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Experimental study and application of mechanical properties for the interface between cobblestone aggregate and mortar in concrete

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HIGHLIGHTS

- We examine both the tensile and the shear bond strengths of the interface between cobblestone aggregate and mortar.
- Increasing the normal stress will increase the shear bond strength of the interface.
- Mohr–Coulomb failure theory can be used to illustrate the interfacial failure at meso-level.
- By using the mechanical properties of the interface, the behavior of concrete can be predicted to a degree of accuracy.

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ABSTRACT

The failure mechanism under the combined state of normal and shear stresses for the interface between cobblestone aggregate and mortar was investigated by testing the interfacial bond strength. It was revealed that the tensile bond strength of the interface between cobblestone aggregate and mortar was about half the tensile strength of the mortar, but the shear bond strength of the interface was close to the shear strength of the mortar. Moreover, the shear bond strength increased with increases in the normal stress when the normal stress was smaller than 60% of the compressive strength of the mortar, but it can be assumed that the shear bond strength decreases with increases in the normal stress if it was larger than 60% of the compressive strength of the mortar. The failure criterion for the interface under combined normal and shear stresses was established by regressing the experimental data. Finally, a two-dimensional mesoscopic mechanical model, in which the mechanical properties of the interface were described by the obtained bond strength and failure criterion, was used to simulate the fracture process of concrete. Verification of the simulation was performed by comparing the simulated results with those obtained from the tests, in which the aggregate roughness was similar to that in the interfacial experiment. It was found that, by using the mechanical properties of the interface in the numerical model, the behavior of concrete could be predicted to a reasonable degree of accuracy. The propagation of cracks and the failure modes of concrete can also be determined using the proposed numerical model.

1. Introduction

It is generally accepted by many researchers that the microstructure of the interface between coarse aggregate and mortar is the weakest link in normal concrete [1,2]. Therefore, the mechanical behavior of concrete is significantly affected by the properties of the interface [3,4].

In the mesoscale, concrete is idealized as stiff aggregates embedded in a soft matrix and separated by a weak interface [5]. Moreover, it has been proven that the study of concrete at the mesoscale is the most practical and useful method for the evaluation of its mechanical properties [6]. Attempts have been made to model concrete analytically at the mesoscale.

The mechanical properties of each phase have a significant effect on crack initiation and propagation. In particular, the accurate understanding of the properties and behavior of the interface is one of the most important issues in mesoscale analyses, because cracks initiate in the weakest region and the interface is generally the weakest link in concrete. However, in most of the investigations in the literature, the parameters used for characterization of the interface are empirical and experimentally determined [6–9]. Moreover, the parameters evaluated using experimental data are not always consistent and show a wide variability [10].

Some studies have been devoted to the determination of the mechanical properties of the interface between coarse aggregate and mortar. Hsu and Slate [11] found experimentally that the

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tensile bond strength of the interface varied from 33% to 67% of the tensile strength of mortar and decreased with increases in the water/cement ratio. However, the "∞" specimens they used did not provide pure axial tension on the failure surface [11].

Taylor and Broms [12] investigated the shear bond strength between the aggregates and the mortar matrix by using sandwiched specimens, in which a thin slab of the aggregate material was cast into the matrix of cement paste or mortar. They concluded that the shear bond strength increased linearly with the normal stress (corresponding to a constant friction angle), which is in accordance with the Mohr–Coulomb failure theory. However, they did not perform research on the bond strength when the normal compressive stress was very large.

Kosaka et al. [13–15] found that the friction angle ranged between 30° and 40° with experiments on the shear bond strength of the interface between aggregate and mortar. Rao and Prasad [16] found that the tensile bond strength of the interface between mortar and rough concrete was about one third of the tensile strength of the mortar. The shear bond strength increased as the roughness of the aggregate surface increased and also as the normal compressive stress increased.

Previous studies have often focused on the bond strength of the interface between aggregate and mortar. However, the influence of mechanical parameters of the interface on the numerical simulation results of concrete, particularly the influence of the interfacial failure criterion on the numerical simulation results of concrete in the mesoscale, has not been studied thoroughly.

As one part of a series of research projects, the objectives of this study were the determination of the mechanical properties of the interface between mortar and cobblestone aggregate in concrete, the verification of the applicability of the mechanical parameters, and the investigation of the influence of the interfacial failure criterion on the numerical simulation results of concrete at the mesoscale. Intensive interfacial tests were conducted to obtain the tensile and shear bond strengths of the interface. The interfacial failure criterion was then established by regressing the experimental data.

A newly developed two-dimensional mesoscopic mechanical model was used to analysis the behavior of concrete, in which the tested results were used to describe the mechanical properties of the interfacial elements. The influence of the interfacial failure criterion on the response of concrete was investigated. Tests for the failure behavior of concrete were conducted to validate the simulated results, and it was determined that the aggregate roughness in the tested concrete was close to that in the simulated interfacial tests.

2. Experimental procedure

2.1. Preparation for aggregate

Crushed stones and cobblestones are widely used as aggregates in concrete. Due to the complex surface of crushed stones, cobblestones were adopted as the coarse aggregates for the concrete specimens in this paper, in order to test their mechanical properties, such as strength, elastic modulus and Poisson's ratio. However, it is difficult to test the bond strength of the interface between cobblestones and mortar, since the cobblestones are too small to be fabricated for testing.

