fiber ratios over 0.5%. The use of longer fibers also caused a significant increase in water absorption values. The increase in water absorption was 40% in M12-1.5 series when compared to the reference.

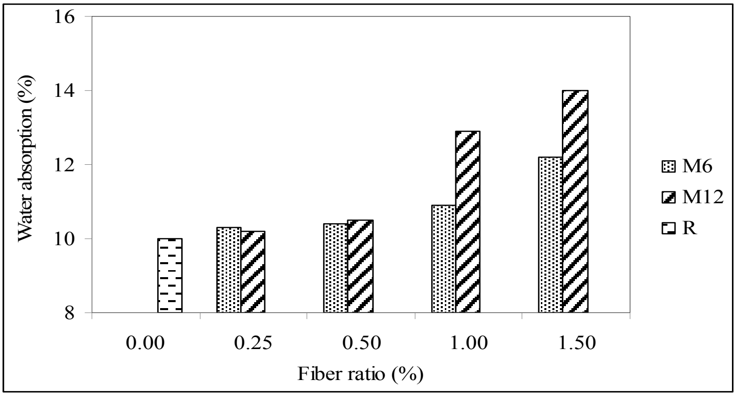


Figure 2. Relationship between fiber ratio and water absorption

3.3. Compressive Strength

The compressive strength was significantly affected by fiber addition especially in series with 1.0 and 1.5% fiber ratios (Fig. 3). While compressive strength of reference mortars was about 57 MPa, the compressive strengths of M6-1.5 and M12-1.5 was only 35.5 and 36.1 MPa respectively, resulting in a decrease of about 38%. However at lower fiber contents (0.25% and 0.5%), the decrease in compressive strength was about 7% and 12% in M12-0.25 and M12-05 series respectively when compared to reference.

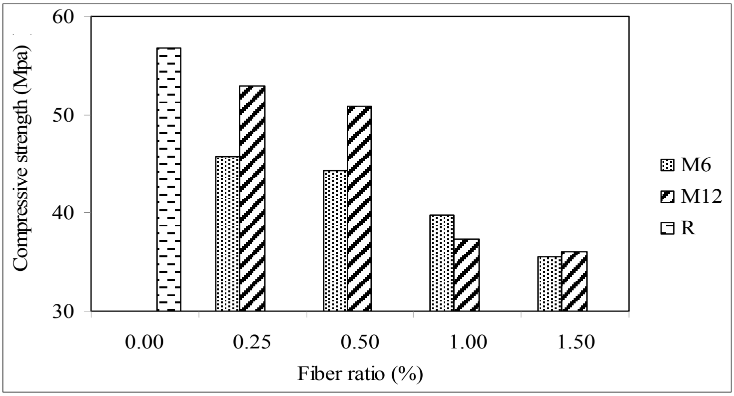


Figure 3. Relationship between fiber ratio and compressive strength

Similar results were reported by several researchers. Sun and Xu [11] reported that when used in higher amounts PF reduced compressive strength significantly. The same finding was also supported by Shekarchi et.al [13]. They reported that excessive fibers content such as 0.7% caused a considerable decrease in strength and that sample compaction and homogeneity were influential in the final strength of the samples. They also mentioned that doubling the fiber length at lower fiber ratios contributed to compressive strength and that the achieved strength values were still below the reference. Gutiérrez et.al [20] found that incorporating fibers into plain mortar caused a reduction in compressive strength and that the addition of a highly active pozzolan or slag could help to compensate for this loss of performance.

3.4. Flexural Strength

As seen in Fig. 4, the effect of fibers on flexural strength varied. At 0.25% fiber content an improvement of about 7% was observed in flexural strength of M12-0.25 series when compared to reference. However at higher fiber contents, flexural strength significantly decreased especially in series with 12 mm length PF. Similar results were reported by several researchers [11-14].

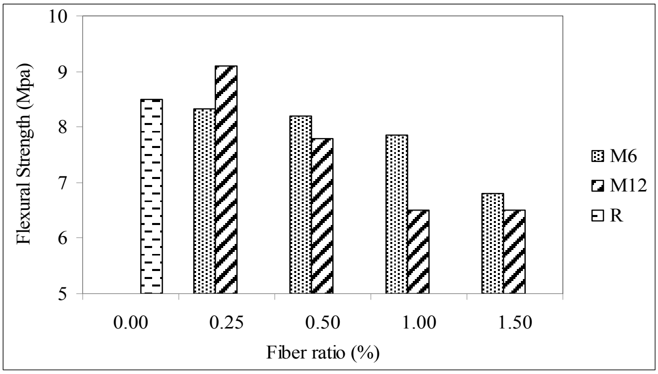
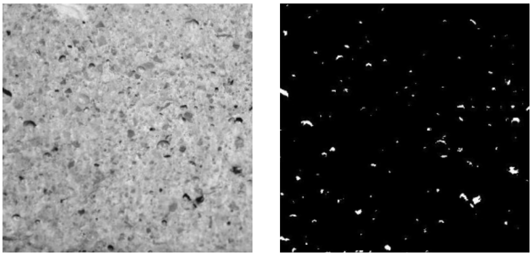


