Experimental Study on Optimization of Mechanical Properties of Fiber-Reinforced Lightweight Concrete

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Abstract: In response to the energy-saving, emission-reduction, and low-carbon targets in the construction industry, this study investigates fiber-reinforced lightweight concrete. Lightweight concrete utilizing volcanic cinder as aggregate is proposed, with polypropylene fibers employed as an admixture. The interfacial bond strength between concrete and steel reinforcement in C30 fiber-reinforced lightweight concrete was studied through pull-out tests. A total of 90 specimens were divided into 9 groups for the pull-out tests. By examining the mechanical properties and microstructure of the concrete samples, the mechanism by which fibers influence the interfacial bond failure of lightweight concrete was understood. The effects of reinforcement bar diameter and bond length on the bond strength of the fiber-reinforced lightweight concrete were investigated. The results indicate that bond strength decreases with an increase in rebar size and embedment length. Based on the experimental data, a constitutive curve for the bond strength of C30 fiber-reinforced lightweight concrete with this specific mix proportion was fitted, providing a reference for the application of lightweight concrete materials.

Keywords: Light Concrete; Volcanic Slag Aggregate; Bonding Strength; Polypropylene Fiber

1. Introduction

In recent years, China's construction industry has begun transitioning from high-speed development to high-quality development, with the industrialization and industrial development of construction information becoming the main direction for future growth in the sector [1-3]. To achieve the first phase of China's "dual carbon" goals-carbon peaking by 2030, maintaining zero growth in CO2 emissions after reaching peak levels, and gradually reducing emissions-comprehensive structural adjustments and industrial upgrades are being implemented across multiple key sectors including industry, construction, technology, and energy. According to statistical data from the 2024 China Urban-Rural Construction Sector Carbon Emission Research Report, the urban-rural construction sector accounted for the majority of national energy consumption and carbon emissions in 2022. The total carbon emissions from construction and building activities nationwide reached 5.13 billion tons of CO2, representing 48.3% of all energy-related carbon emissions in China. Therefore, further enhancing industrial upgrading in the construction sector and reducing resource consumption have become particularly crucial [4-6].

Prefabricated buildings, characterized by standardized design, industrialized production, and intelligent management, have become a crucial approach for sustainable development in the construction industry. Prefabricated components effectively reduce resource and energy consumption during urbanization. However, traditional concrete materials exhibit insufficient performance after component fabrication, leading to structural damage during installation and transportation that compromises building reliability. In practical engineering applications, the bond strength between steel reinforcement and concrete matrix significantly impacts the mechanical properties of reinforced concrete structures [7,8]. The intact bonding between steel reinforcement and concrete matrix ensures complete stress transfer and optimal deformation coordination, thereby preventing localized failure under design loads [9-12]. Building on this premise, developing high-performance lightweight concrete materials becomes essential for further increasing prefabrication rates, reducing structural weight, and enhancing direct bond strength between concrete and steel reinforcement. Fiber-reinforced lightweight concrete demonstrates significant research value due to its excellent crack resistance, lightweight characteristics, and superior thermal insulation and soundproofing properties [13-15]. This study holds great significance for promoting and applying lightweight concrete technology.

Research on fiber-reinforced lightweight concrete has been conducted with partial performance studies. To address the mechanical properties of commercial concrete in practical applications, this study investigates the bonding behavior between cement-based composite materials and ribbed steel bars, analyzing how steel bar diameter and embedded length affect bond strength. A total of 90 drawn specimens were tested to examine changes in mechanical properties and microstructure of fiber-reinforced lightweight concrete, aiming to provide a reference for reliability assessment of reinforced concrete components.

2. Fiber Reinforced Lightweight Concrete Mix Ratio

The experimental study utilized volcanic rock as lightweight aggregate. This material, formed from slag-like porous rocks condensed from molten magma after volcanic eruptions, features abundant availability, large reserves, and low mining difficulty. Through particle size adjustment via crushing, it yields concrete aggregates with high porosity, lightweight properties, and low thermal conductivity. To enhance tensile strength, polypropylene fibers (10mm in length) were incorporated into the concrete, achieving a tensile strength of 400MPa. For preparing high-performance lightweight concrete reaching C30 grade, preliminary trials combined with economic considerations determined a volcanic slag concrete mix design using 1.0‰ of cement content (Table 1). The final product demonstrated an average density of 1800 kg / m³. (Figure. 1)

