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Experimental study on the mechanical properties and microstructure of chopped basalt fibre reinforced concrete

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ABSTRACT

With high ductility and sufficient durability, fibre reinforced concrete (FRC) is widely used. In this study, the effects of the volume fraction and length of basalt fibre (BF) on the mechanical properties of FRC were analyzed. Coupling with the scanning electron microscope (SEM) and mercury intrusion porosimeter (MIP), the microstructure of BF concrete was studied also. The results show that adding BF significantly improves the tensile strength, flexural strength and toughness index, whereas the compressive strength shows no obvious increase. Furthermore, the length of BF presents an influence on the mechanical properties. Compared with the plain concrete, the compressive, splitting tensile and flexural strength of concrete reinforced with 12 mm BF increase by −0.18–4.68%, 14.08–24.34% and 6.30–9.58% respectively. As the BF length increasing to 22 mm, corresponding strengths increase by 0.55–5.72%, 14.96–25.51% and 7.35–10.37%, separately. A good bond between the BF and the matrix interface is observed in the early age. However, this bond shows degradation to a certain extent at 28 days. Moreover, the MIP results indicate that the concrete containing BF presents higher porosity.

1. Introduction

Concrete is a composite material with a low tensile strength and a low tensile strain limit [1–3]. In general, the addition of fibre to the concrete mix can significantly improve the engineering properties of the concrete such as the tensile, flexural, impact, fatigue and abrasion strength, deformation capability, toughness and load bearing capacity after cracking [4,5]. Due to high corrosion resistance, high ductility and sufficient durability, FRC is widely used especially in the military and marine fields, for instance, in fortified structures, blast resistant structures, offshore platforms, the exploitation of undersea oil engineering, etc. [6].

Various types of fibres can be used in cement and concrete composite, such as steel or organic fibres. Among all the used fibres currently, steel fibre has high elastic modulus and stiffness and thus the addition of steel fibre is effective for improving the compressive strength and toughness of concrete. But steel fibre rusts easily. Adding steel fibre to the concrete will increase the structure weight of the concrete and will cause a balling effect in mixing, and thus the workability will be lowered [7]. Glass fibre has high sensitivity to alkaline conditions. The chemically inert and stiffer of carbon fibre has a disadvantage of high cost and anisotropy. Synthetic fibres, mainly polymeric fibre, etc., usually have low elastic modulus, low melting point, and poor interfacial bonding with inorganic matrices. New materials offer the promise of innovative applications in concrete composite. Basalt fibre (BF), is a new kind of inorganic fibre extruded from melted basalt rock and is currently available commercially. The manufacturing process of this kind of fibre is similar to that of glass fibre, but with less energy consumed and no additives, which makes it cheaper than glass or carbon fibres [8–10]. Other advantages such as high modulus, heat resistance, good resistance to chemical attack, excellent interfacial shear strength and currently commercial availability, enable BF a good alternative to glass, carbon or aramidic fibre as a reinforcing material in concrete composite [11].

The study on the chemical durability of basalt fibre was conducted by Ramachandran et al. as early as 1981. Their study demonstrated the potential of BF being used in reinforced cement [12]. A lot of researches have been performed on continuous basalt fibre reinforced polymer (BFRP) as a strengthening material for concrete structures [13–16]. But there are merely limited researches on the effect of short BF on the properties of concrete. Dias and Thaumaturgo [17] investigated the relation between the mixing amount of fibre and the fracture toughness of geopolymeric cement concretes reinforced with BF. The result showed that geopolymeric cement concrete beams reinforced with BF presented higher ultimate load and larger displacement before failure, and was also less sensitive

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to the cracks. Zielinski and Olszewski [18] tested the physical and mechanical properties of cement mortar reinforced with BF at 28 days and obtained the optimum mixing amount of BF. Zhao et al. [19] investigated the impacting behavior and damage evolution of basalt FRC. The result showed that the addition of BF resulted in the obvious improvement of the impact toughness of concrete. Li and Xu [20] discussed the impact behavior of BF reinforced geopolymeric concrete subjected to various high strain rates. The strength and deformation of BF reinforced geopolymeric concrete were further analyzed, and a nonlinear viscoelastic constitutive model was proposed. From the reviews above, it can be seen that there is not enough study on the influence of basic parameters, such as volume content and fibre length, on the properties of basalt FRC. And not much work has been conducted on the analysis of the mechanical properties and microstructure of basalt FRC. To facilitate its use in reinforced concrete, the community requires a better knowledge of the properties of basalt fibre. And the mechanical behavior analysis is the key subject for the structure engineering design.