Figure 4. Relationship between fiber ratio and flexural strength

3.5. Pore Ratio

Three specimens from each of the mixes were selected to determine pore ratio right after the flexural strength test. The care was taken to choose samples with fracture planes almost parallel to the loading direction. Images were collected by high-resolution camera and processed by an image analysis program as shown in Fig 5. Pore area of each specimen was determined and pore diameters were calculated by considering that each pore was circular. Pore ratio (p, %) was then calculated by dividing the total pore area to the cross section area of each specimen. The so obtained pore ratios are presented in Table 4.



(a) (b)

Figure 5. (a) Mortar cross section, (b) Pore structure (white colored)

The results showed that an increase in fiber content resulted in a significant increase in pore ratios, especially in series with higher fiber content, up to 137%. However at lower fiber contents (0.25 and 0.5%) the change in pore ratio varied between 1-23% compared to reference. The increase in pore ratio might be due to the workability. The addition of fibers, as stated before, deteriorated workability (Fig.1) and this might have resulted in higher pore ratios within the mortars.

The variation in pore ratios had a significant effect on physical and mechanical properties of mortars. Fig. 6-8 shows the relationship between pore ratio and compressive strength, flexural strength and water absorption of the mortars. As seen in Fig. 6-8, the increase in pore ratio resulted in a decrease in compressive strength and flexural strength and an increase in water absorption values.

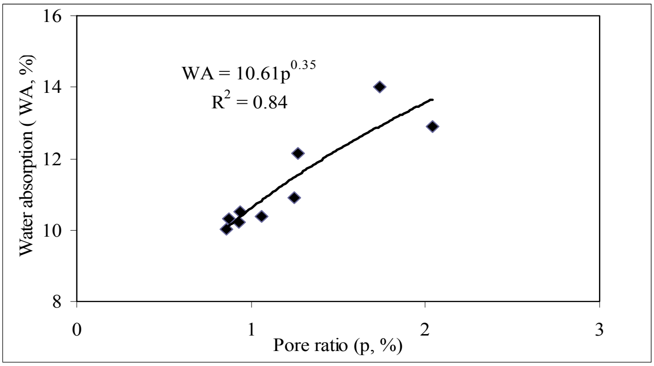


Figure 6. Relationship between pore ratio and water absorption

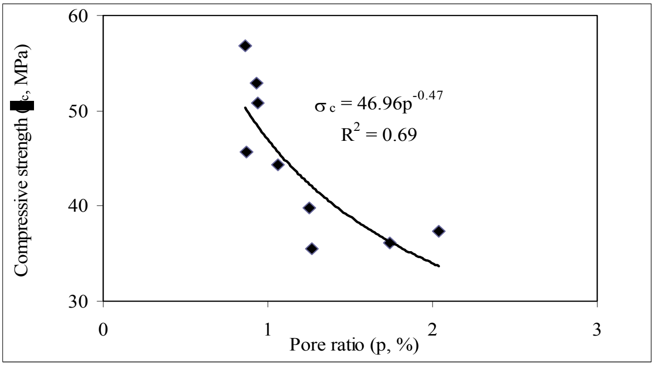


Figure 7. Relationship between pore ratio and compressive strength

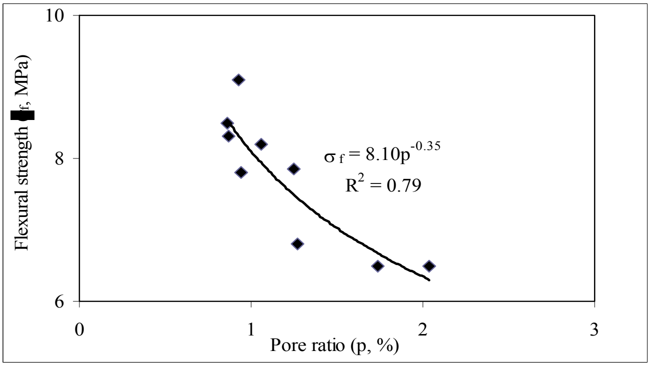


Figure 8. Relationship between pore ratio and flexural strength

3.6. Drying Shrinkage

Fig. 9 and 10 shows the development of drying shrinkage of the mixes with drying time. The shrinkage rate is reduced gradually with elapsed time for all mixes. As seen in Table 4, M12-1.5 possessed the highest and M6-0.25 possessed the lowest shrinkage values of 688 and 500 microstrain, respectively, at the age of 90 days. The increase in fiber ratio generally caused an increase in drying shrinkage of mortars.

