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

Ahmet Çavdar *

Dept. of Civil Eng., Fac. of Engineering, Gumushane University, 29000 Gumushane, Turkey

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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.

* Tel.: +90 5072270572.
E-mail address: ahmcavdar@hotmail.com

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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