Composites: Part B 58 (2014) 463–472

Contents lists available at ScienceDirect

Composites: Part B

journal homepage: www.elsevier.com/locate/compositesb

Investigation of freeze–thaw effects on mechanical properties of fiber reinforced cement mortars

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ARTICLE INFO

Article history:
Received 1 August 2013
Received in revised form 1 November 2013
Accepted 12 November 2013
Available online 20 November 2013

Keywords:
A. Aramid fiber
A. Carbon fiber
A. Glass fibers
B. Environmental degradation

ABSTRACT

Fibers are used for improving some properties of conventional concrete (which is a brittle material) such as tensile strength, abrasion resistance, absorption and crack control. This study investigates the usability of fibers against the harmful effects of freeze–thaw cycles on cement mortars. For this objective, five different types of fibers, i.e., Polypropylene (PP), Carbon (CF), Aramid (AR), Glass (GF) and Poly vinyl alcohol (PVA) in four different ratios (0.0%, 0.4%, 0.8% and 1.2%) were added to cement mortars along with an amount of air agent. These samples were then subjected to five different freeze–thaw cycles (0, 25, 50, 75 and 100). Thus, mechanical behaviors were investigated under freeze–thaw effects.

The most important results of the study are summarized; the fibers increase flexural strength and deflection ability of the samples while decreasing compressive strength, dynamic modulus of elasticity and specific mass. The highest flexural strength was obtained with a 1.2% addition of CF fiber for the samples in normal conditions. The mechanical properties of the samples subjected to repetitive freeze–thaw cycles were also investigated; the best flexural strength was provided with 1.2% CF addition, while the highest dynamic modulus of elasticity was obtained with a 1.2% PP addition.

1. Introduction

Cementitious composites are generally brittle and low-tensile strength materials. Fibers enhance this weakness by increasing tensile strength, ductility and toughness, and therefore, durability. Contradictory test results have been reported by different studies; additionally, the efficacy of the fiber reinforcement is dependent on many factors, including the properties of the matrix, as well as fiber geometry, size, type, volume and dispersion [1–5].

In cold environments, freeze–thaw cycles can be harmful to a porous and brittle material such as concrete when it is subjected to lower temperatures. Concrete subjected to repetitive freeze–thaw cycles may deteriorate rapidly by losing strength and/or crumbling. When water begins to freeze in a capillary cavity, the increase in volume accompanying the freezing of the water requires a dilation of the cavity equal to 9% of the volume of frozen water, or forcing of the amount of excess water out through the boundaries of the specimen, or combination of both effects [4]. The magnitude of this hydraulic pressure depends on the permeability of the cement paste, the degree of saturation, the distance to the nearest unfilled void and the rate of freezing. If the pressure exceeds the tensile strength of the paste at any point it will cause local cracking. In repeated cycles of freezing and thawing in a wet environment, water will enter the cracks during the thawing portion of the cycle only to freeze again later and there will be progressive deterioration with each freeze–thaw cycle. Thus, the strength of sample decreases with freeze–thaw cycles [6]. In addition, the surfaces of samples will scale off and crumble due to the expansion caused when water freezes to ice.

Fiber reinforcement may reduce this effect by improving ductility, toughness and tensile strength [7–11]. Steel, glass, carbon and polymer based fibers are commonly employed in many fiber reinforced composite applications [12]. Of these, glass fiber (GF) is the most commonly used [13]. Polypropylene (PP) fiber is a cheap and popular material used in the concrete industry, and many researchers have studied the mechanical properties of PP reinforced concrete [3,14]. Polyvinyl alcohol (PVA) based fibers perform extremely different in a cement based matrix due to its surface formation and high strength [2,15,16]. In relation to most functional properties, carbon fibers are exceptional when compared to other fiber types [2,17–19]. The term “Aramid fiber” is an abbreviation of aromatic polyamide fiber. This type of fiber’s molecular chains is highly aligned in the fiber direction and is relatively inflexible. Molecules are arranged in parallel hydrogen bonded sheets. They have high longitudinal strength (covalent bonds) and low transverse strength (hydrogen bonds) [3,20–22]. Some researchers prefer to simultaneously use different types of fibers [23] or different lengths of fibers [24] as reinforcement in cementitious matrix composites.

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http://dx.doi.org/10.1016/j.compositesb.2013.11.013

The main objective of this study was to investigate the effects of the different types of fibers on mechanical properties of cement mortars subjected to freeze–thaw cycles. For this objective, five different types of fibers (PP, CF, AR, GF, PVA) in four different ratios (0.0%, 0.4%, 0.8%, 1.2%) were added to cement mortars along with some amount of air agent. These samples were then subjected to five different freeze–thaw cycles (0, 25, 50, 75, 100). Then, flexural strengths, compressive strengths and modulus of dynamic elasticity were obtained. In addition, mass properties and deflections were established. The results were compared with control samples.

In many studies of concrete suffering from freezing and thawing cycles, the dynamic modulus of elasticity and weight loss have generally been the main focus. These studies, however, have not provided information on the mechanical properties of concrete under compressive and tensile stress states. Because maximum numbers of freeze–thaw cycles are chosen very high as 300–400, concrete cracks. Thus, it is not possible to obtain compressive and flexural strength. In this study, because the maximum number of freeze–thaw cycles was chosen as 100, visible deteriorations could not occur in the samples; thus, it was possible to apply flexural and compressive strength tests in addition to ultrasonic velocity tests to samples.

2. Materials and methods

2.1. Materials

Five different types of fibers were used in the experiments. These were PP, CF, AR, GF and PVA. Some properties of these fibers are presented in Table 1.

As can be seen in Table 1, the specific masses of the fibers varied between 0.91 and 2.68 g/cm^3; fiber diameters were between 14 and 660 μm, elongations between 1.8% and 10%, tensile strengths between 300 and 4200 MPa and Young moduli were between 4000 and 240000 MPa. The most brittle material was carbon fiber and the most ductile was polypropylene fiber.

CEM I 42.5 R type cement was used in the experiments. The compositions and physical and mechanical properties of the cement are presented in Table 2. The experiments were conducted according to EN 196 [25]; thus, CEN-standard sand was used as aggregate in mortars. The air entraining agent (AE) used in the experiments was specific inorganic powder and had 0.95 g/cm^3 of specific mass.

2.2. Methods

In accordance with the objective of the study, seventeen different fiber reinforced cement mortars were prepared with five different fiber types and three different proportions (Table 3) in total. These mortars were subjected to five different freeze–thaw cycles (0, 25, 50, 75 and 100).

