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Interfacial bonding of fine aggregate concrete to low modulus fibers

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ABSTRACT

The present work describes the feasibility of using cost effective and low modulus polymeric fibers including Nylon 6,6 and Acrylic fibers as reinforcement of fine aggregate cementitious composites. For this purpose, the pullout energy and interfacial bonding strength of fibers to the different matrix compositions where evaluated using a pullout test. Surface free energy of the fibers and different fine aggregate composites were also evaluated using the sessile drop method. Fiber to cement bonding strength, thermodynamic work of adhesion and surface free energy (wetting affinity) were assessed by changing maximum aggregate size, water to cement (binder) ratio, using fly ash as supplementary cementing materials (SCMs) and fiber type. Both chemical and mechanical interfacial interactions were measured and it was found that the Nylon 6,6 fiber showed highest pullout energy and flexural toughness due to more mechanical interlocking to the matrix.

1. Introduction

Cementitious materials are brittle in nature and many efforts have been made at enhancing the ductility of these materials to overcome this problem. Briefly, random and distributed fiber reinforcement is one of the most effective means of imparting ductility into concrete materials [1]. The major role of fibers in fiber reinforced concrete is the bridging action at the fractured zone. The bridging action of fibers is mainly attributed to its bonding properties to the cementitious matrix [2].

Fiber reinforced cementitious materials show two different behaviors after the first peak [3]. The first one shows the strain-softening behavior with the improved ductility, but the second one has the strain-hardening behavior associated with higher toughness, ductility and strength.

The strain hardening behavior can be achieved by using high modulus fibers such as polyvinyl alcohol (PVA). Engineered cementitious composites (ECCs) containing PVA fiber which were introduced by Li [4] are the most significant developments in the field of strain-hardening fiber reinforced cementitious composites with the tensile strain capacity of 2–5%.

Ductile cement-based composites on the basis of low fraction of polymeric fibers are unique due to their high tensile strain capacity [5]. They have moderate strength but high tensile failure strain. The higher ductility of cementitious composites depends on the fiber–matrix interactions. Attempts have been made to generate the extremely ductile cementitious composites using fiber/matrix interface tailoring [6–7]. The high and very low fiber/matrix interface strength leads to a tendency of fiber rupture and easy fiber pull-out, respectively, which limits the tensile strain capacity and energy absorption of the resulting composite. It has been found that low modulus polymeric fibers generally result in strain softening behavior due to their low tensile capacity [10,20–21,29].

Both the chemical interaction and the mechanical bonding have a contribution to the fiber/matrix interface strength. Moreover, for interface tailoring, the study of surface chemical properties of in contact materials and the adhesion phenomena between them needs to be understood.

Based on previous researches [8–10], Nylon 6,6 and Acrylic fibers due to their higher bonding to cementitious materials and good dispersion in the matrix are selected as the most promising low modulus fibers.

The objective of this study is to elucidate the influence of maximum aggregate size, water to cement ratio and cement replacement with SCMs on the surface chemical properties of the cement based matrix. For this purpose, surface chemical properties were determined by using contact angle measurements. The interfacial bonding strength between Nylon 6,6 and Acrylic fiber and the matrix were also evaluated. The interfacial properties of the fiber/matrix were evaluated by interfacial shear strength (IFSS) using the pull-out test. Moreover, the thermodynamic work of

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adhesion and loss function between the fibers and matrix was determined.

2. Backgrounds

The strength of adhesion to a solid surface can be measured using suitable force measurements, or can be estimated from a value of the thermodynamic work of adhesion (or specific adhesion) (W) [11], which is a reversible energy required to separate the two adhered materials [12]. The specific adhesion includes the contribution of all types of interfacial physical and chemical interactions and it is related to the intermolecular forces that operate at the interface between two materials [13]. The thermodynamic work of adhesion can be estimated from the surface properties, particularly the surface free energy of the adhered materials [14].

The schematic of wetting equilibrium for a sessile drop on the planar solid surface is shown in Fig. 1. According to Young's equation [15], the surface tension of materials at the three-phase contact point with the equilibrium contact angle θ conforms to the following relation:

$$\gamma_{SV} = \gamma_{SL} + \gamma_{LV}\cos\theta \tag{1}$$

when the $\gamma_S \geqslant \gamma_{SL} + \gamma_{LV}$, the liquid can be spread on the solid surface and spontaneous wetting occurs.

