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Numerical study of the effect of ITZ on the failure behaviour of concrete by using particle element modelling

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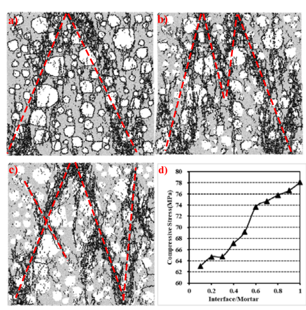
HIGHLIGHTS

- Aggregate particles were generated with the random irregular polygon.
- The meso-parameters and macro-parameters are inversed under FJM.
- The effect of ITZ strength on tensile is greater than that of compressive.
- ITZ is no longer the weakest area when its strength surpasses 70% of the mortar.

GRAPHICAL ABSTRACT

Concrete uniaxial compressive failure form at: (a) ITZ/Mortar = 0.1; (b) ITZ/Mortar = 0.5; (c) ITZ/Mortar = 0.9; and (d) uniaxial compressive strength under different ratio of ITZ/Mortar.



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ABSTRACT

The interface transition zone (ITZ) is the weakest area in the concrete three-phase medium, which directly affects concrete strength, stiffness, and durability. Because the ITZ has small-scale characteristics, conventional testing methods cannot be used to study its effect on concrete strength. The objective of this paper is to study the mechanism of ITZ in the process of concrete failure by means of a mesoscopic numerical model, and propose an efficient numerical simulation method for improving the numerical simulation in terms of concrete micromechanics. First, the random irregular aggregates are generated by PFC2D (Particle Flow Code in two-dimensions), and the percentage of aggregates is verified by image processing technology. Next, the contact properties of different media of concrete are defined by using the flat-joint model; based on this, the numerical simulation of Brazilian splitting test (BST) and uniaxial compression test (UCT) is carried out, and the simulation results are compared with the physical test data to verify the model. Finally, after processing the uniaxial compression and tensile test numerical simulation by using the proposed method, it was found that when the strength of ITZ is at least 70% of the strength of cement mortar, concrete can be regarded as a two-phase medium comprising aggregate and cement mortar; thus, ITZ can no longer be considered the weakest area.

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1. Introduction

Concrete is a type of defective quasi-brittle material, whose crack propagation is manifested as the initiation, expansion, and penetration of microcracks until the macro-cracks occur, and the characteristics of failure are similar to those in a sudden rupture. At the microscopic level, concrete is considered a three-phase composite comprising aggregate, cement mortar, and interface transition zone (ITZ) [1,2], and its macro-mechanical properties depend on the properties of the mesoscopic performance of each phase medium. Use of the macro-model cannot explain the relationship

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between the internal structure of the concrete and the macro-mechanical properties, nor can it reasonably explain the crack propagation law. In addition, the damages caused by mesoscopic heterogeneity and failure caused by stress concentration are difficult to describe using a macro-model; therefore, it would be worthwhile to conduct the study via a *meso*-mechanical model. At present, there are two major categories of the mesoscopic numerical model: the continuous medium mechanics model, which considers concrete as a continuum, and the non-continuous mechanics model, where concrete is considered as discrete media.

The finite element method (FEM) is the most representative method for the continuous medium mechanics model, and it generally includes the Mohamed-Hansen (M-H) model [3–6], the stochastic mechanical model [7], and the random aggregate model [8,9]. The randomness of the distribution of aggregates in the matrix and mechanical properties of the components are considered in the M-H model from the *meso*-structure of the concrete. However, the M-H model is only suitable for simulating mechanical tests where tensile failure is the primary focus, since it is assumed that the element only undergoes tensile failure, not shear or compression failure. The stochastic mechanical model was proposed by Tang Chun'an et al., and assigns a constituent material with a given Weibull distribution. The maximum tensile stress criterion and the Mohr-Coulomb criterion are considered to be the failure criteria of the element, and the tensile criterion has priority. The stochastic mechanical model simulates the damage process of concrete under the condition of tensile, shear, and uniaxial compression, but it does not consider the randomness of the spatial distribution of aggregate since it will have effects on the simulation results. The random aggregate structure (RAS), proposed by Liu Guangting and Wang Zongmin, can be used to model the aggregates and mortar directly in the specimen section, and to define the mechanical properties according to the position of distinct types of elements, thus characterizing the three-phase structure of the concrete. This model can characterize the random distribution of aggregate and simulate the fracture process in the mesoscale. However, ITZ mesh and mesh size selection are problems that urgently need to be solved. In addition, the lattice model [10–12] could satisfy the basic assumptions of continuum in the form of discrete rod units, beam elements, and frame elements, which could effectively simulate the fracture process caused by tensile damage. Nevertheless, it is not ideal for simulating the macroscopic mechanical properties of concrete under compression, and the failure process of the element is irreversible, and this is difficult to reveal the unloading problems.