Table 2
Chemical, physical and mechanical properties of the CEM I 42.5 R type cement.

Chemical analysis (%)		Blaine surface (cm^2/g)	3626
SiO_2	21.86	Initial setting time (min)	170
Al_2O_3	4.39	Final setting time (min)	225
Fe_2O_3	3.05	Specific gravity (g/cm^3)	3.06
CaO	60.62	Le Chatelier expansion (mm)	2
MgO	2.55	Strength (MPa)	
SO_3	2.35	1st day	12.5
LOI	2.26	2nd day	23.1
Total	97.08	28th day	57.4

The flexural and compressive strength tests were conducted according to the principles suggested in EN 196 [25]. The “test mortar” consisted of 450 g of cement, 1350 g of graded standard sand and 225 g of water; thus, the water/cement ratio was 0.50. The powder state air entraining agent was batched with the mixture in the last 30 s of the mixing cycle of the mortar. While the fiber reinforced mortars were being produced, after pouring water into the cement–sand mixtures, the selected fibers were added to the fresh mortar. Then, the mortars were mixed as long as was needed in order to obtain homogeneous mixtures. The homogenous dispersion of the fibers in the samples could be seen on cracked samples after samples had been tested. Following the molding process, the molds (with the mortars in them) were placed in a moist room at 21 ± 1 °C for 24 h and removed at the end of this period; the prismatic mortar specimens were stored in tap water for 40 days. Thus, the mortars were maturated sufficiently prior to the freeze–thaw cycles. According to the objective of the study, freeze–thaw cycles were applied to the samples.

2.3. Repetitive freeze–thaw experiments

The freeze–thaw tests were realized according to Turkish Standard, TS 699 [26]. This standard is generally used as an alternative to CEN/TS 12390-9 [27] to determine the freeze–thaw resistance of concrete in Turkey [7]. The working principle of freeze–thaw equipment is given in Table 4. The samples were subjected to five different freeze–thaw cycles (0, 25, 50, 75, 100). Because the maximum number of freeze–thaw cycles chosen was 100, visible deteriorations did not occur in the samples. Thus, it was possible to apply flexural and compressive strength tests in addition to ultrasonic velocity tests. One cycle took about 6½ hours to complete’. Thus the completion of 100 cycles took roughly 27 days. It was clear that the additional 27-day strength gain was highly important to the mortars which their hydrations are not ultimately completed. To prevent this situation, as the freeze–thaw cycle stages finished, the samples were taken from the freezer equipment and stored in a cure tank until the freeze–thaw cycles of all the samples were completed.

After the freeze–thaw processes had been completed, ultrasonic velocity, flexural strength and compressive strength tests were conducted. The deflections were the maximum deformations of

Table 1
The properties of the fibers used in the experiments.

Properties	Aramid (AR)	Polypropylene fiber (PP)	Glass fiber (GF)	Carbon fiber (CF)	Polyvinyl alcohol fiber (PVA)
Specific mass (g/cm^3)	1.44	0.91	2.68	1.76	1.3
Fiber length (mm)	12	12	12	12	12
Fiber diameter (μm)	12	18	14	6.9	660
Melting point (°C)	149–177	160	860	3500	>200
Ignition point (°C)	450 (roasting)	360	Incombustible	Incombustible	Combustible
Alkali resistance	High	High	High	High	High
Elongation (%)	3.6	8–10	2.4	1.8	7
Tensile strength (N/mm^2)	2920	300–400	1700	4200	900
Young modules (N/mm^2)	83,000	4000	72,000	240,000	23,000

Table 3
Mix designs of seventeen different fiber reinforced mortars.

Fibers			Air entraining agent (AE3) (0.65%) (g)	Standard sand (g)	Cement (CEM-I/42.5R) (g)	Water (g)	*W*/*C*
Type	Volume ratio (%)	Mass (g)	2.925	1350	450	225	0.5
PP	0.40	3.15					
	0.80	6.30					
	1.20	9.45					
CF	0.40	6.08					
	0.80	12.16					
	1.20	18.24					
AR	0.40	4.98					
	0.80	9.95					
	1.20	14.30					
GF	0.40	9.26					
	0.80	18.52					
	1.20	27.79					
PVA	0.40	4.49					
	0.80	8.99					
	1.20	13.48					
Control-1	0.00	0.00					
Control-2	0.00	0.00	0.00				

Table 4
The time elapsed for one freeze–thaw cycle and temperatures subjected.

Stages	Temperature (°C)	Time elapsed (min)
Stage 1	20	1
Stage 2	−15	5
Stage 3	−16	5
Stage 4	−17	5
Stage 5	−18	5
Stage 6	−20	90
Stage 7	−20	121
Make water and wait	20	120
Water discharge	–	25

the midpoint of beams at the moment of breaking. Three specimens were tested for each type of mixture according to the Rilem–Cembureau method in EN 196 [25].

2.4. Determining modulus of dynamic elasticity

Ultrasonic velocity tests were executed with a Proceq Pundit Lab+ device. While modulus of dynamic elasticity was being found, it was benefited from ultrasonic velocity. For this aim, ultrasonic waves were sent from one edge along the long border of the prismatic mortar sample and read from the other edge. Thus, the reach time was determined. Then, the velocity was calculated according to Eq. (1). After wave velocity had been calculated, the modulus of dynamic elasticity was also calculated (Eq. (2)).

$$V = \frac{S}{t} \times 10^6 \tag{1}$$

V is the ultrasonic wave velocity (m/s), S is Interval between transducers (m), and t is the time (μs):

$$E_d = \frac{V^2 \times \rho \times (1+\mu) \times (1-2\mu)}{(1-\mu)} \tag{2}$$

E_d is the modulus of dynamic elasticity (GPa), ρ is density (kg/m^3), and μ is the Poisson ratio.

3. Results and discussions

3.1. The physical and mechanical properties of the fiber reinforced cement mortars

3.1.1. The effects of fiber addition on unit masses of cement mortars

Because unit masses of fibers (except for GF) are lighter than cement mortars, it was expected that the fiber addition would decrease the unit masses of the cement mortars. However, there was a decrease in the GF reinforced mortars, too. It was assumed that because of this decrease, the GF had a hydrophilic structure and had absorbed some of the mixing water, thereby decreasing workability; thus, the mortar was found to not be compacted well. For the same reason, the mechanical properties of the mortars also decreased.

