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Experimental study of early-age bond behavior between high strength concrete and steel bars using a pull-out test

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HIGHLIGHTS

- Early-age bond behavior between steel bars and HSC was investigated.
- A model for early-age bond strength was proposed considering concrete age.
- A model for early-age slip corresponding to bond strength was proposed.
- A model for early-age bond behavior between steel bars and HSC was proposed.

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ABSTRACT

High strength concrete (HSC) is used extensively in practice. However, HSC is prone to cracking at early age, which can be the first step in a construction's deterioration and its malfunction. Reinforcement is one possible way to prevent the negative effect of early-age cracks in HSC structures. The early-age bond behavior is necessary to determine the cracking width of structures. Although the bond behavior between steel bars and normal strength concrete has been studied, study on early-age bond behavior between steel bars and HSC is still lacking. This paper presents an experimental investigation on the bond behavior between steel bars and HSC of different ages using a pull-out test. Test results showed that: (1) the early-age bond strength between steel bars and HSC increased with the increase of age; (2) the bond strength between steel bars and HSC increased with the increase of concrete strength and a model for the early-age bond strength between steel bars and HSC was proposed; (3) the slip corresponding to bond strength decreased with the increase of concrete compressive strength and a model for the early-age slip corresponding to bond strength was proposed; (4) a prediction model for early-age bond stress–slip relationship between steel bars and HSC was proposed based on BPE model, which showed good agreement with test results.

1. Introduction

High strength concrete (HSC) has been widely used in civil engineering because of its better rheological, mechanical and durability properties than conventional concrete [1–3]. Modern HSC offers high strength and low permeability by using superplasticizers and supplementary cementing materials, such as fly ash, silica fume, granulated blast furnace slag (GBFS), and natural pozzolan, which are industrial by-products and help in reducing the amount of cement required to make concrete less costly, more environmental friendly, and less energy intensive [4–6]. Moreover, the development of HSC meets the steadily increasing demands on building higher and faster [7,8]. However, the lower w/c ratio of HSC comes with high self-desiccation [9–11] and high temperature rise in the concrete [12,13], which induces marked autogenous shrinkage [14–16]. When suffered with restraint, it will lead to high cracking potential [17,18]. Limiting cracking width at early age is crucial for HSC structure as cracks in the surface give access to the interconnected network of pores, micro- and macro cracks, especially in an aggressive environment [7,8]. Reinforcement is an effective way to reduce cracking width [7,8,19,20]. In order to determine the cracking width of structure at early age, the bond behavior has to be known [17,21–23]. Although the effect of

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reinforcement on cracking resistance has been studied [7,8,19], research on early-age bond behavior of steel bars and HSC is still lacking. Thus, the early-age bond behavior between steel bars and HSC is necessary for better understanding the cracking resistance.

The early-age bond strength between steel bars and concrete can be influenced by concrete strength (concrete age) [21–25]. Tests on the bond strength of specimens at the age of 1, 3, 7, and 28 days are conducted [21]. It is found that the concrete age has a profound influence on bond strength and the effect is more noticeable during the first three days after casting. Pull-out tests of specimens at the concrete age from 1 to 28 days to quantify bond strength are studied [22] and it is reported that the bond strength of deformed bars is significantly affected by concrete age. Specimens at the age of 1, 3, 5, 7, 14, 21, and 28 days with the maximum axial compressive strength of 35.67 MPa are tested [23] and it is found that the bond strength increases with the increase of concrete age. Pull-out tests on specimens with cubic compressive strength up to 41.00 MPa at the age of 2, 3, 4, 5, 6, 7, 10, 14, and 28 days are conducted [24] and it is found that the bond strength increases with the increase of concrete age, especially during the first 7 days. However, it is found that the bond strength decreases with the increase of concrete age at early age, especially age of 7–14 days with a more minor effect than age of 14–28 days due to the increase in interfacial void content, as indicated by the increase in the contact electrical resistivity [25]. Although tests have been conducted on bond behavior between steel bars and normal strength concrete at early age, experimental studies on the early-age bond behavior between steel bars and HSC remain lacking. Thus, whether and how concrete age influences the early-age bond behavior between steel bars and HSC must be studied for better understanding its bond stress–slip relationship.

Slip corresponding to bond strength is also a significant parameter that determines the bond behavior of HSC structures. For deformed steel bars, a fixed value (1.0 mm) is recommended for slip corresponding to bond strength for unconfined normal strength concrete of C30 based on test results [26], which is in accordance with the result in [27]. 1.0 mm taken as the slip corresponding to bond strength for normal strength concrete and 0.6 mm for high strength concrete is proposed in [28], while 1.04 mm is proposed for average compressive concrete strength of 37.00 MPa at the age of 28 days in [29]. Bar diameter can also influence the slip corresponding to bond strength as 0.04*d* is taken as the slip corresponding to bond strength in [30]. Some researchers suggest that the slip corresponding to bond strength is depended on the clear distance between the lugs of steel bars [27,31–33]. However, a sophisticated model to predict the slip corresponding to bond strength of steel bars considering concrete strength is proposed based on results of pull-out test in [34]. So, whether and how concrete strength influences the slip corresponding to bond strength is still inconsistent. Thus, the slip corresponding to bond strength between steel bars and HSC, especially at early age, should be investigated for better understanding its bond stress–slip relationship.