The discontinuous medium model includes the discrete element model (DEM) [13–16], interface model [17], etc. The DEM has been widely used to study the mechanical behaviour of soil、rock, and concrete [18–21,22–24], because it can visually express the nonlinear damage process of the material with the fracture of the element contact. Owing to the particle element model (PEM), which is a type of DEM, considerable progress has made in the study of concrete *meso*-models in recent years. Azevedo et al. [25] established a circular aggregate *meso*-model to study the effect of various assumed *meso*-parameters of aggregate on the tensile strength and failure modes of concrete; Jun Chen [26] and Yu Liu [27] studied the effect of aggregate size and distribution on asphalt concrete. In the dynamic *meso*-simulation, Qin and Zhang [28] established the PEM based on the background mesh pre-processing method, and simulated the direct tensile and uniaxial compression test (UCT) of concrete under different strain rate conditions. Likewise, they analysed the mechanism of the relevant effects from the perspective of energy consumption and damage to crack morphology. Later, Wu et al. [29–32] validated the PEM in dynamic tests.

Regardless which of the methods mentioned above is used, with a thickness of 20–100 μm [33,34], ITZ is the most important component of the three-phase medium and it is the weakest region of conventional concrete [35,36], which directly affects its strength, stiffness, and durability [37,38–41]. Thus, ITZ has been the focus of concrete research. Maso et al.'s experimental research shows that the ITZ is the weakest area in concrete and has a significant effect on the fracture path and mechanical strength of concrete [42]. Diamond et al. [43] observed by SEM that in the fracture process of concrete, the initial crack is usually located in the interface between the aggregate and the cement paste. Through the microstructure study of ITZ, Chen Huisu et al. [44] found that the porosity of the ITZ was much higher than that of the hardened cement paste, when the concrete reached the ultimate hydration degree. Because the ITZ cannot be separated from the aggregate and hardened cement paste independently, the conventional test method cannot be used to study the effect of ITZ performance on concrete [45]. Several simulation models have been developed to study properties of ITZ. To take into account the inhomogeneity of the ITZ, Lutz et al. [46] approximated the elastic modulus of ITZ as a power-law function of radial distance from the centre of the aggregate and derived an analytical solution for the bulk modulus of concrete. Nadeau [47] has calculated the ITZ properties by supposing an evolution of the water-to-cement (w/c) ratio according to the distance from the aggregate boundary. Zheng proposed an n-layered spherical inclusion model to predict the elastic modulus of concrete with inhomogeneous interfacial transition zone (ITZ) [48]. However, it is easy to notice that a FEM is impossible to realize because it needs a too high number of elements due to a high ratio between the specimen volume size and the element size required to represent a layer. Taken into account the ITZ properties in the calculation with a limitation of the finite elements, Grondin et al. [49] have considered a three-phase material for concrete: aggregates, the bulk paste, and an effective mixed interphase (EMI).

Based on the *meso*-mechanics numerical models mentioned above, this study adopts the discontinuous medium model to generate a random aggregate model using PFC2D. After that, the accuracy of the mesoscopic model will be verified by comparing the numerical simulation results of the BST and the UCT with the physical mechanics test results. Moreover, to explore the mechanism of ITZ strength in the process of concrete failure, this study intends to obtain the effect of different interface strengths on compressive and tensile strength, and the failure mode of concrete, by utilizing a method that keeps the mesoscopic parameters of aggregate and mortar unchanged, and only changes the strength of the ITZ.

2. Experimental campaign

2.1. Specimen preparation

The composition of the C60 concrete used to produce the specimens is presented in Table 1. The ingredients of the aggregates are granite and limestone with moisture content 0.8% and 1.05%, respectively. Three cubes (150 mm × 150 mm × 150 mm) and three cylinders (Φ150 × 300 mm) were prepared. All the specimens were demoulded within 48 h after casting, and then cured in a humid chamber room with a temperature of 20 °C ± 1 °C and relative humidity ≥ 95% until the 28th day for the BST and UCT

2.2. Test methods and results

The three cubic and three cylindrical specimens were tested respectively in accordance with the Chinese standard (Standard test method of mechanical properties on ordinary concrete) [50].

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