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Concrete Bonding Properties of Polyvinyl-Alcohol Fibre in Fabricated Structures

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This paper aims to identify the bonding performance of superposed member of ordinary concrete and polyvinyl-alcohol (PVA) fibre-reinforced concrete, and that between rebar and PVA fibre-reinforced concrete. To this end, tensile tests were performed on specimens of six different contact surfaces between PVA fibre-reinforced concrete and ordinary concrete. The results show that PVA fibre-reinforced concrete has a much greater bonding performance than the ordinary concrete, which increases with the roughness of the contact surface. Moreover, PVA fibre-reinforced concrete of two different rebar diameters were designed for pull-out tests. The bonding performance between the concrete and rebar was contrasted with that between ordinary concrete and rebar. In this way, the author determined the failure mechanism of the bonding between PVA fibre-reinforced concrete and rebar, and derived the constitutive relationship between bonding stress and slip. The research findings lay the basis for the application of PVA fibre-reinforced concrete in fabricated structures.

1. Introduction

The polyvinyl-alcohol (PVA) fibres is a kind of fibre made from polyvinyl alcohol through wet spinning, heat treatment and crimping-oiling in water at normal temperature. This type of fibres is known for its excellent physical and mechanical properties like high strength, high elastic modulus and low ductility (Georgiou et al., 2016). In addition, the PVA fibres boast good chemical resistance, strong corrosion resistance in extreme environments, and high dimensional stability against heat and moisture. Particularly, the PVA fibres exhibit close affinity to cement and plastics. As a result, the PVA fibres have been widely adopted to reinforce cement slabs in the field of construction.

The PVA fibre-reinforced concrete can be obtained by incorporating PVA fibres into concrete at a certain proportion. Compared with ordinary concrete and steel fibre-reinforced concrete, the PVA fibre-reinforced concrete enjoys a low self-weight and high toughness (Georgiou et al., 2016), durability and fatigue resistance. In Reference (Deng et al., 2007), the load-deformation curve shows that the PVA fibre-reinforced concrete withstands the load after cracking, and the failure mode shifts from brittle failure to ductile failure; this means the PVA fibres can greatly enhance the ductility of the concrete (Amin et al., 2013). Currently, PVA fibre-reinforced concrete has been extensively applied to architecture and civil engineering in Europe and the US, ranging from slope reinforcement, deck repair to beam connection. A similar trend has been seen in China in recent years.

In China, the research and development of PVA fibre-reinforced concrete has just started. The PVA fibres for our research were imported due to the inconsistent performance of domestic fibres. However, China has already become the leading producer of PVA fibres in the world. China consumes 1/3 of the concrete available on the world market, an evidence of the strong demand for fibres in architecture and civil engineering. All these promise a huge market for any mature domestic technique of PVA fibre-reinforced concrete. Therefore, it is imperative to explore the features of PVA fibre-reinforced concrete.

Despite the excellent performance, the application of PVA fibre-reinforced concrete is still very limited in China due to the high cost of imported fibres. The PVA fibre-reinforced concrete is particularly suitable for the positions on ordinary concrete that are prone to brittle failure, such as the joint area and the negative bending moment area of continuous beams. Replacing the ordinary concrete with PVA fibre-reinforced concrete can

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reduce the amount of rebar and thus the difficulty of construction. With the proliferation of fabricated structures in China, many scholars are working on the superposition of PVA fibre-reinforced concrete and ordinary concrete, aiming to ensure the reliable connection of structural nodes in such structures. The integrity of the superposed member hinges on the bonding strength between the ordinary concrete and fibre-reinforced concrete, which, in turn, depends on the tensile strength of concrete. In view of the above, this paper superposes ordinary concrete and fibre-reinforced concrete into specimens of six different contact surfaces, and explores the effects of pouring method and contact roughness on the tensile strength through tensile tests.

The bonding between concrete and rebar is essential to the structural mechanics of reinforced concrete. The bond-slip relationship between concrete and rebar directly bears on the reliability of the finite-element analysis of reinforced concrete. Over the years, much research has been done on the bonding strength between ordinary concrete and rebar, but the findings do not apply to PVA fibre-reinforced concrete. What is worse, there is little report on the bonding strength between PVA fibre-reinforced concrete and rebar. To make up for the gap, a pull-out test machine was designed to test the bonding strength between PVA fibre-reinforced concrete and rebar of different diameters. Through the tests, the failure mechanism, influencing factors and bond-slip constitutive relation of PVA fibre-reinforced concrete were obtained, laying the basis for popularization of the material in fabricated structures.

