# AN ENHANCED MODEL FOR SHRINKAGE BEHAVIOR BASED ON EARLY AGE HYDRATION AND MOISTURE STATE IN PORE STRUCTURE

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Drying shrinkage, which has long been a subject of study, occurs when concrete is exposed to a low relative humidity (RH). Shrinkage is also an issue in concrete with a low water/cement (w/c) ratio, which is now being widely used. Although a low w/c results in high strength and low permeability, it has been found that autogenous shrinkage becomes non-negligible. Any shrinkage would induce tensile stress, which can cause cracking and undermine the long-term performance of a structure. To evaluate and predict the influence of shrinkage, empirical formulas have been suggested in previous studies. From another standpoint, shrinkage behavior is associated with microscale thermodynamic properties, such as hydration, pore-structure formation, and the behavior of water in micropores. These properties vary according to the raw materials, mix proportion, age, and ambient conditions of the concrete. Without substantially grasping the relationships among the effects of these properties, it is difficult to provide an appropriate evaluation of shrinkage under arbitrary conditions. Therefore, it is important to establish a model that couples shrinkage behavior with microscale properties.

In a previous study, a multi-scale model for shrinkage behavior was developed by the Concrete Laboratory at the University of Tokyo. In this model, the hydration process, pore-structure formation, moisture equilibrium and transport were simultaneously coupled to explain the state of water in the micropores (Fig. 1 and Fig. 2). The forces driving shrinkage, consisting of capillary tension and surface energy change, were quantified from this understanding of the water state (Fig. 3) and were applied to the cement matrix. In addition, a two-phase stiffness model was established to describe the deformation response. Taking the mix proportion, specimen dimensions, and ambient conditions as inputs, the multi-scale model is theoretically capable of simulating autogenous or drying shrinkage simply by setting

the boundary conditions as sealed or exposed. Although this model has proven to be effective in past verifications, there remain discrepancies from test results. For example, the model greatly underestimates the rapid development of autogenous shrinkage in concrete with a low w/c, as indicated by the arrows in Fig. 4. For practical application, an improvement in precision is desired.
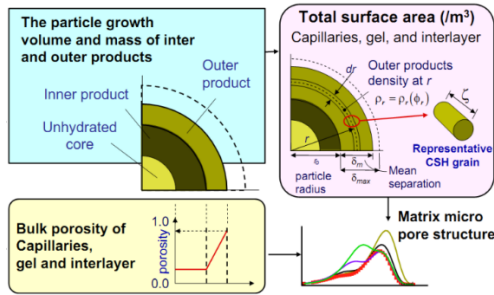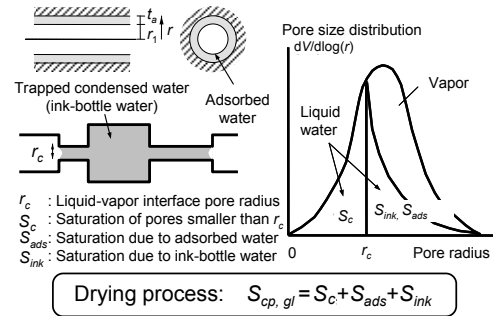


Fig. 1 Pore structure formation



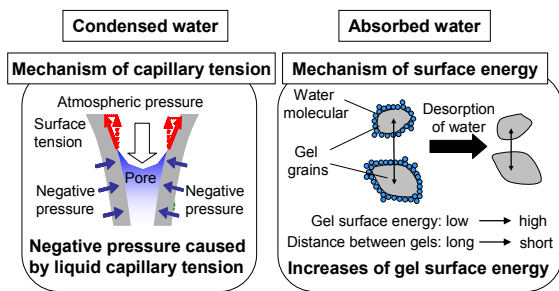Fig. 2 Moisture state in pore structure



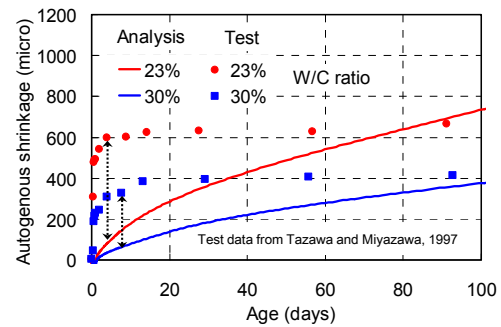Fig. 3 Driving forces in existing model.



Fig. 4 Analysis of autogenous shrinkage

In this paper, the authors further investigate shrinkage on the basis of microscale phenomena, leading to a proposal for an enhanced model of shrinkage behavior. The enhancement work focuses on initial autogenous shrinkage and the intrinsic driving forces behind shrinkage at the microscale. Since the existing model underestimates the rapid development of autogenous shrinkage in concrete with a low w/c, combined with self-desiccation, autogenous shrinkage at an early age is first discussed.

