論 文 の 内 容 の 要 旨

A Multi-scale Study on Stress Development and Pore Structure of Contemporary Expansive Concrete

（膨張コンクリートの応力進展および空隙構造に関するマルチスケール研究）

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The initiation and propagation of unexpected early-age cracking in concrete will lead to rapid deterioration of the concrete structures, which closely associates with the penetration of aggressive substances and the corrosion of steel bars. These cracks reduce the margin of safety and also, jeopardize the durability performance of concrete structures in a long term. Due to its vast significance in engineering, related researches have been widely conducted since last century. To mitigate cracking, expansive additives have generally been used to compensate the shrinkage at early age. However, even though various expansive additives and supplementary cementitious materials (SCMs) have witnessed certain advancements during these years, the problems of early-age cracking are still not fully solved. Especially, it was found on site that the commonly-used calcium sulfoaluminate type additive (CSA) cannot compensate the rapid development of shrinkage during high temperature conditions and cracking was difficult to be controlled under such situation. The addition of fly ash or slag was also found to exert only limited effect on compensating the shrinkage stress. The complexity of these problems is not only related to the physical properties of concrete itself but, is also closely related to the temperature conditions and restraint degrees of the structures. And thus, the empirical method for mix design is not always effective, due to the variation of temperature and restraint conditions in different structures. In the contemporary era, how to design mix proportions using expansive additives remains a critical task for both researchers and engineers. To address such a problem, it requires a systematic evaluation method to quantify the deformation and stress development of concrete materials under varied temperature conditions and restraint degrees.

The first objective of this study is to experimentally evaluate and compare the cracking

performances of OPC concrete and expansive concrete. It highlights the importance of a reliable and effective testing device. The experimental device named temperature stress testing machine has been regarded as one of the most effective and powerful tools. The UTokyo TSTM was originally constructed by Lin (Lin, 2006) in our research lab, which revealed accurate, reliable and reproducible performances. In my current study, some of the features have been updated on this device. Systematic experiments on early-age deformation and stress development of OPC, CSA and MgO concrete have been conducted using TSTM. It is confirmed in the experiments that CSA concrete fails to compensate rapid shrinkage stress effectively under high temperature and full restraint condition, while its hybrid use with lightweight aggregate indicates excellent cracking performance (Firstly discovered by Lin (Lin, 2006)). Apart from CSA, MgO is a relatively new type of expansive additive, which has been used for many dam structures in China. But the stress-related performance and in-depth understanding regarding mechanism of expansion is still strongly required. It was found from this study that MgO concrete can offer prolonged expansion due to the less water dependency for complete hydration. The Type-II MgO can effectively compensate shrinkage stress even under high temperature condition. Also, this study shows for the first time that MgO concrete has better resistance to drying stress than CSA concrete under wetting/drying cycles. Plausible mechanisms can be attributed to the retarded expansion due to less water dependency and the finer pore structure which slows down the water evaporation from pores. Experimental results from nitrogen adsorption-desorption (NAD) tests and mercury intrusion porosimetry (MIP) show that MgO concrete has finer pore structure and more bottle neck pores, thus hindering moisture movement during drying. The experiment results offer us valuable insights on the application of expansive concrete in realistic construction site.

The second objective of the current study is to establish a multi-scale analytical model to quantify the deformation and stress development of concrete materials. It can provide valuable guidance information for mix design in practice. In order to achieve this goal, the microscopic mechanisms related to the effectiveness of expansion should be unfolded. It is found that expansion is closely linked with the pore structure and the moisture state inside these pores. The coupled thermo-hygro-mechanical process is simulated using a similar logic as DuCOM model (Maekawa, Ishida and Kishi, 2009). A new concept to interpret and model the expansion for CSA concrete is proposed. It is considered that the rapid drop of free water availability leads to ineffective expansion of CSA concrete, while a combined use with lightweight aggregate can solve this problem because of internal curing effect. By a coupled thermo-hygro-mechanical computation scheme, the free water availability in pores (nanometer scale) for CSA concrete with/without lightweight aggregate could be quantified reasonably, which can be further upscaled to model expansion and stress development at larger scale. To better elucidate how pore structure may affect the water availability, an innovative pore structure based on the combined effect between densification and volume expansion has been put forward. The proposed pore structure model attempts to link some of the conventional understandings ((Feldman and Sereda, 1970; Jennings, 2008a; Maekawa, Ishida and Kishi, 2009)) with innovative interpretations from ^{1}H-NMR technique. The purpose of this proposal is also to better clarify the role of each category of pores and offer clearer insights on the behavior of moisture movement inside these pores.

In conclusion, this study comprehensively investigates the deformation and stress development of OPC, CSA and MgO concrete using TSTM. It offers us valuable information on their cracking performances under varied temperature and restraint conditions during early age. The stress development of CSA and MgO concrete under wetting/drying cycles are also examined and compared. The pore structures of OPC, CSA and MgO cement pastes are studied by MIP and NAD. Additionally, a pore structure model for both OPC and CSA is proposed and implemented into the coupled thermo-hygro-mechanical model. A new nanostructure is established on basis of conclusions from a series of ^{1}H-NMR studies, which highlights the role of "gateway" gel pores and interlocked inter-hydrate pores for water exchange behavior.