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Mechanical and durability properties of high-strength concrete containing steel and polypropylene fibers

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HIGHLIGHTS

- Steel and PP fibers were used individually and in combination at 1.0% fiber content.
- Introducing silica fume improved mechanical and durability properties of concrete.
- Steel fiber remarkably increased splitting tensile and flexural strengths of FRC.
- Addition of steel and PP fibers reduced the water absorption of concrete.
- Substitution of steel with PP fiber reduced mechanical properties of concrete.

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ABSTRACT

This study investigates the effect of the addition of steel and polypropylene fibers on the mechanical and some durability properties of high-strength concrete (HSC). Hooked-end steel fibers with a 60-mm length were used at four different fiber volume fractions of 0.25%, 0.50%, 0.75%, and 1.0%. Polypropylene fibers with a 12-mm length were used at the content of 0.15%, 0.30%, and 0.45%. Some mixtures were produced with the combination of steel and polypropylene fibers at a total fiber volume fraction of 1.0% by volume of concrete, in order to study the effect of fiber hybridization. All the fiber-reinforced concretes contained 10% silica fume as a cement replacement. The compressive strength, splitting tensile strength, flexural strength, electrical resistivity, and water absorption of the concrete mixes were examined. Results of the experimental study indicate that addition of silica fume improves both mechanical and durability properties of plain concrete. The results also indicate that incorporation of steel and polypropylene fibers improved the mechanical properties of HSC at each volume fraction considered in this study. Furthermore, it was observed that the addition of 1% steel fiber significantly enhanced the splitting tensile strength and flexural strength of concrete. Among different combinations of steel and polypropylene fibers investigated, the best performance was attained by a mixture that contained 0.85% steel and 0.15% polypropylene fiber. Finally, the results show that introducing fibers to concrete resulted in a decrease in water absorption and, depending on the type of fibers, significant or slight reduction in the electrical resistivity of concrete compared to those of the companion plain concrete.

1. Introduction

Concrete is the most widely used construction material, because of the several well-known advantages it offers, such as low cost, general availability, and wide applicability. However, concrete is a quasi-brittle material, and its brittleness increases with its strength. Relatively low tensile strength and poor resistance to crack opening and propagation are the main disadvantages of conventional concrete [1–4].

Development of modern civil engineering construction has generated an essential demand for new types of concretes which should possess improved qualities such as high-strength, toughness, and durability [5,6]. Examples of new types of concretes include high-strength concrete (HSC), high performance concrete (HPC) and high performance fiber-reinforced concrete (HPFRC). The properties of such concretes show a substantial improvement over those of conventional concrete [7,8]. However, HSC is more brittle than normal-strength concrete (NSC) and this limits the

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utilization of HSC. Additionally, it is well understood that the use of supplementary cementitious materials such as silica fume (SF), ground granulated blast-furnace slag (GGBS), and fly ash (FA) as part of binders is required for production of high strength concretes [9,10]. Generally, replacement of ordinary Portland cement (OPC) by pozzolans in concrete can decrease porosity of concrete, especially in the long-term [1]. On the other hand, mineral admixtures such as silica fume also increase the brittleness of concrete [11]. The cracks generally develop over time due to a number of reasons such as plastic shrinkage in pre-hardening state as well as drying shrinkage in hardened concrete. Subsequently these cracks weaken waterproofing capabilities of concrete, exposing the concrete microstructure to destructive substances such as moisture, chloride, sulfates, bromine etc. [12–15]. Therefore, improvement of the properties of hardened concrete is an important goal in concrete science [16].

Fibers are incorporated into cementitious concretes to overcome this weakness, producing materials with increased tensile strength, ductility, toughness and improved durability properties [17–21]. The efficiency of the fiber is dependent upon factors such as the properties of the fiber matrix, volume of fiber inclusion, fiber geometry, type of fiber, and orientation of fiber in the concrete mixture [22,23]. There is a wide range of fibers available to improve toughness and different properties of hardened concrete. The fibers are mainly made of steel, carbon or polymer [24–26]. Among the polymer fibers, polypropylene (PP) has attracted the most attention among researchers because of its low cost, outstanding toughness and enhanced shrinkage cracking resistance in concrete reinforced with this type of fiber [27–29]. However, concrete reinforcement with a single type of fiber improves the properties of concrete in a limited range. On the contrary, hybrid fiber-reinforced concretes, which are reinforced with two or more different types of carefully selected fibers to provide superior properties. Since cracks occur at different stages and sizes in concrete, the use of various fibers with different lengths is a good way to address this problem. In a well-designed composite system, there is a beneficial interaction between the fibers, which in turn results in a better performance of the hybrid system than that of the mono fiber composite [30–34]. The main purpose of the combination of different type of fibers is to control cracks at different zones of the cementitious material, at different size levels and during different loading stages [35,36].

