Analysis of Concrete Shrinkage Coupling with Properties of Aggregate

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1. Introduction

It is well known that aggregate properties strongly affect the time-dependent mechanical properties of concrete, such as shrinkage and creep. Recently, it was reported that concrete used in a prestressed reinforced concrete (PRC) bridge in Japan had exhibited significantly large shrinkage and lead to severe cracking of RC member surfaces In this case, aggregate properties were considered as one of the reasons for the serious damage to the bridge[1]. The dominant aggregate properties to extremely increase concrete shrinkage, however, had been unclear. It is important to study the contribution of each aggregate property that affects concrete shrinkage and to develop a model that simulates the correlative phenomena comprehensively. In this paper, the authors quantitatively investigates the influences of aggregate properties such as water absorption, Young's modulus and aggregate shrinkage on concrete shrinkage using a multi-scale constitutive model.

2. General scheme of multi-scale constitutive model and sensitivity analysis for shrinkage of concrete with different types of aggregate

In the multi-scale constitutive model, concrete is idealized as a two-phase composite with aggregate and hardening cement paste. The aggregates are modeled as elastic particles with a stiffness determined by their density, while the hardening of cement paste is expressed by the progressive formation of finite fictitious clusters as hydration proceeds based on solidification theory[2]. The mechanical behavior and number of a fictitious cluster are associated with the thermodynamic information obtained from a thermodynamics-oriented system named *DuCOM*[3]. Both volumetric and deviatoric terms of stress and strain are computed, taking into account interactions between aggregate particles and the cement paste matrix. Figure 1 represents an overview of the model.

The above model is used to study the concrete used in the actual structure having severe cracking. The shrinkage tests of concretes with different aggregates were carried out by JSCE concrete committee[1] and the mix proportion is shown in Table 1. Since it was reported that small Young's modulus is one of reason to increase the shrinkage[1], sensitive analysis was conducted by varying aggregate Young's modulus and compared with experiment. As shown in Figure 2, the model simulates shrinkage of the Mix B concrete having the normal aggregate reasonably, considering water absorption and aggregate Young's modulus estimated by its density. The shrinkage of Mix A concrete with aggregate causing extremely large concrete shrinkage cannot be expressed in consideration of water absorption and the estimated Young's modulus but be simulated when the aggregate Young's modulus is decreased to 1.0

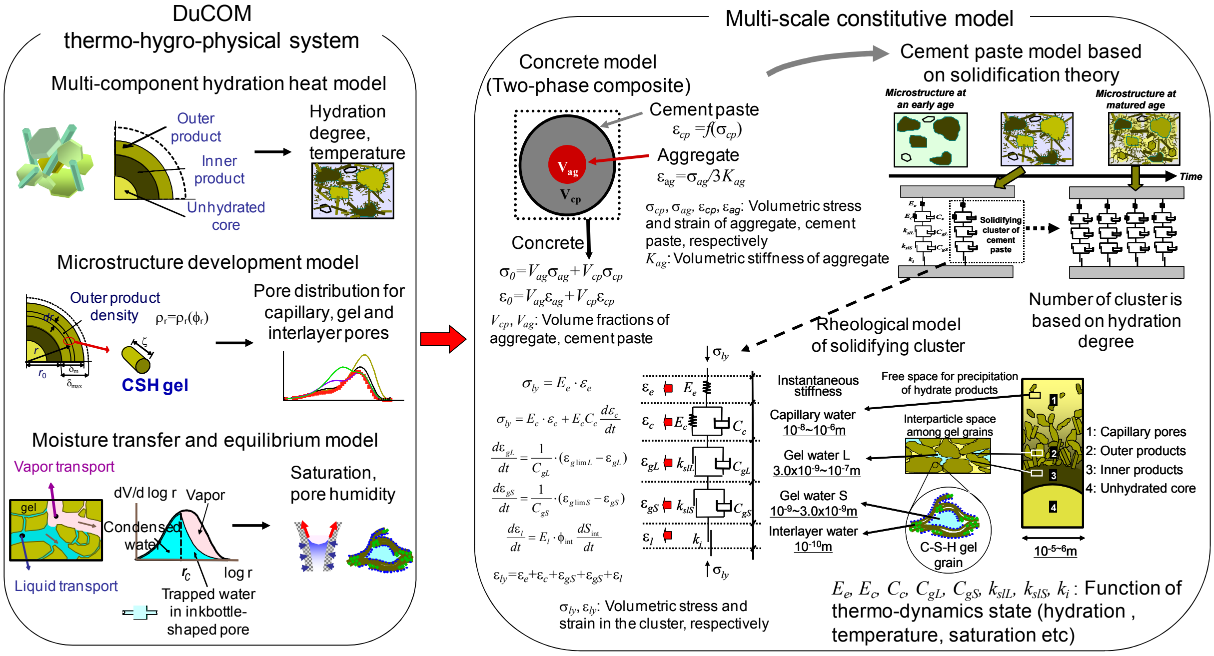

Figure 1 Multi-scale constitutive model[4,5]

GPa. Such an extremely low stiffness, however, is only likely to be found in special aggregate such as artificial lightweight aggregate. Thus, it is suggested that the larger concrete shrinkage may be caused not by the low Young's modulus of the aggregate but by other aggregate properties.

