Construction and Building Materials 157 (2017) 930–942

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental investigation on mechanical properties of Hybrid Fibre Reinforced Concrete

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HIGHLIGHTS

- A new HFRC mixed with steel, basalt and polypropylene fibres is produced.
- The mechanical properties of the HFRC were investigated thoroughly.
- The correlation between direct shear and splitting tensile of HFRC is suggested.

ARTICLE INFO

Article history:
Received 8 April 2017
Received in revised form 11 August 2017
Accepted 18 September 2017

Keywords:
Hybrid fibre
Shear behaviour
Mechanical properties
Macro fibre
Micro fibre
Concrete

ABSTRACT

In order to improve the work behaviour of Plain Concrete (PC) of the shear keys in the immersed tunnel, a series of test programs consisting of direct shear, four points flexure, uniaxial tensile, uniaxial compression and splitting tensile tests were carried out to find the optimized mixture proportion of the fibres in Hybrid Fibre Reinforced Concretes (HFRC). The optimized unit weight of the hybrid fibres was obtained through the parametric studies on the improvements of different fibre contents on the mechanical properties of the HFRC, especially the shear strength and toughness. Additionally, the influences of incorporating hybrid fibres on flexure, direct shear toughness and residual load were also studied. The direct shear strength, shear toughness and residual shear load significantly increased due to the addition of steel fibres and basalt fibres. Through extensive experimental studies, the comparisons of the mechanical properties of the HFRC with different fibre content revealed that group C2 containing 180 kg/m^3 steel fibres and 4.5 kg/m^3 basalt fibres performed the best in terms of shear strength and toughness. The contributions of different types of fibres to the mechanical properties of HFRC were also investigated. The observations from the tests offer a practical guidance to concrete composites designers on the shear strength and shear deformation ability of different structures, especially for use in constructing the shear keys of an immersed tunnel.

1. Introduction

Due to the rapid development in Fibre Reinforced Concrete (FRC) and its extensive applications, FRC is becoming increasingly popular in civil engineering construction. FRC has higher strength, deformation ability and energy dissipation ability than Plain Concrete (PC), it can improve the hysteretic behaviour of columns [1] and decrease the surface cracks in road pavement which consequently improves its service life. FRC can also be used to retrofit the reinforced concrete members after an earthquake or long service life and mitigate the spread of cracks in concrete structures [2]. More recently, FRC has been proposed as the construction material for the shear keys in the joints of immersed tunnels. In an immersed tunnel, the shear keys are essential for withstanding seismic movements. In engineering construction, concrete with high compressive strength is needed for constructing shear keys. Because the ductility of the shear key is important to the seismic resistance and dynamic vibrations, it is also of interest to improve the ductility property of shear keys in an immersed tunnel.

Recently, FRC was used in the joints of an immersed tunnel connecting Hong Kong, Macro and mainland China to improve the mechanical properties of the shear keys. The specific immersed tunnel joint and the shear key are shown in Fig. 1.

Previous extensive studies focused on the enhancement of tensile strength and ductility of mono fibre reinforced concrete (MFRC). These studies mainly focused on steel fibres (SF) [3–5] or polypropylene (PF) and polyvinyl alcohol (PVA) fibres [6–10] with

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https://doi.org/10.1016/j.conbuildmat.2017.09.098
0950-0618/

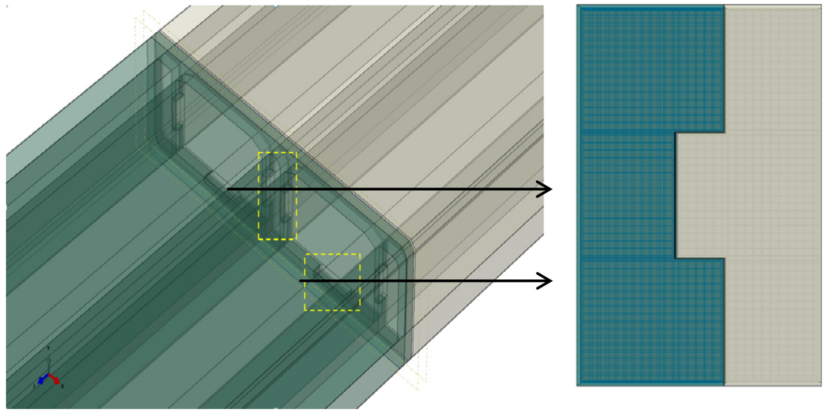

Fig. 1. Immersed tunnel joint and shear key.

different length, equivalent diameter, aspect ratio and volume of fraction. The advantages of MFRC over PC include improved axial and splitting tensile strengths, and ductile tensile behaviour. SF, PP or PVA fibres are normally used to improve the mechanical properties of MFRC [11]. Previous studies have shown that MFRC with low modulus fibres, such as PP or PVA fibres, usually exhibited lower compressive strength, higher strain capacity and larger crack width properties. On the other hand, MFRC with high modulus fibres, e.g., SF, shows higher ultimate strength and lower workability. Thus, it is of interest to generate a synergistic response through combining the advantages of different types of fibres.

