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Staple wire-reinforced high-volume fly-ash cement paste composites

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HIGHLIGHTS

- Effect of fibers in high-volume fly-ash cement paste composites is evaluated.
- Short-length staple wire used as fiber.
- Relationship proposed for strength dependence on fiber spacing.
- Relationship proposed for compressive strength versus flexural strength.
- Sustainable construction is possible using these materials.

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ABSTRACT

Short wire staples, ranging from 0% to 3.5% by volume, were used to reinforce high-volume fly-ash cement paste. Previously proposed spacing equations for steel fibers and the effects of fiber volume on the physical and mechanical properties of the composites were analyzed. The volume of fiber influences physical and mechanical properties of the composites: high regression correlations ($R^2 > 0.8$) for fiber volume were found with unit mass, spacing, and strength ratios after 28 days of curing the pastes. The concept of fiber spacing could be used with accuracy to predict basic physical and mechanical properties of these materials.

1. Introduction

Large quantities of fly ash are produced from thermal power plants. In addition to environmental problems posed by fly ash, increasing demand for raw materials and limited availability of natural resources have given rise to efforts to investigate it for possible reuse [1,2]. The global demand for cement is increasing, having reached an estimated 3.6 billion tons in 2012 [3]. Furthermore, the global construction industry is under pressure to significantly reduce its CO_2 emissions. Reducing the use of Portland cement (more than 20 million tons per year in the United States alone) by recycling large amounts of industrial wastes, such as fly ash, would save natural resources and energy, and reduce CO_2 emissions, landfill volumes, and contamination of water streams [2,4].

Many studies have been conducted by the Canadian Centre for Mineral and Energy Technology (CANMET) since the 1980s [5] to investigate properties of high-volume fly-ash (HVFA) and fiber composites. Utilization of fly ash in civil engineering applications, such as manufacturing bricks, tiles, and highway and subway applications, nevertheless remains low; however, the use of HVFA cement paste composites and fundamental understanding of their performance are rapidly increasing in the field of civil engineering [5–7].

Fibers of steel, natural and synthetic materials, and glass are often used in engineered cementitious composites (ECCs) [8–17] that are commonly used in building construction [8,9]. ECCs are reported to exhibit superior resistance against environmental conditions. Compared with traditional concrete, in which the first crack develops into a failure plane, ECCs enhance the weak flexural strength of composites by acting as crack arresters, enabling many microcracks to be stabilized by bridging by the fibers [8–17]. Valeria and Nardinocchi [8] showed that drying shrinkage was reduced by using steel fibers in cement paste composites. Additionally, they reported that polymeric fibers enhanced the mechanical properties

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of ECCs. Natural fibers provide adequate strength and better bonding capacity to cement pastes by enhancing the flexural strength, toughness and crack resistance, and have superior technical feasibility owing to similar materials properties to those of composites manufactured with synthetic fibers [14]. Natural fibers are nonhazardous and more sustainable [13,16,17]. Previous research has shown that composites reinforced with short-fiber polymers show good impact resistance and have low mass [8,14,16,17]. Fiber reinforcement in cement paste composites, however, has not yet been fully evaluated and only a few research studies are available [9,16,17].

It is becoming popular to reinforce cement paste and concrete with small, randomly distributed fibers [18]. Fiber-reinforced concrete (FRC) has been applied since the mid-1960s for road and floor slabs, refractory materials, and concrete products [18–21]. The mechanical properties of FRC depend on the amount of fibers: product bending performance is related to the fiber volume fraction [21]. Danso et al. [22] studied various natural fibers by considering the effect of their aspect ratio. Güneyisi et al. [23] studied the effect of steel fibers and their aspect ratio, showing that these fibers enhanced the bond strength and ductility of concrete composites containing fly ash.

The history of the development of FRC, through the American Concrete Institute (ACI) Committee 544, began in about 1970 [19,20]. ACI has been active in the collection of data and dissemination of information related to this relatively new material, and has numerous publications relating to fiber reinforcement, its mechanics, techniques, and applications, both actual and potential [19,20]. Ongoing research seeks to optimize design procedures and refine equipment for more efficient and economic handling of these materials. Achieving a desired degree of fiber efficiency (i.e., bonding of the fiber with the cement paste) provides reliable pre- and post-cracking strength for performance-related applications [19,20,24].

The fiber reinforcement index (FRI) is used for stiffness determination of fiber composites and affects consolidation of the mixture [21,25]. FRI is defined as the product of the fiber volume (V_f) and its aspect ratio (l_f/d_f), i.e., ($V_f l_f/d_f$), where l_f and d_f denote the length and diameter of the fiber, respectively. Numerous researchers have attempted to correlate strength properties with relative spacing and FRI of fibers [18–21,26–29].