When the air entraining agent, having 2.04 g/cm^3 unit mass, was added to the control sample, its unit mass decreased to 2.00 g/cm^3. After 1.2% of fiber addition, these decreases for PP, CF, AR, GF and PVA were about 4.5%, 3.5%, 4.5%, 2.5% and 5.0%, respectively (Fig. 1, Table 5).

3.1.2. The effects of fiber addition on flexural strengths of cement mortars

Compared with control samples, in general, fiber addition increased the flexural strength of mortars. However, this increase was not clearly determined for PP addition in any addition ratios. The best results were obtained in 0.8% addition ratios for AR and PVA. In higher ratios than this, the contribution to flexural strength was decreased. CF addition increased flexural strength in all addition ratios. For used ratios, CF addition limit was not determined. 1.2% of CF addition increased flexural strength from 9.14 N/mm^2 (control) to 11.18 N/mm^2. For GF, the situation seemed likely that CF. 5% in flexural strength increase (9.62 N/mm^2) was obtained with 1.2% of GF addition (Fig. 2, Table 6).

3.1.3. The effects of fiber addition on compressive strengths of cement mortars

Since the fibers have more ductile structure compared to the cement matrix and aggregate when the fibers are added to mortars, they cause discontinuity in the cement matrix. This is therefore expected to decrease the compressive strength of mortars [2]. This situation was also experienced in this study. As fiber addition ratio increased, compressive strength decreases further. The CF fiber which is most brittle one shows the least there was a decrease in compressive strength. A 1.2% addition of PP, CF, AR, GF and PVA fibers decreased the compressive strength of the mortar by about 18.4%, 5.3%, 12.5%, 10.0% and 18.1%, respectively (Fig. 3, Table 7).

3.1.4. The effects of fiber addition on moduli of dynamic elasticity of cement mortars

When fibers are added to mortar, it is expected that fibers with high Young modulus will increase the moduli of dynamic elasticity of mortars, or vice versa. On the other hand, Eq. (2) shows that the

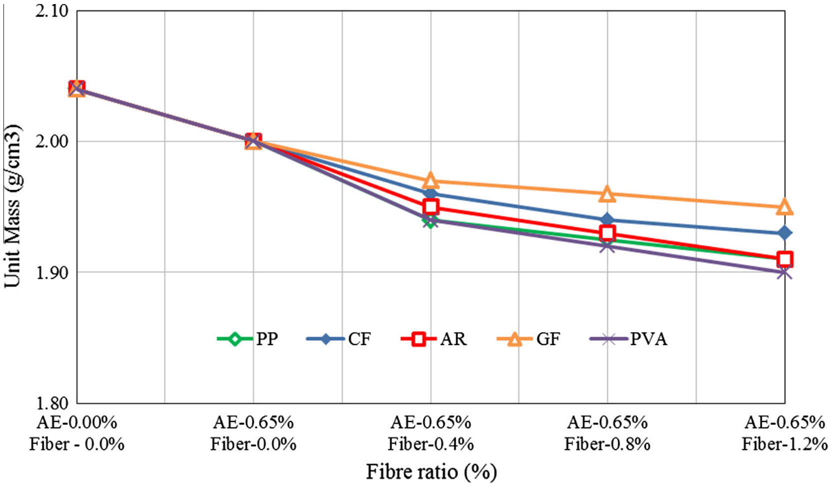


Fig. 1. Relationship between fiber addition ratio and unit masses of the mortars.

Table 5
Unit masses of the fiber reinforced mortars.

Fiber ratio (% by volume)	AE ratio (% by mass)	Unit mass (g/cm^3)				
		PP	CF	AR	GF	PVA
0.00	0.00	2.04	2.04	2.04	2.04	2.04
0.00	0.65	2.00	2.00	2.00	2.00	2.00
0.4	0.65	1.94	1.96	1.95	1.97	1.94
0.8	0.65	1.93	1.94	1.93	1.96	1.92
1.2	0.65	1.91	1.93	1.91	1.95	1.90

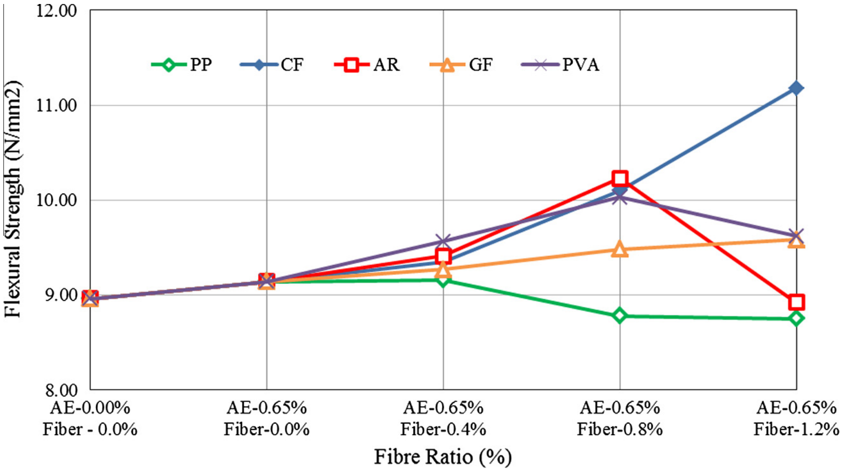


Fig. 2. Relationship between fiber addition ratio and flexural strengths of the mortars.

Table 6
Flexural strengths of the fiber reinforced mortars.

Fiber ratio (volume %)	AE ratio (mass %)	Flexural strength (N/mm^2)				
		PP	CF	AR	GF	PVA
0.00	0.00	8.96	8.96	8.96	8.96	8.96
0.00	0.65	9.14	9.14	9.14	9.14	9.14
0.4	0.65	9.16	9.35	9.41	9.27	9.56
0.8	0.65	8.78	10.10	10.23	9.48	10.03
1.2	0.65	8.75	11.18	8.92	9.58	9.62

modulus of dynamic elasticity is directly proportional to the unit masses of the samples. It was therefore concluded that all fiber types decreased the modulus of the dynamic elasticity of mortars. However, CF, which is the most brittle one, decreased it the least. On the other hand, the most ductile PP decreased the most. A 0.4%-CF addition only did not decrease the Young modulus. The

