Abstract of Dissertation

論文の内容の要旨

title of dissertation

Enhanced Multi-scale Model and Simulation on Early Age Development of Blast Furnace Slag Concrete

（高炉スラグ微粉末を用いたコンクリートの
若材齢固体形成モデルの高度化）

Luan Yao

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欒 尧

Blast furnace slag (BFS) is now widely used as a supplementary cementitious material blended in Portland cement. As by-product from steel manufacturing, partial replacement of Portland cement by slag can reduce the energy consumption and CO_2 emission during production of Portland cement therefore is beneficial to circular economy and sustainable development. Meanwhile it is broadly agreed that concrete made with BFS concrete has many advantages, including improved workability, low permeability and higher strength at later age if the concrete is properly designed and cured, which is beneficial to performance of structure. However some disadvantages may exist for BFS concrete, such as early deterioration due to inappropriate curing, or larger drying and autogenous shrinkage, which tend to induce cracks in concrete thus decrease long time durability of concrete structures. Since those properties are different from those of Portland cement concrete, for better understanding and application of BFS concrete, it is necessary to model and predict its properties.

For life-time simulation of concrete structures, a computational system called DuCOM-COM3, which couples thermo-hygro-physical information of cementitious composites with multi-scale constitutive model, has been developed in Concrete Lab, the University of Tokyo. With this analytical system, various properties during the whole life of concrete such as shrinkage, creep, carbonation, and chloride ion penetration can be predicted. The whole system can be applied to concrete made by Portland cement and give good agreement with experiment. However whether it is applicable to BFS concrete has not been investigated and verified deeply. Therefore, in order to promote the application of BFS concrete and sustainable development of society, in this dissertation the research objective is to enhance the current multi-scale models in DuCOM-COM3 to simulate properties of BFS concrete properly. It is expected that after the enhancement of current models, micro-physical information of slag blended cement paste, such as hydration degree, porosity and pore size distribution, can be predicted reasonably. Meanwhile, based on the proper simulation of micro-physical information, micro-properties of BFS concrete, including strength, water loss behaviors, drying and autogenous shrinkage can also be simulated.

The main studies in this dissertation consists of three enhanced models for slag blended cement paste, i.e. enhanced hydration heat model, enhanced porosity model and enhanced pore size distribution model. The basic methodology includes three steps: first, analysis based on the original model is carried out and discrepancies are found. Second, the reasons for those discrepancies are investigated combining with micro-physical properties of slag cement paste. Then enhanced model is proposed based on the reasonable description of micro-physical properties. Finally, verifications by macro-properties of BFS concrete are conducted.

The multi-component hydration heat model which simulates hydration process of cementitious materials is applied to slag blended cement. Through comparison with experimental data, it is found that based on the original model the hydration degree of slag in blended cement is largely overestimated, and besides the effect of slag replacement ratio on hydration process cannot be reflected properly neither. Therefore hydration mechanism of slag is investigated again, considering the influence of calcium hydroxide as activator and chemo-physical properties of C-S-H gel produced by slag hydration. Since the Ca/Si ratio of C-S-H gel decreases as the slag replacement ratio increases, resulting in both higher tortuosity and negative electric charge accumulation in the pore structure, it is assumed that C-S-H gel produced by slag hydration has a strong influence on calcium hydroxide ions diffusion due to ion absorption and much longer diffusion path, therefore the subsequent hydration of slag tends to be retarded. On the basis of the above assumption, an enhanced model for slag hydration is proposed, taking into account the resistance effect which mainly depends on the slag replacement ratio and thickness of C-S-H layer. The enhanced model is applied again to simulation on slag hydration in blended cement, and the results indicate good agreement with experiment. Besides, amount of calcium hydroxide in the paste and adiabatic temperature rise of slag blended cement can also be simulated agreeably.

Second, an enhanced porosity model which is based on micro-chemo-physical approach is applied to modeling compressive strength of BFS concrete. In previous microstructure model, constant porosity value of C-S-H gel particle is assumed for Portland cement concrete. However, through investigation on micro-pore structure of BFS concrete, a porosity evolution associated with C/S ratio is proposed for C-S-H gel grains, which is supported by several microscopic experiments. In the improved gel porosity model, C-S-H gel grains formed from slag hydration has low porosity at low hydration degree, while much higher when hydration of slag goes on. Therefore, much more capillary space will be filled at later age. Combined with strength model based on capillary porosity, it can be obtained in the analysis that compressive strength of BFS concrete is lower than OPC at early age but higher later, which agrees with experiments by previous researchers.

Furthermore, pore size distribution model for BFS concrete was also modified. Analyses based on previous model are conducted and the disagreement with experiments of moisture loss and shrinkage are pointed out. Pore size distribution of BFS blended cement matrix which is considered as the reason for the disagreement is discussed. Then enhanced specific surface area model for hydration product of BFS blended cement is proposed and thus finer pore structure at later age compared with OPC can be obtained with the enhanced model, which is verified by water desorption isotherm. Finally, verification on moisture loss and shrinkage properties of BFS concrete is carried on based on the enhanced model, indicating the validity of enhancement.