The efficiency of fiber performance in the cement matrix is highly complex and has been studied extensively [30–32]. Addition of fibers improves the tensile strength of HVFA cement paste and increases energy absorption capacity and toughness [23,32–35]. Parameters that relate to fiber geometry can be used in evaluating fiber effectiveness. Specifically, the number of fibers within a unit volume of concrete and their cross-sectional area across a given plane of an FRC volume appear to be the most relevant [36–38]. Fiber spacing is important when considering the effect of damage in a cementitious matrix. The possibility that a crack may expand and reach a critical size, thereby initiating an unstable failure, will depend in some way on the fiber spacing [21,39,40].

The spacing factor and concept of FRI are useful for characterizing and studying the behavior of FRC systems. Romualdi and Batson [18,27] considered the addition of small, randomly distributed fibers to increase the tensile strength of mortar. Their later research [28] showed that close spacing was achieved by adding small fibers and that fiber spacing was related to the strength ratio, defined as the ratio of first crack strength of a fiber-reinforced composite to failure strength of the unreinforced composite. All tests were conducted at a constant steel content of 2% by volume. Additionally, variations in spacing were demonstrated by varying the fiber diameter. Experimental results of other researchers [41,42], however, showed that the spacing did not accurately predict the first crack strength of fiber composites. Romualdi and Batson [27] first calculated the average spacing of randomly distributed fibers using the formula derived by Synder and Lankard [26] (shown as Eq. (1)); later, they employed a different spacing formula proposed by McKee [29] (Eq. (2)) as slightly modified by Soroushian [24,39,40]:

$$S = 13.8 d_f \sqrt{\frac{1.0}{\rho}}, \tag{1}$$

$$S = \left(A_f * \frac{l_f}{V_f} \right)^{1/3}, \tag{2}$$

where S is fiber spacing in mm, d_f and l_f are the diameter and length of the fiber, respectively, and ρ is the percentage reinforcement by volume, defined as the percentage of fiber volume in the entire volume of an FRC. V_f is the volume fraction of fiber (i.e., the ratio of the total volume of a fiber to the composite volume) and A_f is the cross-sectional area of a fiber ($\pi d_f^2/4$). Eq. (1) illustrates the sensitivity of results to the fiber length, effect of fiber reinforcement upon first crack strength, and spacing between the fibers. Eq. (2) shows that the volume fraction of fiber is not constant and has an effect on spacing.

Although the ability of fibers to improve the tensile and flexural performance of a cementitious material has been validated, the amount of fiber that can be practically incorporated into a mixture is limited by the occurrence of balling, which negatively affects its workability. This issue can be partially alleviated by using short-length fibers [25,31,43,44].

V_f, FRI, and fiber spacing are important properties: most studies on the use of fibers to enhance composite properties have focused on their content and orientation [11,14,45–53]. A few studies have incorporated short fibers into HVFA cement paste composites [5,23], but none have considered incorporating staple wires. Previous research on the concept of spacing showed that it does not accurately predict properties of the composite. The lack of research data on spacing, V_f, and FRI in HVFA cement paste composites provided the rationale for this study. The validities of previously proposed equations for spacing by Synder and Lankard [26], Soroushian and Lee [39], Romualdi and coworkers [24,28,39,40], and McKee [24,29,39,40] were checked with respect to V_f and spacings in HVFA cement paste composites. The staple wire was used in cement paste composites to manufacture ecological building materials for civil engineering construction works and to improve the compressive and flexural strength. When compared with steel or polypropylene fiber, staple fiber has relatively lower cost, ease of the dispersion in the cement paste and produce higher strength.

2. Experimental materials and methods

2.1. Materials

Portland composite having the strength of class 42.5 MPa cement was used. The Blaine fineness was 3930 cm^2/g and specific gravity was 2.96. High lime fly ash (CaO > 10%, Class C) from the Soma thermal power plant, Turkey, was used. The Blaine fineness was 2050 cm^2/g and its specific gravity was 2.08. The chemical compositions of the cement and fly ash are presented in Table 1.

Staple wire, comprised mainly of copper and nickel, was used as a fiber. Its mechanical properties, as obtained from the manufacturer (Ege Çelik Endüstrisi San. Tic. Aş., Turkey), are presented in Table 2. Its elastic modulus was 38,745 MPa; its diameter (d_f) and length (l_f) were measured as 0.58–0.60 mm and 24–26 mm, respectively. The aspect ratio of the staple wire was calculated from the measured length and diameter and was held constant in this study. The average density was 7.85 g/cm^3. A photograph of the staple fiber used in this work is shown in Fig. 1; its stress–strain behavior is shown in Fig. 2.