In this study, a total of 12 different mixtures were manufactured to investigate the effect of steel fiber, polypropylene fiber, and hybridization of two fibers. Among these mixtures, three hybrid fiber-reinforced concretes were produced to study the effect of fiber hybridization at a total fiber content of 1.0%. The mechanical properties of concrete such as: compressive strength, splitting tensile strength, and flexural strength were evaluated to establish the optimum percentage of steel and polypropylene fibers. The present study was aimed at investigating the behavior of fiber-reinforced concretes with low fiber volume fractions, as this material is widely used in various applications, but the research on the topic has been limited. Furthermore, research on durability properties of fiber-reinforced concrete, such as electrical resistivity and water absorption, has been very limited and the results of the existing studies have been contradictory [37–39]. The study reported in this paper was aimed at making a significant contribution toward the understanding of these important properties of fiber-reinforced concrete.

2. Test program and procedures

Concrete mixes with water–cement ratio of 0.3 were produced. Silica fume as a cement replacement was added by 10% of weight to fiber-reinforced concretes. The freshly concrete was cast in 100-mm cubic specimens in order to obtain compressive strength, electrical resistivity and water absorption. Splitting tensile strength tests were done on cylindrical specimens with a 100 diameter and 200 mm height. Flexural tests were performed on prismatic beams with dimensions of $80 \times 100 \times 400$ mm. The experiments were carried out at 7, 28, and 91 days of curing age, and in all tests three specimens were tested for each curing age.

2.1. Materials and mixing procedure

Ordinary Portland cement (ASTM Type I) produced by the Hekmatan factory was used in the present study. Silica fume that was used in the present study was a commercially available by-product of the ferrosilicon factory in Semnan. The chemical and physical properties of the cement and silica fume are given in Table 1. Coarse aggregate with a maximum size of 19 mm and fine aggregate with a 3.4 fineness modulus were used. The volume fraction of the coarse aggregate and sand was equal to 50%. The specific gravity and water absorption of the coarse and fine aggregates were 2.69 and 0.56% and 2.61 and 1.92%, respectively. The grading curves of the aggregates are shown in Fig. 1, and the passing percentage is presented in Table 2. A Carboxylic 110 M (BASF) was used as a superplasticizer to adjust the workability of the concrete mixtures. Hooked-end steel fibers with a 60-mm length and an aspect ratio of 80, and polypropylene fiber with a 12-mm length were employed in this study. The geometry and the properties of fibers are provided in Fig. 2 and Table 3, respectively.

Concrete mix proportions are provided in Table 4. In the table, the content of superplasticizer is given as a percentage of the total weight of the cementitious material. During the preparation of concrete mixes, slump tests were conducted in accordance with the ASTM C143 [40] to determine the workability of fresh concrete.

2.2. Specimen molding and testing methods

The specimens were cast in steel molds and were compacted on a vibration table. They were demolded after approximately 24 h and were then exposed to lime-saturated water at 23 °C and 100% relative humidity until their testing ages. Compression tests were carried out on 100-mm cubic specimens using a 3000-KN universal compression machine. Fig. 3 shows the setup used for the flexural tests. The specific electrical resistivity was measured with the AC-Impedance spectroscopy, with a 1.0 kHz frequency and a 1.0 MΩ final capacity. The water absorption tests were

Table 1
Chemical composition and physical properties of cementitious materials.

Item	Cementitious materials (%)	
	Cement	Silica fume
SiO_2	21.2	93.0
Al_2O_3	5.4	1.7
Fe_2O_3	3.4	1.2
MgO	1.4	1.0
Na_2O	–	0.6
K_2O	–	1.1
CaO	63.9	0.3
	Compounds	
C_3S	51.5	–
C_2S	22.0	–
C_3A	6.4	–
C_4AF	10.5	–
	Physical properties	
Specific gravity (kg/m^3)	3150	2210
Specific surface (m^2/kg)	300	14,000