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Flexural behavior and durability properties of high performance hybrid-fiber-reinforced concrete

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HIGHLIGHTS

- New hybrid FRC with the inclusion of DHE steel fibers were developed.
- Simultaneous addition of SF and GGBS in concrete led to a very high durable HPC.
- Introducing 1.2% DHE steel fibers significantly improved the flexural performance of FRC.
- Substitution of steel fibers with PVA fibers reduced the flexural performance of hybrid FRC.
- The addition of steel fibers adversely affected the chloride diffusivity of FRC.

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ABSTRACT

The aim of the present study is to investigate the flexural behavior and durability properties of high performance hybrid-fiber-reinforced concrete. In the fiber-reinforced concrete (FRC) mixes, silica fume (SF) and ground granulated blast-furnace slag (GGBS) were used as mineral admixtures at the proportions of 10% and 30% of the cement by weight, respectively. Double hooked-end (DHE) steel fibers, single hooked-end (HE) steel fibers, and polyvinyl alcohol (PVA) fibers were mixed in different proportions in the concrete to develop hybrid FRC. The total combined volume fractions of the fibers were 0%, 0.6%, and 1.2%. Various tests to obtain compressive strengths, flexural behavior, rapid chloride migration coefficients, and electrical resistivity were carried out. The results indicate that mineral admixtures and particularly silica fume have significant influence on durability properties of concrete. A very high durable concrete can be achieved by simultaneous addition of SF and GGBS in concrete. The results also show that the incorporation of fibers notably improved the mechanical strengths of the concrete. The post-cracking flexural resistance and toughness of the FRC can be effectively increased through the addition of 1.2% DHE steel fibers. It was observed that the substitution of DHE steel fibers with HE steel fibers or PVA fibers led to a reduction in flexural performance of hybrid FRC. It was also observed that the chloride diffusivity of FRC was higher, while the electrical resistivity of FRC was lower than those of similar mixes but without fibers.

1. Introduction

Concrete, with a yearly consumption of more than 25 billion tons [1], is the most used construction material in the world. Nowadays the demand for high performance concrete (HPC) has increased widely throughout the world [2]. As a matter of fact, the addition of a well-defined type of cement, super-plasticizer and mineral admixtures are essential to obtain HPC with desired workability, mechanical, and durability properties [3,4]. Normally, a large amount of cement is required to produce HPC matrix [5,6]. However, some waste by-products materials include the silica fume (SF), fly ash (FA), and ground granulated blast-furnace slag (GGBS) can be used to reduce the amount of cement required and consequently produce more environmentally-sustainable concrete [7–9]. In general, it is well understood that the substitution of ordinary Portland cement (OPC) with mineral admixtures in concrete reduces the porosity and also converts the pores to smaller sizes compared to conventional concrete. According to

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Hassan et al. [10], mineral admixtures can improve the interface of cement matrix with the aggregate and substantially reduce the porosity of the cement matrix. Also, the incorporation of mineral admixtures such as SF and FA can change the mineralogy of the cement hydrates and subsequently results in a decrease in the motion of chloride ions [11–13].

The corrosion of steel reinforcements in concrete is an important issue that could lead to serious deterioration of concrete structures [14,15]. Mechanical loading as well as drying shrinkage can cause conventional concrete to crack with subsequent reduction in the overall strength and stiffness of the concrete structure [16]. Once a crack has formed, water and destructive agents like chlorides and sulphates can penetrate quickly into the concrete, and they subsequently accelerate the corrosion process and seriously degrade the serviceability of the structures [17,18]. One possible solution for controlling crack extension is through reinforcement of the concrete with fibers [19,20]. Using fibers in concrete is recognized as a promising way to make the concrete more homogeneous and produce a material with higher tensile strength, flexural strength, ductility, and energy absorption by controlling crack propagations [21,22].

Several studies have been conducted on HPC and fiber-reinforced concretes (FRC) to evaluate their properties. Song and Hwang [23] reported that an increase in the steel fiber volume fraction up to 2% led to an increase up to 98% in the splitting tensile strength of FRC compared to that of the control concrete. According to the research results of Iqbal et al. [24], an increase in the volume fraction of steel fibers in high strength lightweight self-compacting concrete resulted in a reduction in the compressive strength, while improved the splitting tensile strength, flexural strength, and flexural toughness of the concrete. Yousefieh et al. [25] investigated the effect of fibers on drying shrinkage in restrained concrete. It has been shown that the elastic modulus of fibers had a significant impact on the drying shrinkage of concrete. The inclusion of fibers not only reduced the drying shrinkage cracking, but also increased the initial cracking time of FRC with respect to plain concrete. Zhang and Li [26] studied the effect of polypropylene (PP) fibers on durability of concrete composite containing fly ash and silica fume. They observed that the addition of PP fibers significantly improved the durability properties of concrete. An increase in the content of PP fibers up to 0.12% led to a gradual reduction in water permeability, carbonation depth and drying shrinkage strain of concrete.