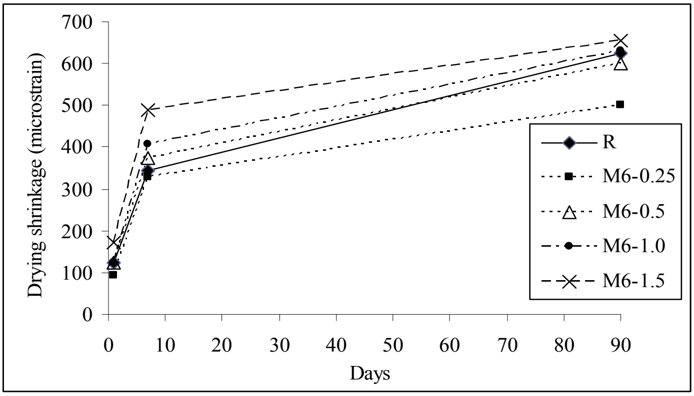


Figure 9. Drying shrinkage of mortars with 6 mm fiber

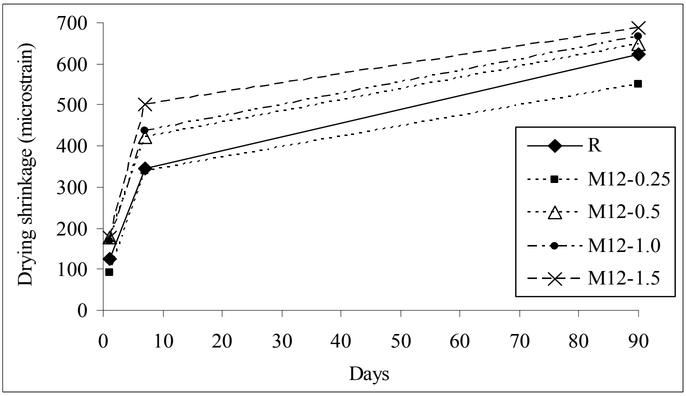


Figure 10. Drying shrinkage of mortars with 12 mm fiber

According to Aly et al. (2005) [1] increasing PF dosages in concrete increased the total shrinkage of concrete which they attributed to the more permeable structure that occurred when PF was incorporated to the mixes. This study also confirms this statement as the increase in PF increased water absorption and pore ratio of the mortars (see Table 4). However at lower contents, PF resulted in a decrease in drying shrinkage of M6-0.25, M12-0.25 and M6-0.5 series as 20%, 12% and 4% respectively. Doubling the fiber length resulted in an increase in drying shrinkage. However there occurred a decrease in this increment when fiber ratio increased. While at 0.25% fiber ratio drying shrinkage of M12-0.25 mortars at 90 days was 10% higher than M6-0.25 mortars, at 1.5% fiber ratio the difference between M6-1.5 and M12-1.5 mortars was just 5%.

4. CONCLUSIONS

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

Workability of mortars incorporating PF is significantly deteriorated by increasing the fiber content. The increase in fiber ratio resulted in a decrease in flow values; a reduction of about 35% was observed in mortars with 1.5% fiber ratio and 12 mm fiber length. Doubling the fiber length also caused additional loss in workability.

The effect of fiber content and length on mechanical properties of mortars varied. While compressive strength significantly decreased by the increase in fiber ratio, a slight improvement was observed in flexural strength at 0.25% fiber ratio. Doubling the fiber length generally had a positive effect on mechanical properties at lower fiber contents but the achieved strength values (except flexural strength at 0.25% fiber ratio) were below the reference.

At lower fiber contents drying shrinkage of mortars possessed lower values compared to reference. However at higher fiber contents drying shrinkage increased.

Strong relationships between pore ratio and water absorption, compressive strength and flexural strength were established. The increase in pore ratio resulted in an increase in water absorption and a decrease in compressive and flexural strength of mortars.

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