The reason for the discrepancy in the existing model is thought to be that, during early self-desiccation, the large degree of deformation cannot be effectively simulated because the skeleton of the cement paste has not completely formed. Hence, the authors discuss the influence of w/c based on a microscale hypothesis (Fig. 5). Initially, the cement particles are dispersed in water and their average spacing depends on the w/c. After initial setting, a portion of the total chemical shrinkage induces micropores, while the residual amount causes autogenous shrinkage. When w/c is high, the average distance between the cement particles is relatively large, so the particles hydrate independently. For a low w/c, the distance decreases and some particles even come into contact with each other. With self-desiccation taking place,

they may tend to move toward each other more significantly as local deformations join up or accumulate, resulting in a significant macro-volume change. Hence, an approximate model is proposed to quantify autogenous shrinkage at an early age based on its relationship with chemical shrinkage. As an approximation, the portion of chemical shrinkage contributing to autogenous shrinkage at an early age is quantitatively calculated from the chemical volume change and the distance between cement particles, and that amount of shrinkage is added to compensate for the underestimation in the existing model.
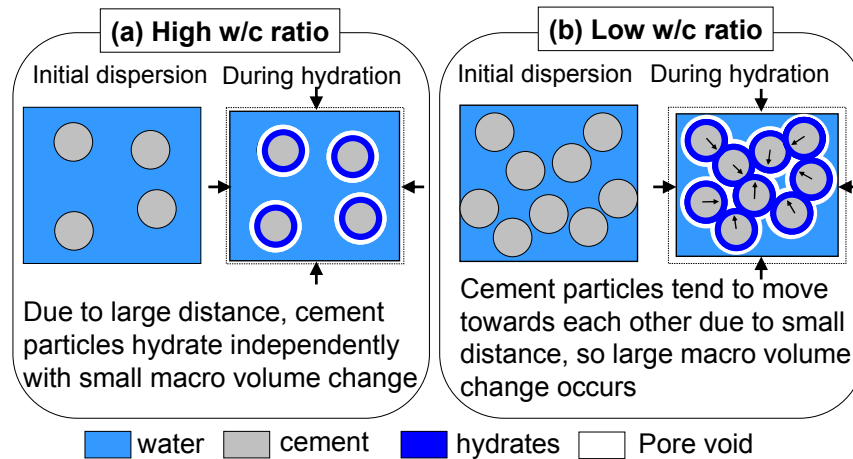


Fig. 5 Influence of chemical shrinkage on macro-volume change as result of inter-particle distance

Furthermore, the driving forces for shrinkage are also discussed and modified in this study. In the existing model, capillary tension was assumed to be the principal driving force in all pores of various sizes, but this would cause an overestimation of the long-term shrinkage in the analysis. Most capillary pores are microscale in reality. Therefore, it is reasonable to assume that capillary tension is active. Conversely, for gel pores at the nanometer scale, capillary tension may not be the dominant mechanism. Evidence for this is that, in fine pores, physically absorbed water occupies a larger portion. Thus, there is a decline in the capillary tension, which is related to the lower proportion of condensed water. It has been pointed out in past research that, in nanometer pores, capillary tension is much smaller than the value calculated by the Kelvin equation. Additionally, in fine pores, the water flow may no longer be continuous. Water is confined by the nanospace and becomes a unit with only some tens of molecules. Thus, water movement may be discrete and closer particle movement. This means that it is more reasonable to treat the driving force in nanopores separately from capillary tension. Therefore, the authors consider the dominant driving force in nanometer-scale pores to be disjoining pressure rather than capillary tension. That driving force is only active at low RH values, and does not contribute significantly to autogenous or drying shrinkage at relatively high RH values.

According to the above discussion, the forces driving shrinkage resulting from capillary tension and disjoining pressure are separated and quantified independently in the enhanced model (Fig. 6). Capillary tension is assumed to be active only in relatively coarse pores, whereas disjoining pressure dominates in