A model for the bond stress–slip relationship is necessary to obtain the cracking pattern and cracking width. Moreover, the bond stress–slip behavior has an important influence on the behavior of reinforced elements in the cracked stage. Cracking widths and deflections are influenced by the distribution of bond stresses along the steel bars and by the slip between steel bars and the surrounding concrete [35]. Experimental and theoretical investigations on bond stress–slip models of mature plain concrete, normal strength concrete and fiber reinforced concrete have been conducted [27,31,33,35,36]. The bond stress–slip relationship proposed in [27] consists of an increasing first branch up to the bond strength. This branch is followed by a plateau during which the slip is increasing for constant bond strength, after which bond strength starts to decrease for increasing slip values. Finally, a constant residual bond strength is reached which is due to pure friction between the steel bar with the cracked concrete lugs and the surrounding concrete. However, experimental study on the early-age bond stress–slip relationship between steel bars and HSC remains lacking. Thus, the model for early-age bond stress–slip relationship between steel bars and HSC must be studied for better understanding the cracking resistance of HSC structures.

Although the relationship between steel bars and normal strength concrete has been studied, the early-age bond stress–slip relationship between steel bars and HSC considering the effect of concrete age is still lacking. Thus, the bond stress–slip relationship between steel bars and HSC of different ages must be investigated. Tests on the effect of concrete age and concrete strength on bond strength, the slip corresponding to bond strength and the prediction model for bond stress–slip relationship between steel bars and HSC of different ages were conducted in present study for better understanding the bond behavior of HSC structures.

2. Experimental investigation

2.1. Materials properties

The mixture proportion of concrete is shown in Table 1. The diameter of the bars used in the test was 16 mm. The cement used in the mix was ordinary Portland cement concrete of 42.5 (Cement II 42.5R) grades with a Blaine fineness of 375 m^2/kg in accordance with China National Standard GB 175-2009. The coarse aggregate used was crushed limestone with maximum particle sizes of 15 mm and the apparent density was 2660 kg/m^3. The fine aggregate used was natural river sand with a fineness modulus of 1.93 and the maximum size was 1.5 mm. The grade of GBFS was S95 and the specific surface area of GBFS was between 420 and 450 m^2/kg, which was in accordance with China National Standard GB 175-2009. A liquid polycarboxylate-based superplasticizer was utilized to adjust the workability of mixtures.

2.2. Test details

All the specimens for the bond stress–slip relationship test were designed with bond length 5 times of the nominal diameter of steel bars, which was 80 mm. The size of specimens was designed as 160 mm × 160 mm × 160 mm. The unbonded segments of the pull-out specimen were created by placing PVC pipe, which was 4 mm bigger than diameter of steel bar and used as a bond breaker, insulated around the bar. Unbonded sections were created on the segment of the bar near to the loading end, which was 80 mm. The detailed schematic drawing of the specimen for the pull-out test is shown in Fig. 1.

Prior to casting, molds and bars were processed into the design sizes, steel bars were properly marked. Then, penetrating bars and PVC pipes, gaps between bars and pipes were filled with double-sided adhesive to avoid the possibility of formation of voids. Then the concrete was casted. Compaction of concrete was done by the vibrator ensuring the complete compatibility of the specimens. Finally, all the concrete specimens were subjected to curing at 20 °C and 95% relative humidity (RH) after casting.

Standard compressive tests of concrete were conducted in identical timelines following the specifications in the standard for test method of concrete structures (GB/T 50152-2012). 6 prismatic concrete blocks with the size of 150 mm × 150 mm × 300 mm and 3 cubic concrete blocks with the size of 150 mm × 150 mm × 150 mm were casted for concrete at the age of 1, 3, 5, 7, 14, and 28 days, respectively, as shown in China National Standard GB/T 50081-2002. The results reported for axial compressive strength and cubic compressive strength were the average strength of specimens tested, as shown in Table 2, respectively.

The cylinder compressive strength could be calculated based on the cubic compressive strength as $f_c' = 0.79 \cdot f_{cu}$ [37–40]. Fig. 2 shows the relationship between the cylinder compressive strength and concrete age. The cylinder compressive strength was 6.76, 24.16, 31.70, 34.03, 41.63, and 49.42 MPa when the concrete

Table 1
Mixture proportions of concrete (kg/m^3).

Cement	Sand	Water	Coarse aggregates	Fly ash	GBFS	Superplasticizer
340	600	156	1157	73	73	6.8