Obviously, the inclusion of a given fiber type can be effective only in a limited dimension of crack size, depending on the fiber type, aspect ratio and modulus of elasticity [27]. Hence, hybridization of two or more precisely selected fibers with different sizes and types can develop concrete with more attractive engineering properties [28–30]. Mehta and Monteiro [31] classified FRC according to their fiber volume fractions. Composites containing less than 1%, between 1% and 2%, and more than 2% fiber volume fractions known as low, moderate, and high fiber content concretes, respectively. Researchers have mainly focused on the progress of hybrid FRC with fiber volume fraction more than 2% to produce high-ductility composites. Therefore, there are very limited experimental data about the hybridization of fibers with a volume fraction less than 1.5%, although it has many applications in the area of building structures and infrastructure. In a recent study, Tabatabaeian et al. [32] assessed the effect of hybrid fibers on rheological, mechanical and durability properties of high-strength self-consolidating concrete (HSSCC). They pointed out that the addition of fibers adversely affected the rheology of HSSCC. Introducing of steel fibers improved mechanical properties of concrete, particularly its splitting tensile strength, while replacing a portion of steel fibers with polypropylene fibers led to a reduction in the strengths of HSSCC. Blunt et al. [15] conducted some studies on corrosion resistance of hybrid FRC. It has been shown that the hybridization of fibers was an effective way to delay the corrosion initiation and to reduce the corrosion rate by increasing resistance to cracking. According to Barnat-Hunek and Smarzewski [33], hydrophobisation can protect the concrete surface of hybrid FRC from corrosion caused by moisture. They observed that using micro-molecular alkyl-alkoxy-silanes led to the best hydrophobising effect on the surface of hybrid FRC.

The objective of the current study is to investigate the flexural behavior and durability properties of high performance hybrid FRC with combinations of metallic and non-metallic fibers at different fiber volume fractions. The effectiveness of double hooked-end steel fibers in concrete was investigated for the first time in this experimental program. Furthermore, a very limited number of studies have been conducted on the durability properties, such as rapid chloride migration test and electrical resistivity of FRC [34–36]. Hybrid FRC was manufactured at low fiber volume fraction by a combination of double hooked-end (DHE) steel fibers with hooked-end (HE) steel fibers or substitution of steel fibers with polyvinyl alcohol (PVA) fibers. The compressive strength, flexural stress-CMOD curves, flexural toughness, rapid chloride migration, and electrical resistivity of concrete were determined at different curing ages of 7, 28, and 91 days. The findings of this research have the potential to significantly contribute toward expanding the use of high performance hybrid FRC to different structural applications.

2. Experimental program

2.1. Materials and mixing procedure

The binder materials employed in this study were ordinary Portland cement (ASTM Type 1) from Lafarge, silica fume from Elkem, and ground granulated blast-furnace slag from Engro. Their chemical composition and physical characteristics are listed in Table 1. The fine aggregates with a 3.2 fineness modulus, and coarse aggregates obtained locally (Singapore) with a maximum size of 19 mm were used at the volume fractions of 45% and 55%, respectively. To adjust the workability of the concrete mixes, a Master Glenium Sky 8808 (B.A.S.F) was added. Double hooked-end and hooked-end steel fibers provided by Bekaert were employed in this study. The polyvinyl alcohol fibers were provided by Kuraray and were used in some mixes. The geometry and the properties of fibers are provided in Table 2.

The water-binder ratio was maintained at 0.25 for all concrete mixes to achieve a compressive strength of greater than 100 MPa. Lim et al. [37] studied the effect of cement replacement with SF and GGBS at different ratios and reported that the highest

Table 1
Chemical composition and physical properties of cementitious materials.

Item	Cementitious materials (%)		
	OPC	Silica fume	GGBS
SiO_2	21.5	93.0	36.0
Al_2O_3	5.5	2.0	9.0
Fe_2O_3	4.5	1.0	1.0
MgO	2.0	1.0	8.0
CaO	63.0	1.0	44.0
C_3S	51.5	–	–
C_2S	22.0	–	–
C_3A	6.4	–	–
C_4AF	10.5	–	–
Specific gravity (kg/m^3)	3150	2200	2720
Specific surface (m^2/kg)	360	–	461

Note: OPC = Ordinary Portland Cement; GGBS = Ground Granulated Blast-furnace Slag.