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EVALUATION OF TENSILE STRENGTH OF SLAG BLENDED CEMENT PASTE USING MULT-SCALE ANALYSIS FRAMEWORK

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Abstract. A multi-scale analysis framework is used to efficiently identify the correlation between the microstructure and tensile strength of slag blended cement paste in this study. This framework confirms that the tensile strength of cement paste can be predicted by considering the effect of microstructure. The framework is applied to cement paste specimens containing blast furnace slag. The tensile strength of the slag blended cement paste is evaluated by experiment and simulation. The slag blended cement paste is observed using micro-CT (computed tomography), which is subjected to a splitting test to measure the tensile strength. The micro-CT images are reconstructed into virtual 3D microstructures to be used as a simulation model. The virtual 3D microstructures are employed to simulate the splitting test through a finite element analysis, with a phase-field fracture model applied to identify the crack patterns within the microstructure. The input parameters required for the simulation are obtained from nanoindentation correlated with characteristics from micro-CT. The framework is subsequently utilized to evaluate the tensile strength of slag blended cement paste and compared with experimental results. This study demonstrates the feasibility of extending the multi-scale framework to cement paste with admixtures.

1 INTRODUCTION

Concrete is commonly used with various admixtures depending on its intended purpose. The admixtures affect the hydration reaction of cement, consequently changing the microstructure of the cement paste which acts as the binder in concrete. Since the microstructure of the cement paste is closely related to the behavior of concrete, it is crucial to analyze the correlation between the microstructure and the behavior of the concrete.

In this study, the correlation between the microstructure and tensile strength of cement paste with slag as an admixture was analyzed using the multi-scale framework [1]. It was demonstrated that the tensile strength of a cement paste without admixture can be predicted by considering the effect of microstructure through the multi-scale framework. In this study, the tensile strength of slag blended cement paste was evaluated using the multi-scale framework to assess whether the framework can be used to evaluate the tensile strength of cement paste with admixtures.

2 SAMPLE PREPARATIONS

Specimens used for tensile strength evaluation in this study were prepared from a cement paste with a water/binder ratio of 0.4. The binder was prepared by mixing cement and blast furnace slag in an 8:2 ratio by weight, and a specimen with only cement as binder was prepared as a control group. The specimens were generated into cubes of $5 \times 5 \times 5$ mm^3 for microscale X-ray computed tomography and tensile strength test. The specimens were cured in water for 28 days before being used in the experiments.

3 EXPERIMENTS

3.1 Micro-CT

The microstructure of the slag blended cement paste specimen was captured using micro-CT, and the tensile strength was evaluated by splitting test. The process of performing micro-CT and the splitting test is illustrated in Fig. 1 (a), and the splitting test setup is shown in Fig. 1 (b).

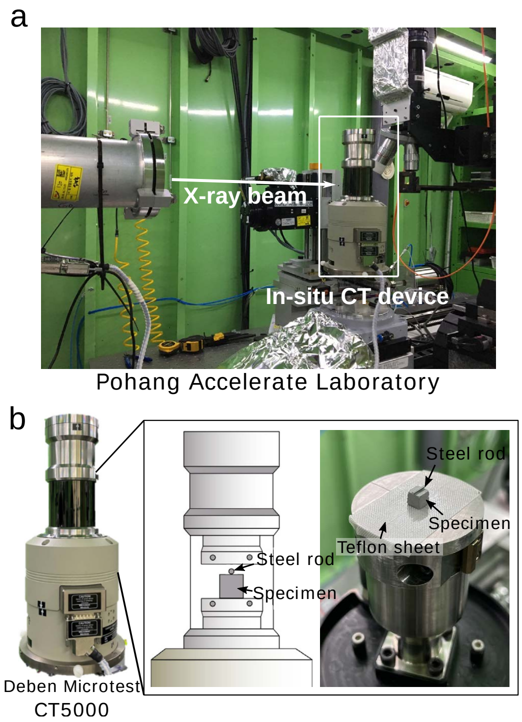

Figure 1: (a) in-situ splitting test in micro-CT and (b) splitting test setup.

Computed tomography is a non-destructive testing method that can obtain the microstructure inside the material in 3D without damaging the specimen. The microstructure of the cement paste specimens before and after the splitting test were taken with a resolution of 6.6 μm/per pixel using micro-CT (Pohang Accelerator Laboratory, Republic of Korea). The microstructures captured by micro-CT are stored as 2D cross-sectional images with a grayscale of 8 or 16 bits. The grayscale values were converted to linear attenuation coefficient (LAC), which is a material property at the same X-ray energy level. In this study, based on LAC, four phases comprising the slag blended cement paste are distinguished: void phase and three solid phases (outer product, inner product, and unhydrated phases), and the simulations were conducted using virtual 3D specimens reconstructed by the 2D microstructures consisting of these phases.