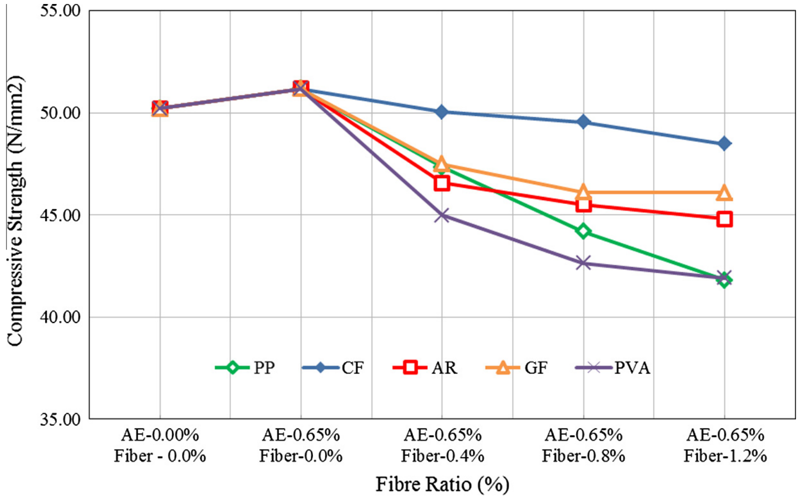


Fig. 3. Relationship between fiber addition ratio and compressive strengths of the mortars.

Table 7
Compressive strengths of the fiber reinforced mortars.

Fiber ratio (Volume %)	AE ratio (Mass %)	Compressive strength (N/mm^2)				
		PP	CF	AR	GF	PVA
0.00	0.00	50.20	50.20	50.20	50.20	50.20
0.00	0.65	51.18	51.18	51.18	51.18	51.18
0.4	0.65	47.34	50.03	46.56	47.48	44.97
0.8	0.65	44.19	49.54	45.52	46.10	42.63
1.2	0.65	41.79	48.46	44.80	46.08	41.90

highest decrease (19%) in modulus of dynamic elasticity was determined in the sample that had 1.2% PP (Fig. 4, Table 8).

Fig. 5 shows that the deflections of the mortars increased by about 30–45% in the case of all types of fiber addition. However, the moduli of dynamic elasticity of the fibrous mortars decreased and because deflections increased, the ductility of the samples increased, too. Thus, it can be said that fiber addition is able to compensate for micro cracks and small inter-stress of mortars with lower modulus of dynamic elasticity and higher deflection capacity.

3.2. The mechanical properties of the fiber reinforced cement mortars under repetitive freeze–thaw effects

3.2.1. The effects of fiber addition on flexural strengths of cement mortars under repetitive freeze–thaw effect

When the effects of freeze–thaw cycles on the flexural strength of the fibrous mortars were investigated, it was seen that, as the number of freeze–thaw cycles increased, the flexural strengths of the mortars decreased. However, the fiber reinforced mortars

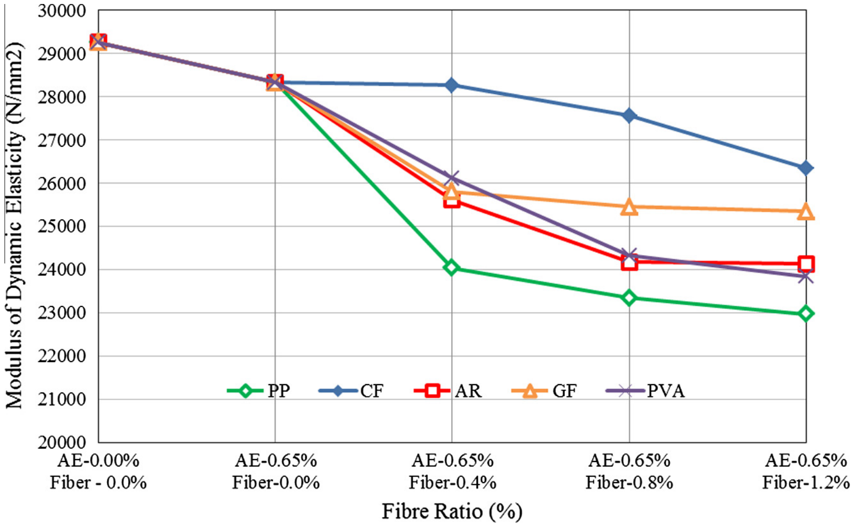


Fig. 4. Relationship between fiber addition ratio and modulus of dynamic elasticity of the mortars.

Table 8
Moduli of dynamic elasticity of the fiber reinforced mortars.

Fiber ratio (Volume %)	AE ratio (Mass %)	Moduli of dynamic elasticity (N/mm^2)				
		PP	CF	AR	GF	PVA
0.00	0.00	29,252	29,252	29,252	29,252	29,252
0.00	0.65	28,335	28,335	28,335	28,335	28,335
0.4	0.65	24,032	28,264	25,612	25,808	26,114
0.8	0.65	23,345	27,562	24,175	25,456	24,326
1.2	0.65	22,968	26,348	24,128	25,346	23,842

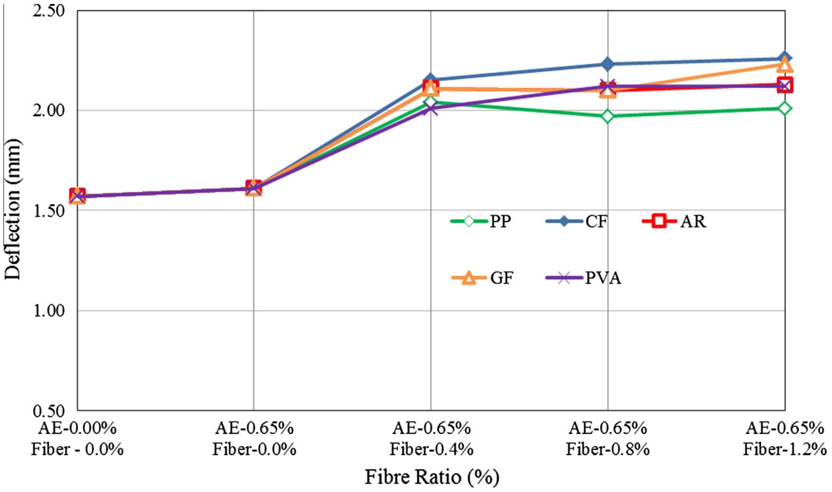


Fig. 5. Relationship between fiber addition ratios and deflections of the mortars.