Table 1 Mix proportions in committee test (kg/m^3) [1]

	Water	Cement	Sand 1		Sand 2		Gravel	
Mix A	172	453	482	S1	119	S2	1053	G1
Mix B	172	453	544	S3	61	S4	1065	G2

S1, S2: similar sand to that used in PRC bridge concrete
S3, S4: normal sand
G1: similar gravel to that used in PRC bridge concrete
G2: normal gravel

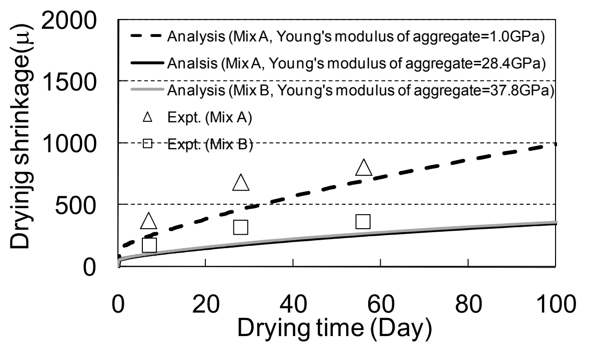

Figure 2 Computed results of shrinkage with aggregates of varying Young's modulus

3. Numerical analysis considering aggregate shrinkage

Through the above investigation, the aggregate shrinkage is taken into account for explaining extremely large concrete shrinkage due to aggregate. The shrinkage strain is added to the volumetric strain of the aggregate arising from the volumetric stress. The drying shrinkage of aggregate is likely to be dependent on moisture states in the aggregate pores based on mechanisms such as capillary pressure and also on the increase in solid surface energy as well as in the concrete. Based on aggregate volumetric change results by Goto and Fujiwara[6], a simple aggregate shrinkage model depending on saturation degree of the aggregate computed in *DuCOM*[3] was proposed and implemented. The maximum aggregate shrinkage is determined by the linear relationship between maximum aggregate shrinkage strain and specific aggregate surface area proposed by Goto and Fujiwara[6]. The constitutive law of aggregate is summarized in Figure 3.

The shrinkage of the concrete with Mix A was simulated once again using the proposed aggregate shrinkage model. The maximum drying shrinkage $\varepsilon_{agmax}{}^{sh}$ is likely to be extremely large so it was set at 1400μ, the largest value of maximum shrinkage reported in previous

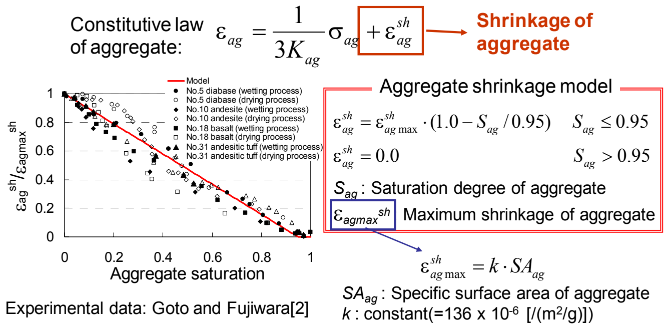

Figure 3 Constitutive law of aggregate

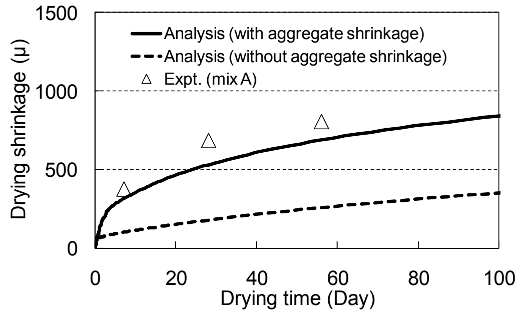

Figure 4 Computed results considering aggregate shrinkage

research[6]. The average elastic modulus of the aggregate was assumed to have the value of 28.4 GPa. As shown in Figure 4, the extremely larger drying shrinkage is reasonably computed when simulated in consideration of aggregate shrinkage.

4. Conclusion

In this paper, the influence of aggregate properties on concrete shrinkage was studied using the multi-scale constitutive model. The sensitivity analysis of concrete shrinkage by varying aggregate Young's modulus indicated that it is not possible to explain the significant increase in concrete shrinkage observed with specific aggregate only in terms of the low elastic modulus of the aggregate. Based on earlier pioneering research, an aggregate shrinkage model was proposed and implemented in the model. This demonstrated that the significant increase in concrete shrinkage can be calculated when aggregate shrinkage is taken into account.

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NOTE

This paper is also published in English in Journal of advanced concrete technology. If you are interested, further details can be found in Asamoto, S., Ishida T. and Maekawa, K. (2008). "Investigations into Volumetric Stability of Aggregates and Shrinkage of Concrete as a composite." *Journal of Advanced Concrete Technology*, 6 (1) pp.77-90.