2. Methodology

2.1 Bonding strength tests

2.1.1 Specimen design

Considering the effect of PVA fibre content on concrete performance, three kinds of concrete were designed with the fibre volume content of 0%, 1.0% and 1.5%, respectively. The PVA fibre is the REC-15 type PVA purchased from Kuraray (Japan). The mechanical properties of the fibre are listed in Table 1.

Table 1: Mechanical properties of PVA fibre

Fineness /detx	Diameter /μm	Length /mm	L/D ratio	Tensile strength /MPa	Elongation %	Elastic modulus /GPa	Density /g.cm^3
15	39	12	300	1600	6	40	1.3

The cement is P.O 42.5 ordinary Portland cement (Tangshan Jidong Cement Co., Ltd.). The fine aggregates are river sands (Mancheng), and the coarse aggregates are continuously graded crushed stones (Mancheng) between 5 and 10mm in diameter. These materials were mixed with tap water, producing a C30 concrete. The mix proportions of the concrete are shown in Table 2.

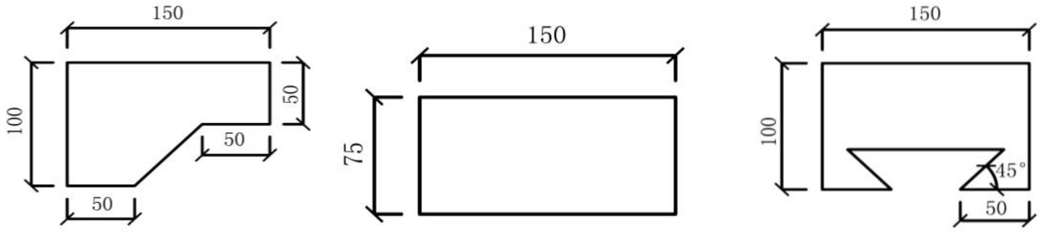
Table 2: Mix proportions of the concrete/(kg/m3)

Strength	Cement	Coal ash	Sands	Stones	Water	PVA fibre content (%)
C30	438	109	494	1051	235	0
C30	469	117	601	981	178	1.0
C30	511	128	520	965	194	1.5

According to Reference (Du et al., 2008), the cube and axial compressive strengths of the PVA fibre-reinforced high-strength concrete (PFRHSC) decrease slightly with the increase in the fibre content, while the elastic modulus has a slight increase. These prove that the PVA fibres can significantly enhance the tensile and bending strengths of the high-strength concrete.

On this basis, two groups of 150mm×150mm×150mm specimens were prepared for the three mix proportions (fibre contents). Each group has six specimens. The specimens were cured for 28 days, and then subjected to standard tests on compressive and tensile strengths. The basic performance indices of the materials were obtained through these tests.

The specimens of different concretes for bonding strength tests were casted in different batches. First, half-mould concrete specimens were casted in a standard mould (150mm×150mm×150mm) and were cured for 28 days after mould removal. Next, the specimens were taken out of the mould, and subjected to surface roughening. The surface roughness was measured by sand filling method. The cross-section shapes of the cured specimens include Z-shape section (Figure (1a)), flat section (Figure 1(b)) and embedded section (Figure (1c)). After that, the roughened specimens were reintroduced to the mould, and the surface was moistened and brushed with pulp slurry. The rest of the slurry was poured into the mould and the specimens were cured again for 28 days. Three specimens were prepared for each cross-section shape and reserved for the tensile tests.



(a) (b) (c)

Figure 1: Cross-section shapes

2.1.2 Test methods

(1) Concrete performance test
The concrete performance was tested according to the Standard for Test Method of Performance on Ordinary Fresh Concrete, China (GB/T 50080-2016).
(2) Mechanical performance test
The compressive and tensile strengths of the concretes were tested according to the Standard for Test Method of Mechanical Properties on Ordinary Concrete, China (GB/T 50081-2002).
The compressive strength is calculated by:

$$f_c = \frac{F}{A}$$

where f_c is the compressive strength (MPa),F is the failure load (N);,A is the area under pressure (mm^2).
The tensile test device is illustrated in Figure 2. The tensile strength is calculated by:

$$f_t = \frac{2F}{\pi A}$$

where f_t is the tensile strength (MPa), F is the failure load (N), A is the area of tensile failure (mm^2).