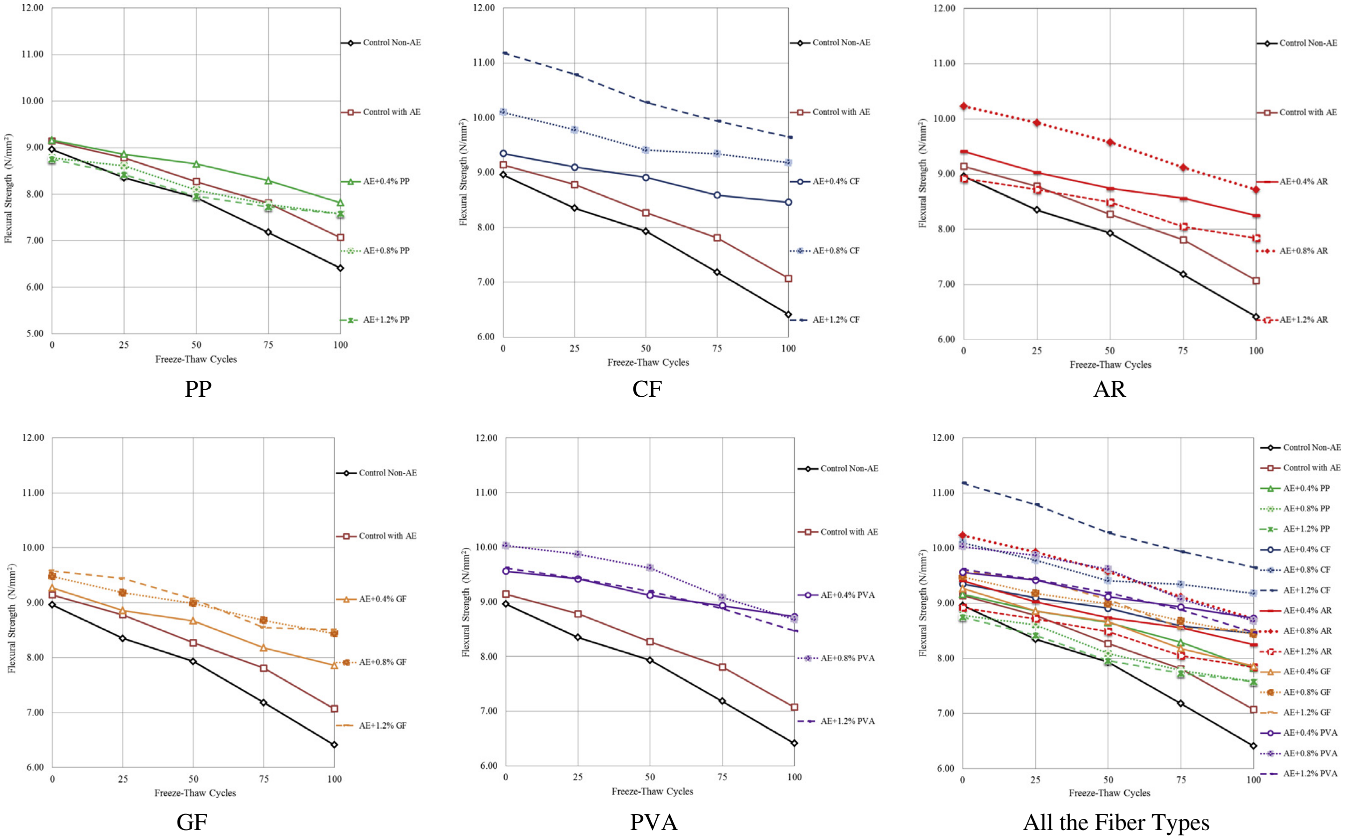
showed better comparative performance than non-fibrous ones (Table 9, Fig. 6). In addition, it was observed that the fiber reinforced samples, which had less flexural strength than the control sample prior to freeze–thaw cycles, showed higher flexural strength than the control sample after freeze–thaw cycles.

After 100 freeze–thaw cycles, flexural strength of the non-additive control sample decreased by 28%. This decrease for the control sample that had 0.65% AE was about 23%. This decrease for all fibrous samples is on average 12%.

The samples with PP showed the best results, with 0.4% by volume of fiber addition ratio. After 100 freeze–thaw cycles, decreases in flexural strength for the samples that had 0.4%, 0.8% and 1.2% of PP were 15%, 14% and 13%, respectively (Fig. 6). These decreases in flexural strength for the same addition ratios of CF were 10%, 9% and 13%, respectively. Decreases for AR addition were about 12%, 15% and 12%, while for GF these ratios were 15%, 11% and 11%. For PVA, these decreases in flexural strengths were about 9%, 14% and 12%, respectively.

Table 9
Flexural strengths of the fiber reinforced mortars under freeze–thaw effects.

Freeze–thaw cycles →		0	25	50	75	100
Flexural strength (N/mm^2)						
Control sample non-additive		8.96	9.14	7.93	7.18	6.41
Control sample with 0.65% AE		9.14	8.78	8.27	7.81	7.07
Sample with 0.65% AE + PP	0.4% PP	9.16	8.86	8.65	8.29	7.82
	0.8% PP	8.78	8.61	8.09	7.78	7.58
	1.2% PP	8.75	8.42	7.96	7.73	7.58
Sample with 0.65% AE + CF	0.4% CF	9.35	9.10	8.91	8.59	8.46
	0.8% CF	10.10	9.78	9.41	9.34	9.18
	1.2% CF	11.18	10.79	10.28	9.94	9.65
Sample with 0.65% AE + AR	0.4% AR	9.41	9.03	8.74	8.56	8.25
	0.8% AR	10.23	9.93	9.58	9.12	8.72
	1.2% AR	8.92	8.72	8.49	8.05	7.84
Sample with 0.65% AE + GF	0.4% GF	9.27	8.86	8.67	8.18	7.86
	0.8% GF	9.48	9.18	8.99	8.68	8.44
	1.2% GF	9.58	9.44	9.07	8.55	8.51
Sample with 0.65% AE + PVA	0.4% PVA	9.56	9.42	9.12	8.93	8.73
	0.8% PVA	10.03	9.87	9.62	9.08	8.68
	1.2% PVA	9.62	9.43	9.19	8.88	8.47



PP CF AR

GF PVA All the Fiber Types

Fig. 6. Relationship between fiber addition ratio and flexural strengths of the mortars under freeze–thaw effects.

Table 10
Compressive strengths of the fiber reinforced mortars under freeze–thaw effects.