The fibres in HFRC can be classified by their modulus (high or low value type) or geometrical size (e.g., macro and micro fibre) [12]. Recently, HFRC [13,14] comprised of two or more different types of fibres has been studied. Compared with the MFRC, HFRC typically exhibits higher/greater compressive and tensile strengths and a stronger energy dissipation ability [15,16]. HFRC with an optimized volume fraction of different fibres can improve the ultimate strength, strain capacity and ultimate crack width [17]. Qian and Stroeven [18] mixed SF and PF in HFRC and noted that a stiffer and stronger SF compared with PF improved the ultimate strength of HFRC, while the more ductile PF compared with SF improved the strain capacity and toughness after post-peak. Park and Kim [19,20] used four types of steel macro fibres and two types of steel micro fibres to investigate the flexural and tensile behaviour of the HFRC. However, the addition of SF at a high volume fraction had some shortcomings, including an increased cost and poor workability. Sivakumaret et al. [21] blended one type of SF and three types of non-metallic fibres in concrete composites to determine the compressive and flexural behaviour of HFRC and found that the SF improved the compressive and flexural strength. Machine et al. [7] used two types of polypropylene fibres in HFRC to investigate the mechanical properties of the HFRC, but the contribution of PP fibres to the post-peak cracking behaviour was not observed to be significant. Yao et al. [22] used SF, PF and Carbon Fibre (CF) at a low fibre volume fraction (0.5%) to investigate the mechanical properties of the HFRC and found that the hybridization containing CF and SF had a better strength and flexure toughness compared with the mixture containing PF and SF. Banthia et al. [23] tested several types of fibres in normal concrete and found that hybridization of PP and CF offered high toughness in HFRC. Dawood et al. [24] tested three types of fibres including SF, palm fibres and Bar-chip fibres to determine the mechanical properties of the HFRC. These previous studies on HFRC mainly focused on compression, flexure and tensile tests. The tests on shear behaviour of HFRC are still limited. Additionally, most studies involving micro fibres in HFRC focused primarily on PP or PVA fibres. Few studies have investigated the properties of HFRC containing basalt fibre (BF). Therefore, in this paper, BF is adopted as a new micro fibre in HFRC and the shear behaviour of the HFRC is primarily investigated. SF is adopted as the macro fibre and PF is adopted as a secondary micro fibre to find the most appropriate type of micro fibre to mix simultaneously with the macro fibre.

In this paper, the mechanical properties of HFRC have been analysed in detail. The correlation between the compressive strength on cubes and compressive strength on prisms, and the correlation between direct shear strength and splitting tensile strength were studied. The specific objectives of this study are to investigate: (1) the influence of different types of fibres on the compression, tension, flexure and direct shear behaviours of HFRC; (2) the influence of different unit weights of fibres on the mechanical properties of HFRC; and (3) the correlations between different aspects of strength (i.e., compression, tension, flexure and shear). This study provides valuable information on the mechanical properties of HFRC and the use of short cut basalt fibres as a micro fibre in HFRC. Useful data on the influence of macro steel fibres blended with different types of micro fibres on the mechanical properties of HFRC are also provided.

2. Materials properties and mix proportions

2.1. Basic constituents of concrete

This study used grade 42.5 ordinary Portland cement in all the HFRC mixtures. Dry and clean natural river sand and crushed granite stone were used in the concrete as the fine and coarse aggregate, respectively. Because the workability of the HFRC is a concern, the cement was replaced by fly-ash and mineral powder at approximately 15% of the volume and 4.2 kg/m^3 of hyper plasticizer was used in all the concrete mixtures. The specific composites were, water:cement:sand:stone:fly ash:mineral powder:polycarboxylic = 139:290:683:1034:65:65:4.2 kg/m^3.

2.2. Fibres

This study used milling SF, BF, and PF in concrete cementitious composites as shown in Fig. 1. The main properties of milling steel fibre are given in Table 1. The BF and PF were used as the micro fibres in the mixtures. BF is formed from high-performance volcanic rocks and is a type of silicate. It has excellent physical properties and corrosion resistance, especially alkali resistance. Thus, BF is a good choice for the construction of shear keys of immersed tunnels undersea and it can effectively improve the mechanical