According to the research results of Rao and Prasad [16] and Alexander et al. [17], with the same mortar and aggregate type (the same physical–chemical interaction), the tensile or shear bond strength of the interface depends on the roughness of the aggregate. Thus, for convenience, marble, which has a similar chemical composition as cobblestone, was used to represent the coarse aggregate in specimens to test interface mechanical properties. If the roughness of marble is close to that of cobblestone, it can be proposed that the mechanical properties of the interface between marble and mortar can mimic that between cobblestone and mortar.

To find a proper interface treatment for ensuring that the surface roughness of marble was similar to that of cobblestone, three kinds of surface roughnesses (saw-cut, fully polished and medium-polished surfaces) were tested, with each type having four or six specimens. The saw-cut marble kept the original cut surface by the cutter without any treatment. The fully polished and medium-polished marbles were polished on the surface with a fine-polishing disc (180 mesh) and a coarse-polishing disc (80 mesh), respectively.

The surface roughnesses of cobblestone and marble were measured using a surface roughmeter (Fig. 1a). By moving the sensor along the surface of the specimen, a surface profile could be obtained (Fig. 1b). Surface roughness is often evaluated by the parameter R_a, which represents the arithmetical mean deviation of surface profile. R_a can be calculated with Eq. (1), in which $Z(x)$ and l represent the surface profile and the sample length of the specimen, respectively.

$$R_a = \frac{1}{l}\int_0^l Z(x)dx \tag{1}$$

The R_a of each specimen is recorded in Table 1. Several typical surface profiles of cobblestone and marble specimens are shown in Fig. 2. It can be seen that the R_a of marble with a medium-polished surface was 4.277 μm, which was 9.5% smaller than R_a of the cobblestone aggregates in concrete. This indicated that the roughness of marble with a medium-polished surface was very similar to that of cobblestone aggregate in concrete and that the medium-polished marble could be used to represent the cobblestone aggregates to study the interfacial bond strength.

2.2. Mix proportion of mortar and concrete

Local Portland cement (425R) was used in the specimens; and, four strength grades (1–4) were prepared by using four different mix proportions. For the mortar, the water/cement ratios were 0.83, 0.65, 0.49, and 0.40 (by weight), respectively; and, the cement/sand ratios were 0.27, 0.40, 0.65, and 0.91, respectively.

Concrete specimens were prepared with the same water/cement and cement/sand ratios as those of the mortar, and the sand/coarse aggregate ratios were 0.70, 0.56, 0.45, and 0.38, respectively. Cobblestones, which had a similar surface roughness with that of the interfacial experiment and obeyed Fuller's gradation [18], with diameters of 5 mm to 20 mm, were used as coarse aggregates. The mass percentages of aggregates with diameters of 5–10 mm, 10–16 mm and 16–20 mm were 70.7%, 18.7% and 10.6%, respectively.

2.3. Test specimens

Specimens for the tensile bond strength tests were made as shown in Fig. 3a. The surface of marble was medium-polished to ensure a similar surface roughness as the cobblestone aggregates in concrete. Prior to casting, the marble plate was stored in water for 24 h; and, after wiping off the surface water, organic glass cylinders were placed on the marble plate and filled with mortar. A safety cover was placed over the specimens when curing to avoid disturbing the mortar cylinders (Fig. 3b). The cylinder diameter and height of the specimens were 50 mm and 60 mm, respectively; and, there were six identical specimens for each strength grade of mortar.

Specimens for the shear bond strength tests, which contained prism marble with a medium-polished surface and prism mortar similar to that used by Kosaka et al. [13], were made as shown in Fig. 4a. The inclination, α, of the aggregate varied. The relationship between the normal and shear stresses at the aggregate/mortar interface under applied ultimate load can be obtained using Mohr stress circles (Fig. 4b). The stresses on the failure plane can be derived by the following equation:

$$\begin{cases} \sigma_i = P/A \cdot \sin^2\alpha \\ \tau_i = P/A \cdot \sin\alpha \cdot \cos\alpha \end{cases} \tag{2}$$

where τ_i and σ_i are the shear and normal stresses on the surface, respectively; P is the applied axial load when the interface fails; and, A is the cross-sectional area of the specimen.

By varying inclination α and constructing the stress circles corresponding to the failure on the interface, a series of points representing the various stress conditions leading to failure (Fig. 4b) can be determined.

To investigate the shear bond strength at different normal stress conditions, the inclinations were designed as 30°, 40°, 50° and 60°. After cutting and medium-polishing, the marble was stored in water for 24 h; and, the prism specimens were then cast in 50 × 50 × 200 mm molds with marble aggregate placed in the molds, as shown in Fig. 4c.

Mechanical experiments were also carried out on the mortars to obtain their basic mechanical properties. For each strength grade of mortar, six cubic specimens with each side of 70.7 mm and six cylinder specimens of 50 mm diameter and 200 mm height were made for uniaxial compressive and tensile strength tests.

In order to validate the simulation results discussed in Section 4, concrete compressive strength, elastic modulus, and Poisson's ratio were obtained by testing 24 (six of each grade) concrete prism specimens with a height of 300 mm and cross sections of 100 × 100 mm; and, concrete tensile strength were obtained from 24 (six of each grade) tensile specimens of 50 mm diameter and 200 mm height. As with the mortar, four kinds of strength grades were designed to cover a common range of mix proportions for concrete.