For solid–liquid systems the thermodynamic work of adhesion can be expressed as respective surface free energies (Eq. (3)) (Dupre's equation):

$$W = \gamma_S + \gamma_L - \gamma_{SL} = \gamma_L(1+\cos\theta) \tag{2}$$

where, γ is the surface free energy, and the subscripts L, S, and SL are for the liquid, solid and interfacial phases. The surface free energy of a liquid or a solid is expressed as the sum of components due to dispersion forces, superscript d, and polar (e.g. hydrogen bonding) forces, superscript p:

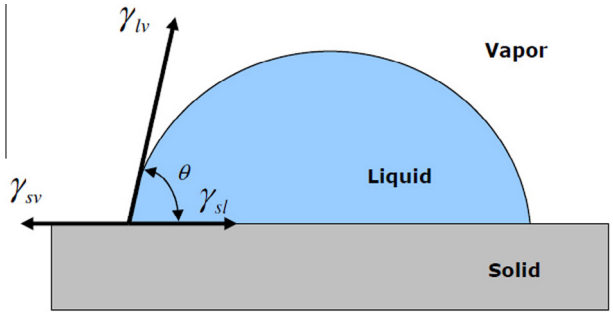

Fig. 1. Schematic description of liquid contact angle.

$$\gamma = \gamma^d + \gamma^p \tag{3}$$

The thermodynamic work of adhesion (W) can be determined by applying the Owens & Wendt equation [16]:

$$\frac{\gamma_L(\cos\theta+1)}{2\sqrt{\gamma_L^d}} = \frac{\sqrt{\gamma_S^p}\sqrt{\gamma_L^p}}{\sqrt{\gamma_L^d}} + \sqrt{\gamma_S^d} \tag{4}$$

where γ_L, γ_L^p and γ_L^d are known for the test liquids and θ is the contact angle of liquids with the solid surface. Surface free energy of a solid is obtained by plotting $\gamma_L.(\cos\theta+1)/2(\gamma_L^d)^{0.5}$ versus $(\gamma_L^p)^{0.5}/(\gamma_L^d)^{0.5}$ for two or more liquids of which their surface tension and components are known. The slope of the fitted line and the intercept give $(\gamma_S^p)^{0.5}$ and $(\gamma_S^d)^{0.5}$ respectively.

The interactions of polymers, adhesives and fibers to cement pastes (without aggregates) were previously investigated [17–20]. The present work describes the interaction between fibers and the cementitious matrix which contains fine aggregates.

3. Materials and methods

3.1. Materials

3.1.1. Fibers properties

The fibers used in this study were Nylon 6,6 (N66) and Acrylic (Ac) fibers which were manufactured by Zanjan's Tire Cord Co. and Iran Polyacryl Co., respectively. The cross-section of the fibers which were investigated by an optical microscopy is shown in Fig. 2.

The Acrylic fiber has a kidney-shaped cross sectional shape, which is produced by wet process spinning. The wet spun Acrylic fiber has shown better performance in bonding to the cementitious materials in comparison to the dry spun fiber [10,21]. To assess the accurate dimensions of the non-round fibers, the image processing software that allows segmenting the cross section of the fibers was employed. By using this software, geometrical dimensions of the fibers including area and perimeter were determined. The geometrical dimensions are given in Table 1.

The physical/mechanical properties of the fibers are given in Table 2.

3.1.2. Cement

The cement used in this study was Portland cement Type II, which was produced by Tehran Cement Co. according to ISIRI 389 standard.

3.1.3. Aggregate

The aggregate type was silica sand. Three different maximum aggregate sizes; 200, 300 and 600 μm were used in this work.

Table 1
Properties of the fiber's cross-section.

Fiber type	Area (mm^2)	Perimeter (mm)
Nylon 6,6	5.72×10^{-4}	8.48×10^{-2}
Acrylic	7.61×10^{-4}	9.77×10^{-2}

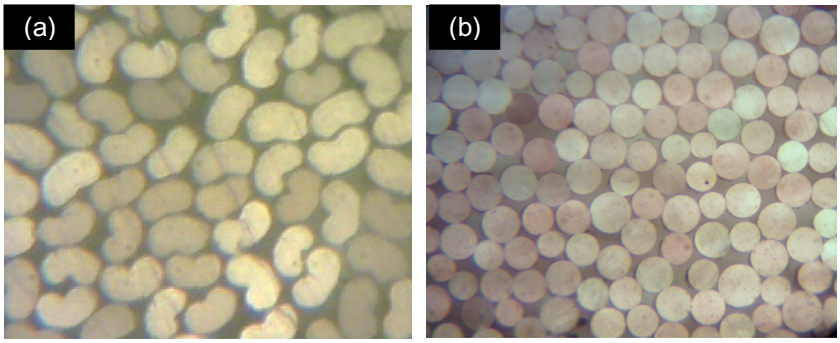

Fig. 2. Cross-sectional shape of fibers, (a) Acrylic, (b) Nylon 6,6.