Freeze–thaw cycles →		0	25	50	75	100
Compressive strength (N/mm^2)						
Control sample non-additive		50.20	51.18	46.15	44.20	41.83
Control sample with 0.65% AE		51.18	49.53	47.85	46.04	44.21
Sample with 0.65% AE + PP	47.34	46.16	44.78	43.35	41.74	7.82
	44.19	43.03	41.36	40.24	39.38	7.58
	41.79	40.87	39.96	39.33	38.16	7.58
Sample with 0.65% AE + CF	50.03	48.68	47.47	45.86	45.28	8.46
	49.54	49.01	46.63	45.02	43.85	9.18
	48.46	47.57	45.79	44.56	43.47	9.65
Sample with 0.65% AE + AR	46.56	45.10	44.15	42.79	42.17	8.25
	45.52	45.10	44.07	43.31	42.48	8.72
	44.80	43.92	42.38	42.01	41.06	7.84
Sample with 0.65% AE + GF	47.48	46.73	45.83	43.27	41.86	7.86
	46.10	45.61	43.89	42.03	41.91	8.44
	46.08	45.42	43.73	42.38	40.39	8.51
Sample with 0.65% AE + PVA	44.97	44.27	42.07	41.36	39.64	8.73
	42.63	40.74	40.02	39.01	37.68	8.68
	41.90	41.09	40.35	39.76	39.04	8.47

The samples that had 1.2%-CF, 0.8%-AR, 0.8% PVA and 0.8%-GF showed the best performance against repetitive freeze–thaw effects in terms of flexural strength.

3.2.2. The effects of fiber addition on compressive strengths of cement mortars under repetitive freeze–thaw effect

The compressive strength decrease started from the 25th freeze–thaw cycles for the samples that were both fibrous and non-fibrous (Table 10, Fig. 7). However, the strength loss was less for fiber reinforced mortars than for the control samples. After 100 freeze–thaw cycles, the compressive strength of the control samples without AE decreased about 17%, while the compressive strength of the control sample with AE decreased 14%. The conditions for the fibrous samples after 100 freeze–thaw cycles were as follows.

Although the samples with PP generally had less compressive strength than control samples, strength loss percentages in PP-fiber reinforced mortars were less than in the control samples. PP showed the best contribution with a 0.4% addition ratio. For this addition ratio, the decrease was roughly 11%. CF also presented the best contribution with 0.4–0.8% addition ratio. For these

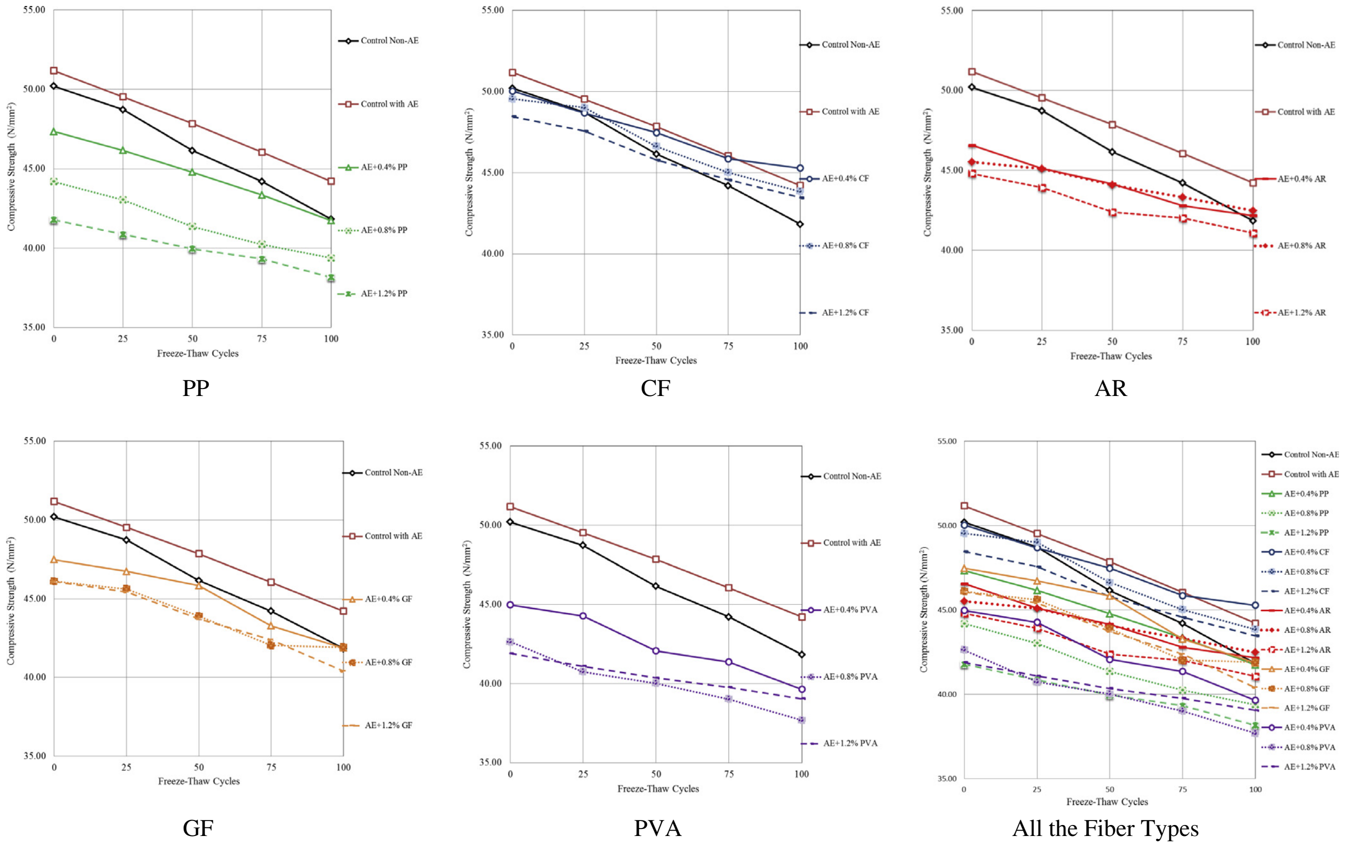


Fig. 7. Relationship between fiber addition ratio and compressive strengths of the mortars under freeze–thaw effects.

