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Experimental study on bond behaviour between BFRP bar and engineered cementitious composite

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HIGHLIGHTS

- Effects of various parameters on bond performance between BFRP bar and ECC are presented.
- Change mechanisms of bond behaviours are discussed.
- PVA fibres in ECC matrix enhance the bond performances between BFRP bar and cementitious matrix.
- Some factors are recommended to provide sufficient bond between BFRP bar and ECC matrix.

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ABSTRACT

To understand the bond behaviour between the basalt fibre reinforced plastic (BFRP) bar and the engineered cementitious composite (ECC), pullout tests were performed in this paper to study the effects of the bar diameter, the embedded length, the cover thickness, and the properties of matrix materials on the bond performance. The test results indicate that the bond strength is generally controlled by the shear resistance of the BFRP bar surface layer for most of the specimens with pullout failure. For the specimens with a cover thickness of 5.5 mm, splitting failure occurred. The bond strength between the BFRP bar and cementitious matrix decreases with an increase in the bar diameter, and the specimen with a shorter embedment length achieves a higher bond strength. A linear equation can be used to describe the relationship between the average bond strength and the embedment length. The bond strength increases with the increase in cover thickness; however, this increase can be neglected when the ECC cover thickness exceeds 20 mm. The addition of PVA fibres decreases the damage and enhances the bond performances between the bar and the matrix.

1. Introduction

The performance of reinforced concrete (RC) structure in an aggressive environment is generally determined by the corrosion of steel rebar in concrete. To overcome this corrosion issue, fibre-reinforced polymer (FRP) bar has been considered as a promising alternative for the conventional steel rebar due to its high strength-to-weight ratio, excellent corrosion resistance, low cost, ease of handling, and good fatigue properties [1–3]. To evaluate the crack width and spacing and to understand the load transfer mechanism between FRP bar and concrete, various studies have been performed to evaluate the bond performance between carbon/glass FRP bar and concrete. It is concluded that the parameters such as the type of FRP bar, the bar surface, the bar diameter, the embedment length, the test setup and the concrete strength have a considerable effect on the bond behaviours [4–8].

As a new type of FRP material, basalt fibre reinforced plastic (BFRP) bar was recently produced using basalt fibres. In addition to the excellent corrosion resistance and mechanical performance, the basalt fibre is environmentally harmless and has a good range of thermal performance, superior electro-magnetic property, and good resistance to UV light and impact, which makes it better than the glass fibre and less expensive than the carbon fibre. Several studies have been performed on the mechanical properties of BFRP bar reinforced concrete elements, revealing a good integrity of these two materials. Lin and Zhang used the four-point bending beam test to study the flexural and bond–slip behaviour of FRP-reinforced concrete beams reinforced with CFRP, GFRP, and

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BFRP bars with different surface conditions. They found that the BFRP-reinforced concrete beams perform much better than CFRP- and GFRP-reinforced concrete beams due to the strong bond in the BFRP-reinforced concrete beam [9]. However, due to the much lower modulus of BFRP bars compared to steel bars, the deflections and the average crack widths of beams with BFRP reinforcement were significantly higher than those of the RC beam [10]. Mahroug et al. developed an experimental study on the mechanical behaviour of concrete slabs reinforced with BFRP bars, and they reached the same conclusion as the beam study [11]. Therefore, the cracks in concrete will result in a serviceability problem for the BFRP bar reinforced concrete structures. To address this serviceability problem, the addition of fibres in the cement matrix is believed to be an effective solution on the basis of the existing studies.

Engineered cementitious composite (ECC) is a new generation of high performance fibre reinforced concrete with the characteristics of high ductility [12–13]. Due to the bridging effect of structural fibres, ECC displays a characteristic of multiple stable micro-cracks, unlike the single unstable cracking of normal concrete under tension. In addition, ECC's high tensile ductility and self-controlled micro-crack width lead to its good durability under different mechanical and environmental conditions [14–16]. Some available studies have provided the advantages of applying ECC material into structures, which prevent the brittle fracture of element. Because BFRP bar and concrete are brittle materials and the crack width in BFRP bar concrete members is larger than that in RC structures, ECC can be a good choice to replace the concrete in the structural member. To develop a good performance of composite structure, the assessment of bond behaviour between BFRP bars and ECC matrix is a key aspect, but few relevant studies reported on this issue.

However, several studies have been performed to examine the effects of structural fibres on the bonding properties between G/CFRP bars and concrete, which provides insight into the change mechanism and regulations. Firas et al. conducted a pullout test to reveal the bond of CFRP bars in ultra-high performance fibre reinforced concrete (UHPFRC). Their results clearly indicated that the use of UHPFRC increased the CFRP bar/concrete interface shear strength, and the bond failure was caused by the inter-laminar rupture mechanism. Due to the high autogenous shrinkage of UHPFRC, the ultimate bond strength was mostly expected during early age (3 days) [17]. Kim et al. investigated the pullout behaviours of GFRP bars as well as steel bars in concretes reinforced with steel, PP and PVA fibres. Their results indicated that the structural fibres in the interface changed the bond behaviours before and after the maximum stress and resulted in significant improvement of the relative bond strength [18], which agreed with the test results reported by Won et al. [19] and Mazaheripour et al. [20]. However, Belabi and Wang found that the fibres in concrete had a moderate improvement in the ductility but no distinct effect on the bond strengths between C/GFRP bars and concrete [21].