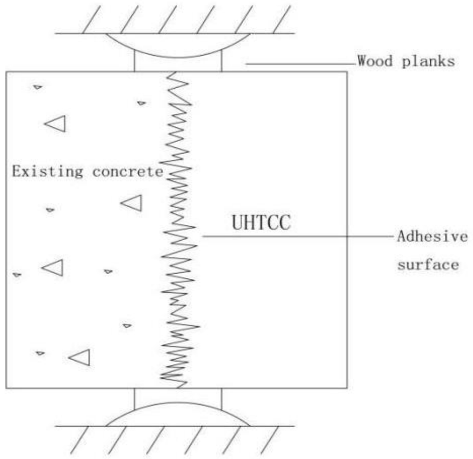


Figure 2: Tensile test device

2.1.3 Results analysis

The cured specimens were grouped and numbered, and subjected to the compressive and tensile tests. Through the tests, the standard compressive strength and the mean tensile strength were measured as 31.5MPa and 6.6MPa, respectively. The results basically agree with the theoretical values. According to the tensile test results in Figure 3, the load displacement curve of ordinary concrete specimens decreased rapidly and the section was completely broken, indicating that these specimens suffered from brittle failure. By contrast, the failure mode of PVA fibre-reinforced concrete varied with fibre contents. Crack propagation was observed on the specimens with the fibre content of 1.5%. However, the descending segment of the curve was flat, the lateral deformation was large, and no breakage was seen at the end of the test.

Figure 3: Tensile test results

The bonding strength between ordinary concrete and fibre-reinforced concrete is mainly identified by analysing the results of both compressive and tensile tests. The specimens for the compressive tests were poured along the direction of the cross-section, and the new concrete was casted vertically to the contact surface between it and the old concrete, because the contact surface needs to be placed vertically to the press machine during the compressive tests. This pouring and vibration method may reduce the continuity of the contact surface between new and old concretes, and weaken the tensile strength of such specimens (whose contact surface is vertical). Therefore, special attention should be paid to the bonding quality (SAHMARAN et al., 2013). In addition, the slum of fibre-concrete mixture is smaller than that of reference concrete, regardless of the type and content of fibres. This is attributable to the growth in concrete consistency with the addition of the fibres (Li et al., 2018).

The test results on specimens of different cross-section shapes are presented in Figure 4. The results show that both compressive and tensile strengths increased with the fibre content, when the cross-section shape remained the same. During the test, some specimens with no bonding agent was broken into two pieces during the removal of the mould, and no new bond was formed between the planes. It can be concluded that the specimen is less likely to fail with a rougher and larger contact surface. The bonding strength of concrete interface is affected by multiple factors. The bonding performance can be greatly enhanced through proper treatment of the interface and application of bonding agent, so as to ensure the safety and durability of the concrete structure (Shang and Lu, 2015).

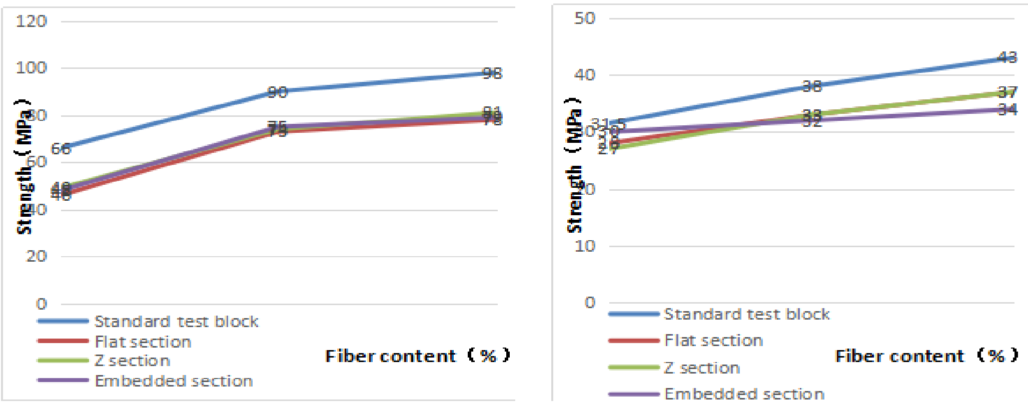


Figure 4: Test data

2.2 Rebar pull-out tests

2.2.1 Test preparations

Reinforced concrete, the fundamental material for construction, has been widely implemented in various fields. In addition to the basic mechanical properties, the bonding performance between concretes is an important issue in the structural design of reinforced concrete (Gao et al., 2015). The better the bonding strength, the more stable the concrete structure, and the smaller the material consumption. The bonding force between concrete and rebar consists of three components: chemical bonding force, friction resistance and mechanical bite force. Considering the pull-out features of the specimens, pull-out tests were conducted to disclose the effects of fibre content and rebar diameter on the bonding performance.