3.2 Splitting test

The splitting test was performed in a one-side loading. A steel circular rod with a diameter of 1 mm was placed on top of the cube-shaped specimen, and the specimen was placed on the stage of an in-situ load cell (Deben Microtest CT5000). The stage of the load cell is covered with a Teflon sheet to ensure that the specimen slides enough on the top surface of the stage. Then activate the load cell to apply a load to the rod on top at a rate of 0.01 mm/s until failure. The relationship between the maximum load (P) applied to the specimen and the tensile strength (σ_t) is given by

$$\sigma_t = \alpha \frac{2P}{\pi D^2}, \tag{1}$$

where, α is the parameter which is determined by taking the ratio of the maximum load (P) between the two-side splitting and one-side splitting simulations, and is found to be 0.89 in [2]. D is the length of one-side of the cube specimen. A total of 10 specimens were used for the splitting test, of which one specimen was subjected to micro-CT imaging. The tensile strength of the slag blended cement paste measured by the experiment is 5.86 MPa.

4 SIMULATIONS

4.1 Virtual specimens

The simulation of the slag blended cement paste specimen was performed using finite element analysis to simulate the same one-sided splitting test as the experiment. The simulation was conducted using a 3D microstructure reconstructed from micro-CT images. In this study, a large domain excluding the noise generated during micro-CT acquisition was first separated from the entire $5 \times 5 \times 5$ mm^3 cube, and then a region of 1.67 mm^3 were selected at random locations within the domain to create virtual specimens. The virtual specimens of $5 \times 5 \times 5$ mm^3 cube were generated by stacking the randomly selected region in a $3 \times 3 \times 3$ format by mirroring and repeating the process. For the simulation, three virtual specimens each were generated in the large domain of the slag blended cement paste and the cement paste without slag. The virtual specimens were rescaled to $100 \times 100 \times 100$ voxels in consideration of the computational cost of the simulation.

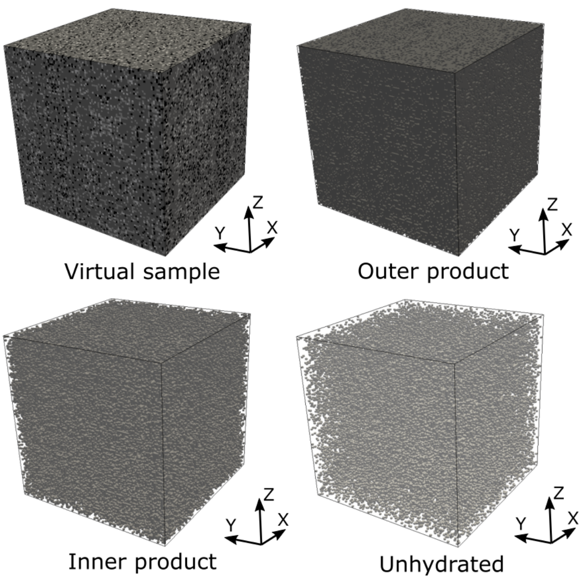

Figure 2: Simulation model and three solid phases.

The simulation models based on the micro-CT images are assigned a LAC value for each voxel. Using this LAC value, the simulation is performed by distinguishing the virtual microstructure into four phases. Among the four phases, the void and unhydrated phases were obtained by using a Gaussian curve fitting to the LAC distribution of the virtual specimens. The other two phases, inner product and outer product, were distinguished based on the ratio between the two products obtained by nanoindentation [3]. The microstructure used as the simulation model and the three solid phases comprising the microstructure are shown in Fig. 2. The void phase is represented by removing voxels from the simulation model. More details about this process were proposed in [1].

4.2 Input parameters

To perform the simulation, the properties of each phase (Young's modulus and tensile strength) must be obtained as input parameters. The Young's modulus is determined by

$$E_s = 69.2 \times \bar{\chi}_s + 1.22 \quad \text{[GPa]}, \qquad (2)$$

which is obtained from the correlation between the LAC of high resolution micro-CT and the Young's modulus of nanoindentation. E_s is the Young's modulus and the $\bar{\chi}_s$ is the average of the LAC values of all voxels corresponding to each phase. This linear relationship between LAC and Young's modulus was obtained for cement paste specimens without slag admixture [1]. In this study, the correlation between LAC distribution and Young's modulus obtained in cement paste was verified to be applicable to cement paste with admixtures. The tensile strength (σ_s) is given by