Figure. 1 Appearance of the Materials Used (A)Natural Lightweight Rocks And (B)Polypropylene Fibers Used in This Investigation

Table 1. Volcanic Slag Concrete Mix Ratio

Material	Scale	Dosage(kg)
Volcanic slag aggregate	1800	1000
Ordinary portland cement	550	305.6
Polypropylene fibre	1	0.3
Water	770	235.3
Grade II fly ash	100	30.6

3. Test Design of Fiber Reinforced Lightweight Concrete

A lightweight concrete cube containing partially embedded deformation reinforcement bars was tested with dimensions of 150 mm ×150 mm ×150 mm. Plastic PVC hoses were installed at both ends to control the anchorage length of the reinforcement (Figure 2). Three different diameters of deformation reinforcement bars (16mm, 20mm, and 24mm) were used, along with three distinct contact lengths: 50mm, 70mm, and 90mm. Five samples were tested under each condition to minimize measurement errors.

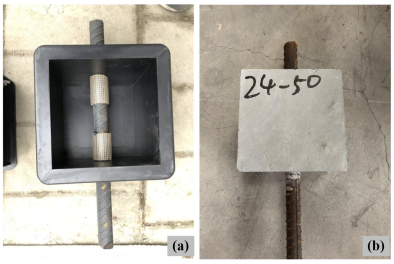

Figure. 2 Specimen for Pullout Test (A) Test Block Mold (B) Test Block

Before bond failure occurs, the bonding strength between deformed steel reinforcement and concrete primarily stems from mechanical interlocking effects between them, with concrete's mechanical strength playing a dominant role. During drawing deformation of steel reinforcement, tensile forces generate shear stresses through the ribbed structure of the steel reinforcement on the concrete surface. This mechanical interlocking effect laterally restricts the extraction of the steel reinforcement. Consequently, research has been conducted on the compressive and tensile strengths of lightweight concrete to investigate how changes in concrete's mechanical properties affect bond strength.

Table 2 details the diameter of steel bars and anchorage length conditions for the test specimens. Each specimen is denoted by the initial letter C and a number representing the steel bar diameter and embedded length respectively (e.g., C/16/50 indicates that 16mm diameter steel bars are inserted into lightweight concrete test blocks with a contact length of 50mm). The internal steel bars in all test blocks were selected as HRB400 steel bars from China, which are ribbed steel bars with a nominal HRB400 reinforcement steel, which has a yield strength of 400 MPa, is employed as longitudinal reinforcement in structural members requiring high load-bearing capacity.

Table 2. Classification of Test Blocks

Designation	Bar Type	Diameter	Embedment Length
C/16/50	HRB400	16mm	50mm
C/16/70			70mm

C/16/90			90mm
C/20/50		20mm	50mm
C/20/70			70mm
C/20/90			90mm
C/24/50		24mm	50mm
C/24/70			70mm
C/24/90			90mm

The drawing test apparatus is shown in Figure 3. Each specimen is restrained by a steel frame composed of two 30mm thick steel plates and five 25mm diameter steel bars. The central steel bar on the top plate is clamped by an MTS loading frame. The specimen's steel bars pass through a reserved opening in the base plate and are secured by lower clamps. Lubricating oil is applied between the specimen and base plate to reduce friction during drawing tests. A displacement gauge measures the relative movement between the steel bars and specimen, while tensile force is recorded by a force measurement unit in the loading frame. The bond strength of volcanic slag concrete is determined using Equation (1).

$$\tau = \frac{P}{\pi d l} \quad (1)$$

Where: P P is the peak tensile d d force (N), the l diameter l of the steel bar (mm), and the burial length of the steel bar (mm).

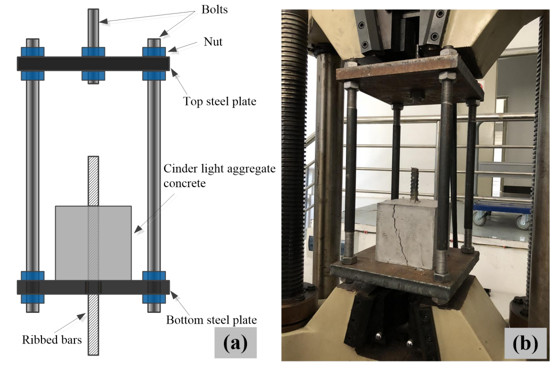

Figure 3. Pull-Out Experimental Installation (A) Design Diagram of Experimental Apparatus (B) Test Device