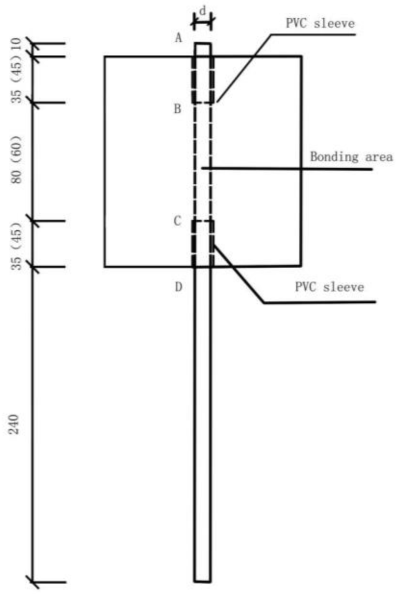


Figure 5: Details of the test *Figure 6: Pull-out test speicmen*

As shown in Figure 5, each concrete specimen was designed as a standard cubic block. Under external loads, the rebar may suffer from stress concentration, and differ greatly from actual rebar in stress state. To ensure the validity of test results and eliminate end effects, the rebar in the specimen was covered with a 35mm-long casing at each end to separate it from the concrete. The segment between the two casings is called the bonding segment: l=5d (Gao et al, 2015). In the pull-out tests, the rebar diameter was set to 16mm or 12mm, and the fibre content was set to 0% or 1.0%. The cured specimens are shown in Figure 6.

2.2.2 Data analysis

Four sets of test data were acquired and plotted into curves (Figure 7). It can be seen from Figure 7 that the peak bonding stress increased slightly with the growth in the volume content of PVA fibres. The peak bonding stress is positively correlated with the rebar diameter. Splitting failure was observed in all specimens. There was no obvious slip prior to the failure. After a period of loading, the specimens were split directly and the split surface was relatively complete. The failure surfaces are basically the same as those in the tensile tests.

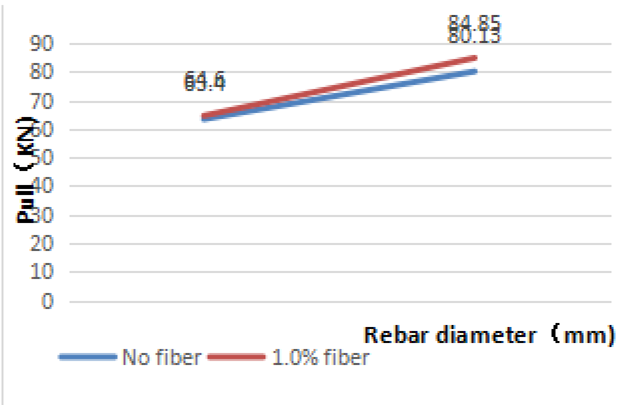


Figure 7: Pull-out image

3. Conclusions

Bonding and pull-out tests were carried out on concretes considering factors like fibre volume content and rebar diameter. The main conclusions are as follows:

(1) When the fibre volume content is lower than 2.0%, there is a positive correlation between fibre volume content, tensile strength, compressive strength and peak bonding stress. The tests have shown that the peak bonding stress at the fibre content of 1% is similar to that at the fibre content of 2%, two times larger than that at the fibre content of 0%. The reason is as follows: when both the fibres and the cement matrix are under stress, the bridging effect of fibres could protect the overall force transmission performance of PVA fibre-cement composite from the weakening effect of microcrack formation, and increase the relative sliding resistance between the composite and the rebar. The higher the fibre volume content, the less the weakening effect; the greater the resistance, the higher the peak bonding stress.
(2) The tests on specimens of different bonding surfaces show that the roughness and area of the contact surface are positively correlated with both compressive and tensile strengths.
(3) The greater the rebar diameter, the larger the peak bonding stress. Splitting failure is the common failure in the pull-out tests.

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