$$\sigma_s = H_s/\xi, \qquad (3)$$

where H_s is the hardness of the solid phase and ξ is a constant parameter that depends on the simulation model and the correlation between the variation of the ξ and the simulation results has been reported in [2,4]. This parameter ξ was determined to be an integer that makes the simulation results as close as possible to the experiment results. Since the hardness (H_s) obtained from nanoindentation can be expressed in

$$H_s = 0.005178 {E_s}^{1.495} \quad \text{[GPa]}, \qquad (4)$$

the tensile strength is determined by the Young's modulus [5]. Thus, the phase properties for the simulation are obtained by a combination of higher resolution micro-CT and nanoindentation taken at lower scales and used for the higher scale simulation.

4.3 Finite element method and boundary conditions

The splitting test simulation was performed by a finite element method, and a phase-field crack model was applied to implement the crack growth in the virtual specimens [6]. In the phase-field crack model, the diffusive crack length required for crack propagation was determined to be twice the mesh size as in previous studies, in order to represent the crack width as small as possible within the mesh size limited by computational cost. The boundary conditions applied in the simulation are shown in Fig. 3. As in the experiment, the bottom of the specimen was fixed in the z-direction, and the top of the specimen was simulated to be loaded by a steel rod with a diameter of 1 mm using displacement boundary condition.

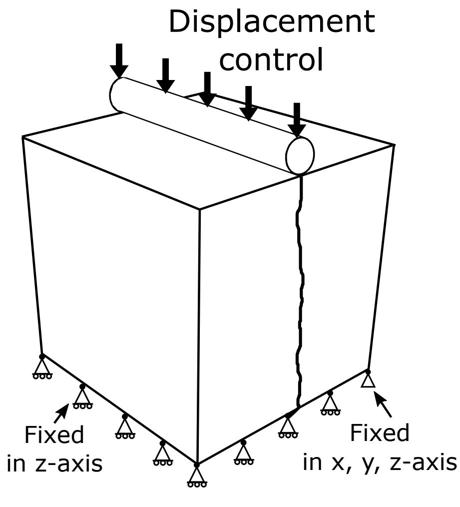

Figure 3: Schematic of boundary conditions.

5 RESULTS

The comparison results of the tensile strengths obtained from the splitting test experiment and the simulation are presented in Table 1. To ensure a close match between the average tensile strengths of the cement paste specimens obtained from the simulation and the experiment, the parameter ξ was adjusted. In the experiment, the average tensile strength of the cement paste was measured to be 6.54 MPa. After adjusting ξ, the simulation yielded an average tensile strength of 6.36 MPa, resulting in an error of approximately 3%. Applying the same parameter ξ to the slag blended cement paste resulted in the average tensile strength of 4.97 MPa. Comparing this value to the experimental measurement (5.86 MPa), a reduction of 15% was observed in the average tensile strength of the slag blended cement paste as obtained from the simulation. These results indicate that there is a difference in the comparison of tensile strengths from experiments and simulations for slag-blended cement paste.

Table 1: Comparison of tensile strength

	Tensile strength [MPa]	
	Experiment	Simulation
Cement paste	6.54	6.36
Slag blended cement paste	5.86	4.97

6 CONCLUSIONS

In this study, the multi-scale analysis framework proposed for tensile strength evaluation in previous studies was applied to cement paste with admixtures. In previous studies, the framework was used to evaluate the tensile strength of cement paste without admixtures. However, this study confirmed that the framework can accurately reflect the effect of admixtures on the microstructure of cement paste and its resulting tensile strength. The multi-scale framework obtains input parameters at lower scales and uses them for higher scale simulations, so that the properties and microstructure of the various phases comprising the cement material can be sufficiently considered. The tensile strength of the slag blended cement paste was found to be lower than that of the cement paste, primarily due to the consideration of phase properties and microstructure within the framework.

The phase properties and microstructure are changed by slag admixture, and the trend of tensile strength similar to the experiment is confirmed in the simulation. However, despite efforts to closely match the tensile strength of the experimental cement paste with that of the simulated paste, a discrepancy in the tensile strength of the slag blended cement paste is observed between the experiment and the simulation. This difference is due to the fact that the correlation between Young's modulus and LAC, which was obtained at a lower microscale to obtain the input parameters, did not take into account the effect of slag admixture. The correlation between Young's modulus and LAC of slag blended cement paste will be applied to this framework in future studies to verify the changes in tensile strength. This study confirms the feasibility of extending the multi-scale analysis framework of predicting tensile strength to cement paste with admixtures.

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