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Capillary tension theory for prediction of early autogenous shrinkage of self-consolidating concrete

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HIGHLIGHTS

- We establish a prediction method of early autogenous shrinkage of self-consolidating concrete.
- The computational model of the autogenous shrinkage was determined by capillary tension theory and microstructure pore.
- We study the evolution laws of pores distribution of the self-consolidating concrete with various mix designs.
- The development of compressive strength and elastic modulus of self-consolidating concrete at various ages.

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ABSTRACT

Based on the capillary tension theory and microstructure pore of concrete, a prediction method of early autogenous shrinkage of self-consolidating concrete (SCC) was established. Self-consolidating concrete (SCC) specimens with different strength grades were prepared. The physical and mechanical properties (autogenous shrinkage, Poisson's ratio, modulus of elasticity and compressive strength) of SCC with different strength grades were tested at the age of 3, 7, and 28 days. The 3, 7 and 28 days pore distribution of capillary pores of SCC with different strength grades were also tested. Negative pressure of capillary and autogenous shrinkage were determined by means of capillary tension theory. Finally, based on the calculation results, a prediction method of early autogenous shrinkage of SCC was established. The results show that predicted values derived from this model matched very well with measured values.

1. Introduction

With the widespread use of SCC in civil engineering, the presence of cracking and shrinkage at early age have been issues which have gotten more and more attention in the fields of materials and engineering. In fact, cracks of structures are primarily caused by deformations which are usually related to temperature, shrinkage and differential settlements, while only a small number are caused by imposed loads. This can explain the main reason why so many structures have different cracks during the construction period, and some cracks even appearing during curing period. Autogenous shrinkage is defined as a concrete volume change during the process of hydration which is under conditions of constant temperature and constant weight. It is merely a result of the internal chemical and structural reactions of the concrete components. There are two main reasons of autogenous shrinkage: low water to binder (W/B) ratio and a large number of active mineral admixture [1–3]. It has been found that, with the decrease of W/B ratio and the increase of active mineral admixture, the ratio of autogenous shrinkage to total shrinkage increases significantly. In this case, without appropriate treatment, cracks in concrete could easily appear at early age. Therefore, studies on early autogenous shrinkage of SCC have positive significance for crack resistance of concrete structures.

The previous studies were mainly concentrated on measurement method of autogenous shrinkage [4,5], factors [6,7] and formation mechanism [8,9]. However, few studies have investigated theoretical computational models of autogenous shrinkage of concrete. Scholars proposed several computational models based on theoretical and experimental studies. Microcosmic computational models include: Hua–Acker–Ehrlacher macroscopic model [10]: This model assumed that negative pressure of capillary action mainly led to autogenous shrinkage. Based on capillary tension theory and viscoelastic mechanics, autogenous shrinkage model of cement paste was established. However, the model has a certain limitation as it can only calculate one-dimensional deformation. Hua–Acker–Ehrlacher Microcosmic model [11]: The model assumed that unhydrated cement paste was a type of isotropic and linearly elastic material and hydration products were viscoelastic

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materials. The concept of stiffness tensor was introduced into the model, and the autogenous shrinkage process was interpreted from a micro perspective of hydrate particles. Experimental results verified the validity of the model.

Empirical equations which are derived from test results include: The Tazawa model [12]: Based on regression analysis for mineral composition of ordinary Portland cement, this model can predict autogenous shrinkage of cement paste, and the influence from aggregates was determined by the introduction of the Hobbs drying shrinkage model. However, in this model the influence from other admixtures of Portland cement has not been taken into account. The problem that autogenous shrinkage and drying shrinkage change nonlinearly in certain part of concrete has not been taken into consideration either. Japanese Industrial Standard model [13]: In the case of concrete with a w/c ratio from 0.2 to 0.6, the autogenous shrinkage of concrete in the model could be calculated by factors including, cement type, hydration time, initial setting time, temperature and water-to-binder ratio. However, it has been found that the model has certain limitations: restrictions of steel bars and effects of other conditions have not been taken into account. In addition, the accuracy of correction factor needs to be improved. Thus the model has a relatively small application scope [14].

Thus, previous studies about prediction methods of autogenous shrinkage value based on micropore structure and capillary tension theory are insufficient. Existing studies indicates that, cement hydration leads to the change of pore structure of hardened cement paste and the decrease of inner relative humidity, which result in significant variation of capillary tensile stress. This is the main cause of augotenous shrinkage of concrete. In this work, the theory of the variation was explicitly investigated, mechanical and physical properties (autogenous shrinkage, Poisson's ratio, modulus of elasticity and compressive strength) were measured, and negative pressure of capillary and autogenous shrinkage were determined by means of capillary tension theory. Finally, based on the calculation results, a prediction method of early autogenous shrinkage of SCC was established. The results show that predicted values derived from this model matched very well with measured values.