The main objective of this investigation is to study the effect of the fundamental parameters, namely the volume fraction and the length of BF, on the mechanical behavior of concrete, compared with polypropylene (PP) FRC. The fundamental properties of basalt FRC such as slump, flexural strength, compressive strength, splitting tensile strength and toughness index were tested and analyzed in this study. Through scanning electron microscope (SEM) and mercury intrusion porosimeter (MIP) measurement, the microstructure of BF cement paste such as bonding performance and pore structure were studied in detail.

2. Experimental programs

2.1. Materials

Type I Portland cement provided by Cement Australia Pty Limited was used in this study. Characteristic properties of cement are given in Table 1. The fine grade fly ash, provided by Blue Circle Company in Australia was used. Physical and chemical properties of fly ash are given in Table 2. The coarse aggregate used is calcareous crushed stone with 5 mm of the maximum size. The fine aggregate is natural river sand with 0–3 mm in diameter and a fineness modulus of 2.64. The details of mix proportions are shown in Table 3. Three types of fibre were used, including PP fibre and BF with 12 mm (BF I) and 22 mm (BF II) in length. The diameter of BF is about 20 μm. The chopped BF and PP fibre were provided by Ejin basalt fibre Limited Company in Shanghai and Hansen Steel Fibre Limited Company in Wuhan respectively. The mixing content of the BF was designed as 0%, 0.05%, 0.1%, 0.3% and 0.5% of the total volume of the mix, whereas the PP fibre volume fraction was 0%, 0.05%, 0.1% and 0.3% respectively. Physical and mechanical properties of the fibres are summarized in Table 4.

Table 1
Characteristics of cement.

Chemical properties		%
CaO		63.39
SiO_2		19.96
Al_2O_3		5.17
Fe_2O_3		3.41
MgO		1.61
SO_3		2.13
K_2O		0.80
Na_2O		0.13
Loss on ignition		1.12
Physical properties		
Specific gravity		3.10
Specific surface (cm^2/g)		4120
Initial setting time (min)		90
Final setting time (min)		340
Mechanical properties		
Compressive strength (MPa)	3 days	31
	7 days	43
	28 days	56

Table 2
Physical and chemical properties of fly ash.

Chemical properties	%
Al_2O_3	24.10
CaO	1.59
Fe_2O_3	2.87
K_2O	1.44
MgO	0.42
MnO	0.06
Na_2O	0.49
P_2O_5	0.19
SiO_2	65.90
TiO_2	0.91
Loss on ignition	1.53
Physical properties	
Fineness (%)	87
Specific gravity	2.10

2.2. Mixing and curing

The mixing process started with the dry mixing of the coarse and fine aggregates for 1 min. Then, the cement was added and followed by the dry mixing for another 1 min. Further, fibres were added into the dry mixture for another 1 min. Finally, water was added slowly. The fresh concrete was mixed for 3 min to ensure even dispersion of fibres in the concrete. The fresh concrete was cast in 75 × 75 × 305 mm prismatic molds for flexural strength test, in Ø100 × 200 mm cylinder molds for compressive strength test and in Ø150 × 300 mm cylinder molds for splitting tensile strength test separately. In this study, every test result consists of the average of three replicate tests. After casting, specimens were cured at 20 °C in molds covered by a polyethylene film to prevent moisture loss. Then, the specimens were de-molded after 24 h and were moved to saturated lime water at 20 °C until the testing.

2.3. Testing methods

The compressive strength was tested according to Australian standard, AS 1012.9-1999 at 7, 28 and 90 days, respectively [21]. The splitting tension test was carried out at 28 days according to Australian Standard, AS 1012.10-2000 [22]. Flexural strength was carried out according to the Australian Standard, AS1012.11-1985 [23]. The flexural toughness of FRC was estimated based on the ASTM: C 1609. Flexural strength at 7, 28 and 90 days was respectively tested through the third-point bending experiments conducted on the universal testing machine (Instron Model 8033). The span of flexural experiment was 225 mm. The load was applied by displacement control with a rate of 0.2 mm/min

Table 3
Concrete mixture proportions used in the study.

Cement (kg/m^3)	Fly ash (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3) <5 mm	Water (kg/m^3)
448.84	126.14	624.35	1024.04	269.68