4. Material Mechanical Properties and Data Processing

The microstructure of the samples was analyzed by scanning electron microscope using 150 mm × 150 mm × 150 mm standard samples after fire. After the test, fragments from the fractured specimens were obtained as samples. An SEM (TESCAN MIRA3, Czech Republic) was utilized to observe the microstructure of the post-fire concrete specimens. SEM is a standard analytical tool in materials research, encompassing metallic sectors such as steel and non-ferrous metals, as well as non-metallic fields including chemicals, petroleum, geology, polymers, and construction materials. The fracture specimens were first inspected at room temperature as a control result. It can be seen that the presence of PP fibers effectively improves the tensile strength and bonding stress of concrete, and reduces internal defects in concrete materials (Figure. 4).

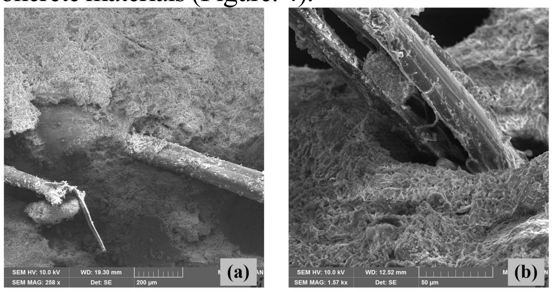

Figure 4. Microstructures of Cinder Concrete with Pp Fibre After Heat Treatment (A) 258x (B) 1570x

Figure 5 displays the tensile-slip curves of individual specimens. The bonding strength of each specimen was calculated using Formula (1) based on the test peak load. The average bonding strength values from 10 specimens per group are summarized. As the curves show fundamental similarity, we selected representative examples for illustration. For all obtained tensile-displacement curves, bonding strength-displacement data were organized according to different variables, and a bonding strength-displacement constitutive model was established through fitting.

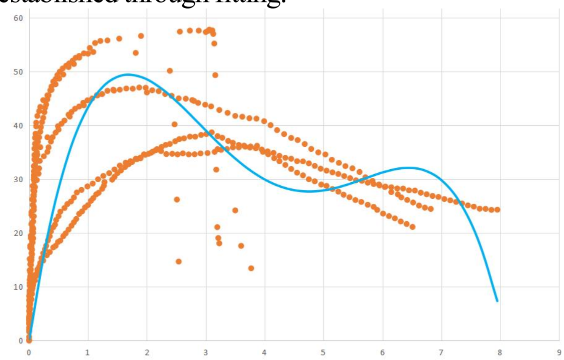

Figure. 5 Pulling Force-Slip Curves of Specimens

Based on the test results, constitutive relationships for bond strength were developed across different temperatures, with a particular focus on defining the relationship at 22°C.

$$\tau = -0.03497s^4 + 6.0104s^3 - 34.666s^2 + 72.375s \quad (2)$$

In tensile tests, the effects of different factors on bond strength were investigated by altering the diameter of steel bars and bonding length. The average bond strength of specimens decreased with increasing steel bar diameter and embedded length. The percentage reduction in bond strength under various temperatures was determined. When the rod diameter increased from 16mm to 25mm, the average bond strength of fiber-reinforced lightweight concrete decreased by 15.47% at room temperature. Similarly, when the bonding length increased from 50mm to 90mm, the average bond strength also decreased by 15.12% at room temperature.

5. Conclusions

Prefabricated buildings are currently in the stage of transformation and rapid development. This paper obtains the ultimate bonding stress and slip of fiber-reinforced lightweight concrete through the central pull-out test. Through the analysis of the influencing factors of steel diameter and bonding length, the following conclusions are obtained:

1.Through the observation of the test components at the micro structure, PP fiber can effectively improve the tensile strength and defects of lightweight concrete, while the high porosity of volcanic slag aggregate can effectively reduce the self-weight of the structure and further improve the mechanical properties of the prefabricated components.

2.With the increase of the diameter of the steel bar, the bonding strength between the steel bar and the volcanic slag concrete gradually decreases. With the increase of the bonding length, the bonding strength between the steel bar and the volcanic slag concrete gradually decreases.

3.The bonding strength-displacement constitutive law of C30 fiber-reinforced lightweight concrete was obtained by fitting the experimental data, so as to provide reference for the practical application of modified materials.

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