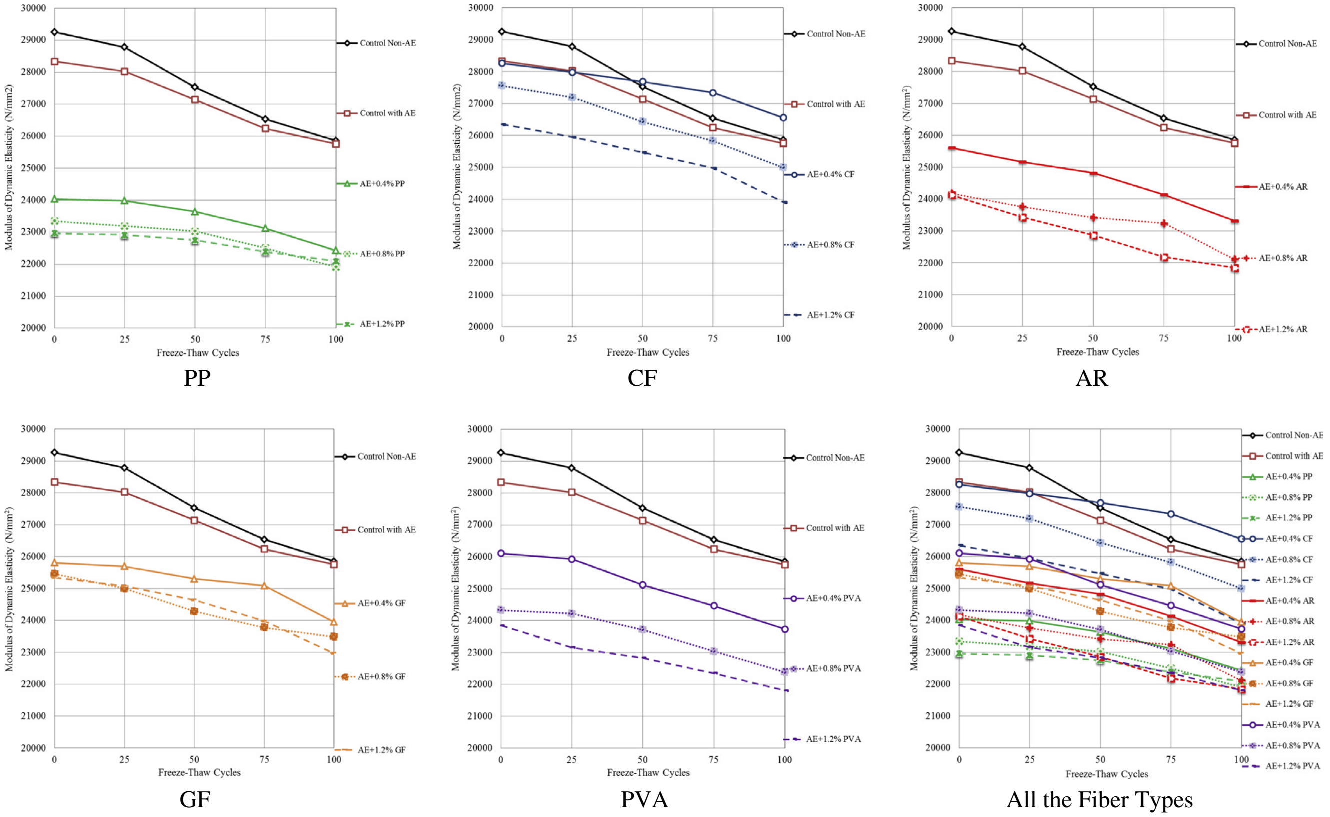
Table 11
Moduli of dynamic elasticity of the fiber reinforced mortars under freeze–thaw effects.

Freeze–thaw cycles →		0	25	50	75	100
Modulus of dynamic elasticity (N/mm^2)						
Control sample non-additive		29,252	28,335	27,528	26,535	25,857
Control sample with 0.65% AE		28,335	28,024	27,139	26,240	25,754
Sample with 0.65% AE + PP	24,032	23,986	23,637	23,118	22,432	7.82
	23,345	23,188	23,029	22,506	21,910	7.58
	22,968	22,912	22,753	22,394	22,097	7.58
Sample with 0.65% AE + CF	28,264	27,979	27,688	27,338	26,553	8.46
	27,562	27,190	26,430	25,824	24,999	9.18
	26,348	25,948	25,470	24,980	23,908	9.65
Sample with 0.65% AE + AR	25,612	25,167	24,823	24,138	23,315	8.25
	24,175	23,764	23,424	23,239	22,113	8.72
	24,128	23,428	22,862	22,182	21,845	7.84
Sample with 0.65% AE + GF	25,808	25,698	25,302	25,086	23,950	7.86
	25,456	25,000	24,285	23,775	23,487	8.44
	25,346	25,075	24,639	23,981	22,972	8.51
Sample with 0.65% AE + PVA	26,114	25,931	25,121	24,467	23,733	8.73
	24,326	24,220	23,711	23,040	22,384	8.68
	23,842	23,159	22,830	22,352	21,804	8.47

ratios, the compressive strength was higher than in the control samples after 100 freeze–thaw cycles. For other addition ratios, the strength results were also good. Addition of 0.8%-AR decreased the compressive strength only 7% after 100 freeze–thaw cycles. On the other hand, although PVA decreased compressive strength of mortars in the highest ratio, it increased freeze–thaw resistance significantly.

3.2.3. The effects of fiber addition on moduli of dynamic elasticity of cement mortars under repetitive freeze–thaw effect

Similar to flexural and compressive strengths, repetitive freeze–thaw cycles decreased the moduli of dynamic elasticity of the samples (Table 11, Fig. 8). After 100 freeze–thaw cycles, modulus of dynamic elasticity of the control samples without AE decreased about 12% and decreased about 9% for the control samples with AE.



PP CF AR

GF PVA All the Fiber Types

Fig. 8. Relationship between fiber addition ratio and modulus of dynamic elasticity of the mortars under freeze–thaw effect freeze–thaw effects.

However for the samples with fiber and AE, modulus of dynamic elasticity fell between 3.5% and 9.5%.

After 100 freeze–thaw cycles, modulus of dynamic elasticity decreased 4% with 1.2% PP addition, 6% with 0.4% CF addition and on average 9% with AR addition. These decreases were about 8% for GF and PVA.