2. Microcosmic mechanism of early autogenous shrinkage of SCC:

2.1. Elastic deformation of SCC

A concrete element is taken, and E is taken as the modulus of elasticity, μ is Poisson's ratio, and σ_x, σ_y, σ_z, ε_x, ε_y and ε_z, are the stresses and strains in X, Y, Z direction, respectively, as shown in Fig. 1.

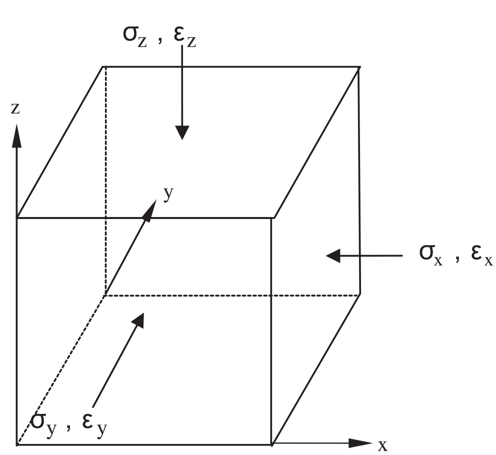

Fig. 1. Geometry of SCC element in a specimen for a triaxial state of stress.

Based on mechanics of materials, the volumetric strain is expressed as:

$$\theta = \varepsilon_x + \varepsilon_y + \varepsilon_z = \frac{1-2\mu}{E}(\sigma_x + \sigma_y + \sigma_z) \quad (1)$$

We assume that forces in all directions are equal, when concrete compacts. Thus, the linear strain of concrete in each direction is:

$$\varepsilon = \frac{1-2\mu}{E}\sigma \quad (2)$$

2.2. Calculation of negative pressure of capillary

Based on the Laplace equation, the pressure differential between liquid phase and gas phase is caused by meniscus of capillary water. Thus the pressure can be given by

$$\Delta p = \frac{2\gamma \cos\theta}{r} \quad (3)$$

where γ is the Surface tension on the inner walls of capillary, $\gamma = 7.28 \times 10^{-2}$ N/m (20 °C); θ is the contact angle on liquid–solid interface and r is the critical diameter of capillary pore

Because concrete is a hydrophilic material, contact angle on walls of capillary can be taken as 0°. Critical diameters of capillary pores at different curing ages are measured by mercury injection test.

3. Materials and experimental procedure

3.1. Raw materials

The cement used in this study is type I/II Portland cement. Supplementary cementitious materials are fly ash. The concrete mixtures are prepared with locally available aggregates: siliceous river sand and crushed limestone gravel. The specific gravity of sand is 2.7 g/cm^3, fineness modulus 2.8, and particle size distribution is from 0.16 to 5 mm. The specific gravity of gravel is 2.7 g/cm^3, crush index of 8.1%, and particle size distribution is continuous grading of 5–25 mm. The water reducer is polycarboxylate superplasticizer with water reduction rate 25–30%. The chemical and physical properties of cement and fly ash are given in Tables 1 and 2, respectively.

3.2. Experimental method

3.2.1. Measurement method of early autogenous shrinkage

By means of the high accuracy and high stability of potentiometric transducer LVDT, a measurement system for early autogenous shrinkage of concrete was designed and developed, as shown in Fig. 2. The dimension of concrete specimens is 100 mm × 100 mm × 515 mm. The measurement system includes: specimens, LVDT sensor, Patrol Metrics Monitor and automatic collection computer system. With the application of this testing device, multiple specimens were tested simultaneously or asynchronously. And the computer control system automatically collected and processed early data. The formworks were made from steel, and the bottom formworks were coated with sealing oil and two layers of polyvinylchloride films successively. After initial setting of concrete, both the two ends and the two sides of the formworks were dismantled. Specimens are then wrapped completely by plastic films, sealed by sealing ribbons, and a glass sheet attached on each end of specimen. After installing of the devices and connecting the computer, the system recorded the variation in concrete shrinkage rate with age. In this test, the system measured data beginning at the initial setting through the curing age of 28 days. After 28 day standard curing, autogenous shrinkage of concrete almost stablized. Because a thermocouple was pre-embedded in each specimen, the system deducted the effect of internal warming on concrete during data post-processing. The test was specific a certain condition (20 °C ± 2 °C, 60% ± 5% RH).

3.2.2. Compressive strength and modulus of elasticity. Compressive strength and modulus of elasticity were tested in accordance with ASTM-C39 [15] and ASTM-C469 [16], respectively.