fine pores on the nanoscale. A boundary pore radius $r_{br}$, which is assumed to be 10 nm, is set as the separator between capillary tension and disjoining pressure. These two driving forces are quantified from the water state in the pores using proposed formulas.
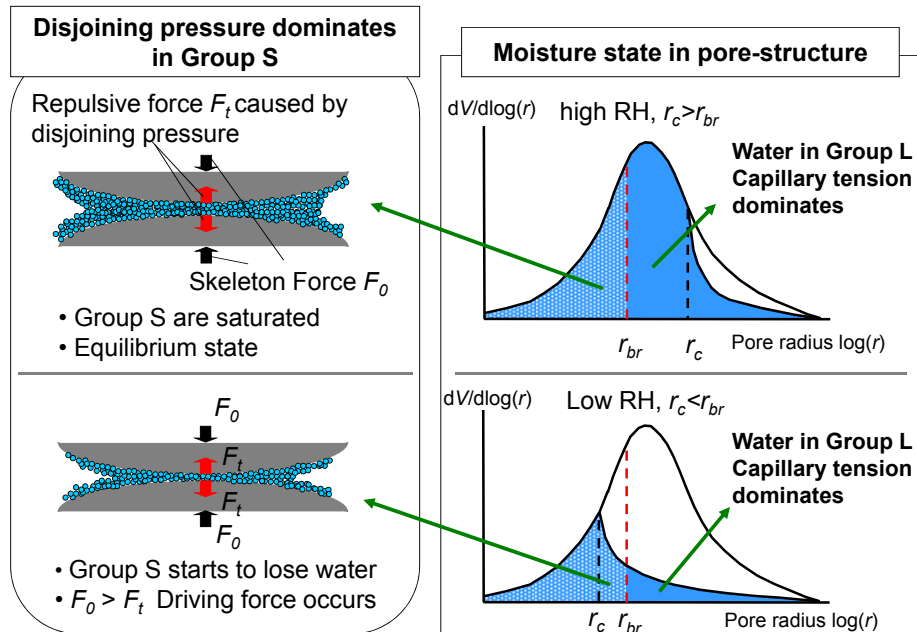


**Fig. 6** Driving forces in pores with different sizes

The autogenous shrinkage shown in Fig. 4 is recalculated using the enhanced model (Fig. 7). In this analysis, it can be seen that shrinkage strains increase rapidly in the initial days of curing before rising more gradually as time passes. These results agree better with the test results than the existing model. Shrinkage amounts under drying conditions for various w/c are also calculated (Fig. 8). The results are in clear agreement with the test results, with the reduced shrinkage at lower values of w/c well modeled. Further, the results of analysis using the existing and enhanced models for a normal w/c (50%) are compared (Fig. 9). Here, whereas analysis with the existing model underestimates shrinkage for the first tens of days (though the final value is satisfactory), the enhanced model is consistent with the test results over the whole drying period.
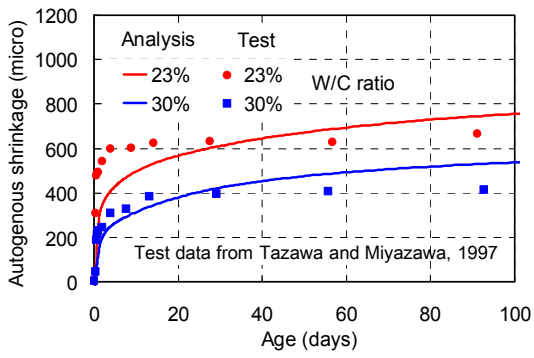
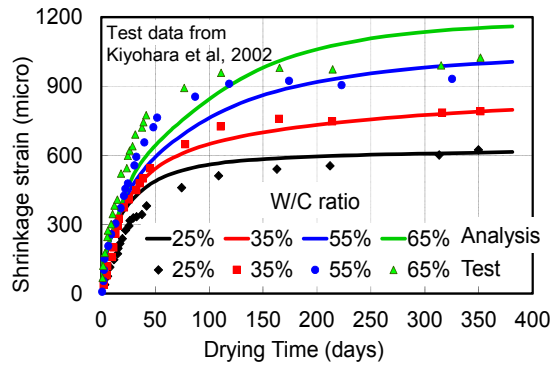Fig. 7 Analysis of autogenous shrinkage with enhanced model



Fig. 8 Analysis of shrinkage behavior under drying conditions with enhanced model
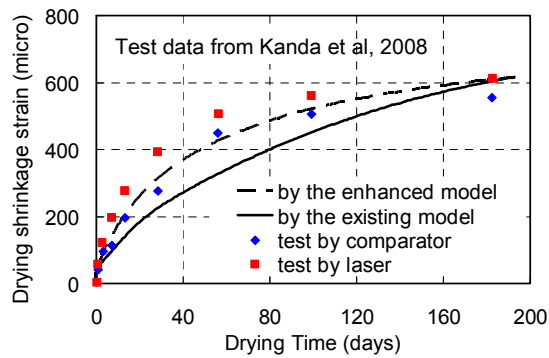


Fig. 9 Comparison of drying shrinkage precision between existing model and enhanced model