To better understand the bond behaviour between the BFRP bar and ECC, pullout tests were performed in this study to reveal the bond change mechanism and regulations. The influences of varying parameters, such as the bar diameter, the embedded length, the cover thickness, and the properties of matrix materials, on the bond performance are discussed on the basis of the relationship between the average bond stress and slips.

2. Experimental programme

2.1. Materials

Three diameters of BFRP bars, namely 4 mm, 10 mm, and 16 mm, were considered in this study for the direct pullout test. These BFRP bars were manufactured by the pultrusion process and are composed of basalt fibre and thermosetting resin. As shown in Fig. 1, the outer layer of each BFRP bar was wrapped with a basalt fibre braid to protect the surface and enhance the bonding strength between the BFRP bar and the cementitious materials. The BFRP bars exhibit linear elastic behaviour up to brittle failure. The elastic modulus of BFRP bar is 50.6 GPa, and the tensile strength is 750 MPa.

To reveal the effect of the matrix performance on the bond behaviour, two types of cementitious materials, ECC and cement mortar (CEM), were designed in the study. The cement used for cementitious materials was a P.O.42.5R ordinary Portland cement that complies with China code GB8076-1997. A type of local fine sand with an average size of 150 μm was used as fine aggregate. The water–binder ratio was 0.3 for all materials. To produce a high toughness ECC material, a certain amount of fly ash (FA), silica fume (SF) and metakaolin (MK) was used in the cementitious binder, and a type of polyvinyl alcohol (PVA) fibre was used to reinforce the cementitious composites with a volume fraction of 2%. The properties of PVA fibre are presented in Table 1. In addition, an SP8-CR water reducer was used to optimise the workability of the ECC. The mixture proportions are presented in Table 2.

Uniaxial tensile tests were conducted on the specimens with dimensions of 400 mm × 100 mm × 15 mm to characterise the tensile behaviours of the ECC and cement mortar, as shown in Fig. 2. The tensile stress–strain curves of ECC specimens are shown in Fig. 3. A strain-hardening characteristic is displayed for the ECC material with a strain capacity of approximately 2.0%. The average tensile strength of ECC is 3.97 MPa, while it is 3.46 MPa for the cement mortar. The ECC exhibits better ductility than the cement mortar with a strain capacity of 0.024%. These ECC materials also exhibit saturated multiple cracking with a crack width at ultimate strain limited to below 175 μm and an average crack width below 115 μm. In addition, a number of cubic specimens with sizes of 150 mm × 150 mm × 150 mm were also casted and tested in compression. The compressive strengths of ECC and CEM are 45.8 and 49.3 MPa, respectively.

2.2. Specimens

The direct pullout test was used in this study to evaluate the bond behaviours between the BFRP bars and the cementitious matrix. The prismatic specimens were 100 mm × 15 mm × 150 mm,100 mm × 20 mm × 150 mm,100 mm ×30 mm × 150 mm,100 mm × 40 mm × 150 mm,100 mm × 50 mm × 150 mm,100 mm ×100 mm × 150 mm, and 150 mm × 150 mm × 150 mm in size, with a single BFRP bar embedded along the central axis, as shown in Fig. 4. The variables considered in this experiment were the bar diameter d (4 mm, 10 mm, and 16 mm), the embedded length l_a (2.5d, 5d, 10d and 15d), the cover thickness c (5.5 mm, 8 mm, 13 mm, 18 mm, 23 mm, 48 mm, 67 mm, 70 mm and 73 mm), and the properties of cementitious materials (ECC and CEM). As summarised in Table 3, three specimens of each type and a total of 51 specimens were prepared for the pullout tests.

The specimens were cast in prismatic moulds with a BFRP bar horizontally placed at the centre. As shown in Fig. 4, the debonded parts of the specimen were created using two soft plastic tubes to minimise the stress concentration near the

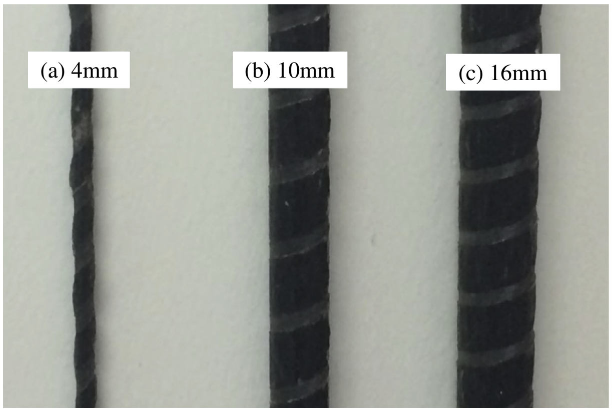

Fig. 1. Characteristics of BFRP bars.

Table 1
Properties of PVA fibre.

Length (mm)	Diameter (μm)	Nominal strength (MPa)	Elongation (%)	Elastic modulus (GPa)	Density (g/cm^3)
12	39	1620	7	42.8	1.3