4. Conclusions

The objective of the study was to investigate the mechanical behaviors of mortars with different types and percentages of fibers under repetitive freeze–thaw effects. The flexural and compressive strengths and deflections and moduli of dynamic elasticity of the samples prepared for this objective were determined. The conclusions obtained from this study can be summarized as:

i. Fiber reinforced mortar properties without considering freeze–thaw effects:
   - Flexural strengths were generally increased with fiber addition. However, the optimum addition ratio is variable for each type of fiber. CF and GF present the best performance with 1.2%, however, AR and PVA show it with 0.8% addition ratio. If true type (CF) and optimum percentage (1.2% by volume) is chosen, the fibers contribute to flexural strength of mortars at high level (22%).
   - For all fiber percentages used in this study, the compressive strengths fell. With 1.2% of fiber addition ratio, the compressive strengths of the mortars containing PP, CF, AR, GF and PVA decrease about 18%, 5%, 12%, 10% and 18%, respectively. It was observed that decreases in the compressive strength of mortars that had CF were left at reasonable levels. On the other hand, fibers decreased modulus of dynamic elasticity; however, ductility are increased.

ii. Fiber reinforced mortar properties under repetitive freeze–thaw effects:
   - All mechanical properties of the samples fell under repetitive freeze–thaw effects. However, fibrous samples presented better performance than non-fibrous ones.
   - It was observed that even though the flexural strengths of the fibrous samples were less than that of the control samples prior to freeze–thaw cycles, fiber reinforced mortars were higher than them after 100 freeze–thaw cycles. After 100 freeze–thaw cycles, flexural strength, compressive strength and modulus of dynamic elasticity of the control samples decreased by 23%, 14% and 9%, respectively. These decreases for fiber reinforced mortars were on average 12%, 10% and 8%, respectively. The best flexural strength was provided by 1.2%-CF addition.
   - Although the fibers decreased the compressive strength of mortars, the decreases were less than in the non-fibrous control sample after 100 freeze–thaw cycles. For modulus of dynamic elasticity, there were similar outcomes to that of compressive strengths. The highest dynamic modulus of elasticity was obtained with 1.2% PP addition.
   - Briefly summarized, the best addition ratios were 1.2% for CF, 0.4–0.8% for AR, 0.8% for GF, 0.4% for PVA and 0.4% for PP by volume for all properties and all conditions in this study.

References

[1] Balaguru PN, Shah SP. Fiber-reinforced cement composites. New York: McGraw-Hill Inc.; 1992.

[2] Çavdar A. A study on the effects of high temperature on mechanical properties of fiber reinforced cementitious composites. Compos B Eng 2012;43(5):2452–63.

[3] Çavdar A. The effects of high temperature on mechanical properties of cementitious composites reinforced with polymeric fibers. Compos B Eng 2013;45(1):78–88.

[4] Mehta PK, Monteiro PJM. Concrete: microstructure, properties, and materials, 3rd ed. New York; 2006.

[5] Kuder KG, Shah SP. Processing of high-performance fiber-reinforced cement-based composites. Constr Build Mater 2010;24:181–6.

[6] Shang HS, Song YP. Experimental study of strength and deformation of plain concrete under biaxial compression after freezing and thawing cycles. Cem Concr Res 2006;36:1857–64.

[7] Karahan A, Atiş CD. The durability properties of polypropylene fiber reinforced fly ash concrete. Mater Des 2011:1044–9.

[8] Ozbay E, Karahan O, Lachemi M, Hossain KMA, Atis CD. Dual effectiveness of freezing–thawing and sulfate attack on high-volume slag-incorporated ECC. Compos B Eng 2013;45(1):1384–90.

[9] Richardson AE, Coventry KA, Wilkinson S. Freeze/thaw durability of concrete with synthetic fibre additions. Cold Reg Sci Technol 2012;83–84:49–56.

[10] Yun HD. Effect of accelerated freeze–thaw cycling on mechanical properties of hybrid PVA and PE fiber-reinforced strain-hardening cement-based composites (SHCCs). Compos B Eng 2013;52:11–20.

[11] Zhang P, Li QF. Effect of polypropylene fiber on durability of concrete composite containing fly ash and silica fume. Compos B Eng 2013;45(1):1587–94.

[12] Duzgun OA, Gul R, Aydin AC. Effect of steel fibers on the mechanical properties of natural lightweight aggregate concrete. Mater Lett 2005;59(27):3357–63.

[13] Asokan P, Osmani M, Price ADF. Improvement of the mechanical properties of glass fibre reinforced plastic waste powder filled concrete. Constr Build Mater 2010;24:448–60.

[14] Sun Z, Xu Q. Microscopic, physical and mechanical analysis of polypropylene fiber reinforced concrete. Mater Sci Eng, A 2009;527:198–204.

[15] Felekoğlu B, Tosun K, Baradan B. Effects of fibre type and matrix structure on the mechanical performance of self-compacting micro-concrete composites. Cem Concr Res 2009;39:1023–32.

[16] Li VC, Wang S, Wu C. Tensile strain-hardening behavior of polyvinyl alcohol engineered cementitious composite (PVA-ECC). ACI Mater J 2001;98(6):483–92.

[17] Chung DDL. Cement reinforced with short carbon fibers: a multifunctional material. Composites Part B 2000;31:511–26.

[18] Garces P, Fraile J, Ortego EV, Amoros DC, Alcocel EG, Andion LG. Effect of carbon fibres on the mechanical properties and corrosion levels of reinforced portland cement mortars. Cem Concr Res 2005;35:324–31.

[19] Wang C, Li KZ, Li HJ, Jiao GS, Lua J, Hou DS. Effect of carbon fiber dispersion on the mechanical properties of carbon fiber-reinforced cement-based composites. Mater Sci Eng, A 2008;487:52–7.

[20] Bhargava AK. Engineering materials–polymers, ceramics, composites. Prentice Hall Limited; 2004.

[21] Sawyer L, Grubb D, Meyers G. Polymer microscopy. 3rd ed. Springer; 2008.

[22] National Research Council, Polymer science and engineering. Washington: National Academy Press; 1994.

[23] Pereira EB, Fischer G, Barros JAO. Effect of hybrid fiber reinforcement on the cracking process in fiber reinforced cementitious composites. Cement Concr Compos 2012;34(10):1114–23.

[24] Caggiano A, Cremona M, Faella C, Lima C, Martinelli E. Fracture behavior of concrete beams reinforced with mixed long/short steel fibers. Constr Build Mater 2012;37:832–40.

[25] EN 196, Test Methods for Cement, CEN TC 51.

[26] TS 699, Natural building stones – Methods of inspection and laboratory testing, Turkish Standard, Ankara; 2009.

[27] CEN/TS 12390-9, Testing hardened concrete – part 9: freeze–thaw resistance – scaling, technical specification, European Committee for Standardization; 2006.