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Modeling of volume changes of concrete mixed with expansive additives

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HIGHLIGHTS

- We modeled volume changes of concrete mixed with expansive additives.
- Shrinkage was modeled by considering the behavior of the moisture in pore.
- Expansion was modeled by considering the volume increase rate of hydrates.
- Volume changes modeled by considering a balance of cement and expansive additives.
- Volume changes of concrete could be estimated sufficiently by using a composite model.

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ABSTRACT

This study modeled volume changes of concrete mixed with expansive additives, a countermeasure to shrinkage. Volume changes of expansive paste are determined from the balance between the shrinkage of cement and the expansion of the additives. Therefore, in this study, volume changes were modeled by applying a balance to the hydrates of cement and the expansive additives. The shrinkage of cement was modeled by assuming that it is caused by capillary tension. This modeling was based on the behavior of the moisture inside the cement's pore structure, by taking into account the pore size distribution and the thermodynamic equilibrium state of the moisture. Using the concept of effective radius factor, the expansion of the expansive additives was modeled by considering the volume expansion of the additive particles caused by an increase in the outermost radius of particles of the hydration products that were formed at an early age. The values predicted by the model were consistent with the measured values, which confirms the model's validity. Furthermore, the volume changes of concrete were estimated with sufficient accuracy by analyzing the behavior of the paste using a composite model of aggregate and paste.

1. Introduction

When cement is used as the binder in a concrete structure, cracking will eventually occur due to the shrinkage of cement. The shrinkage of cement becomes a causative factor in the generation of cracks in a concrete structure because the shrinkage generates a tensile stress that confines the concrete. Because these cracks affect the concrete's safety, usability, durability, and appearance, it is important to prevent their formation to ensure the structure's longevity and required performance [1,2]. Given this background, application of expansive additives has been demonstrated to be an effective means of reducing shrinkage and increasing crack resistance; thus, their application to construction projects is gradually becoming popular [3,4].

In this study, we aimed to model the volume changes of concrete mixed with expansive additives, which is used as a countermeasure for reducing the shrinkage of cement, as shown in Fig. 1. The shrinkage of cement was modeled by considering the behavior of the cement's pore structure and the moisture inside the structure. The expansion of the expansive additives was modeled by considering the rate of volume increase of external hydration products under the influence of hydration. Furthermore, volume changes of hardened cement paste blended with expansive additives were modeled and validated using the balance rule of cement and expansive additives, according to which the volume changes of cement paste are determined from the balance between

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the modeled shrinkage of cement and the modeled expansion of expansive additives.

2. Modeling of shrinkage phenomenon

2.1. Modeling of pore structure

To model the shrinkage of cement, it is important to identify the distribution of pore diameter in the pore structure. However, because a detailed modeling of the pore structure is challenging, average features of the pore structure are generally used in the modeling. In this study, pore diameter distribution was modeled by referring to previous studies [5–7].

Fig. 2 shows the pore diameter distribution of hardened cement paste. On the basis of the previous studies [5–8], the cumulative pore volume was expressed by assuming that the cumulative pore distribution is linear, as expressed in Eq. (1).

$$V_{\leqslant\phi} = a \cdot \ln(\phi/\phi_0) \quad (1)$$

where ϕ is the capillary pore diameter (nm), $V_{\leqslant\phi}$ is the capillary pore volume of all pores with diameter $\leqslant\phi$ (mm^3/mm^3), and ϕ_0 is the minimum capillary pore diameter (2 nm [9]). a is a constant that represents an increase in the pore space with respect to pore diameter (mm^3/mm^3) and satisfies the following equation:

$$a = \frac{V_{\text{pore}}}{\ln(\phi_{\max}/\phi_0)} \quad (2)$$

To model the pore structure for a random age by applying Eq. (1), it is necessary to express V_{pore} and $\phi_{\max}$ as functions of hydration. To obtain $\phi_{\max}$, Maruyama assumed that the maximum pore diameter in the pore distribution is suitable for use as the threshold pore diameter. Moreover, by focusing on the high correlation between the representative pore radius r_{pore} and the radius of a hypothetical capillary pore that could be obtained from the Computational Cement Based Material (C-CBM) model [8] shown

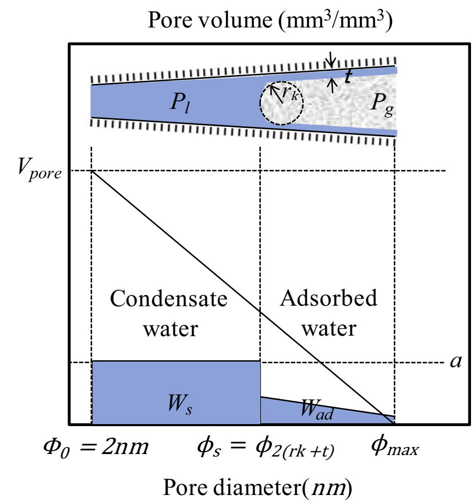

Fig. 2. Modeling of pore diameter distribution.

in Fig. 3, Maruyama applied a linear equation (Eq. (2)) derived from the experimental results of previous studies [10,11]. In the present study, $\phi_{\max}$ was obtained by applying Maruyama's linear equation to the relationship between the maximum pore diameter $\phi_{\max}$ and the representative pore radius r_{pore}:

$$\phi_{\max} = \exp(44.6 \cdot r_{\text{pore}} - 9.23) \quad (3)$$

In addition, V_{pore} can be acquired from the hydration reaction rate by using the volume increase rate V. For the cement volume that contributes to the reaction in the hydration reaction model, the volume increase rate V of cement is obtained by adding approximately 75% of the water volume in the total volume of

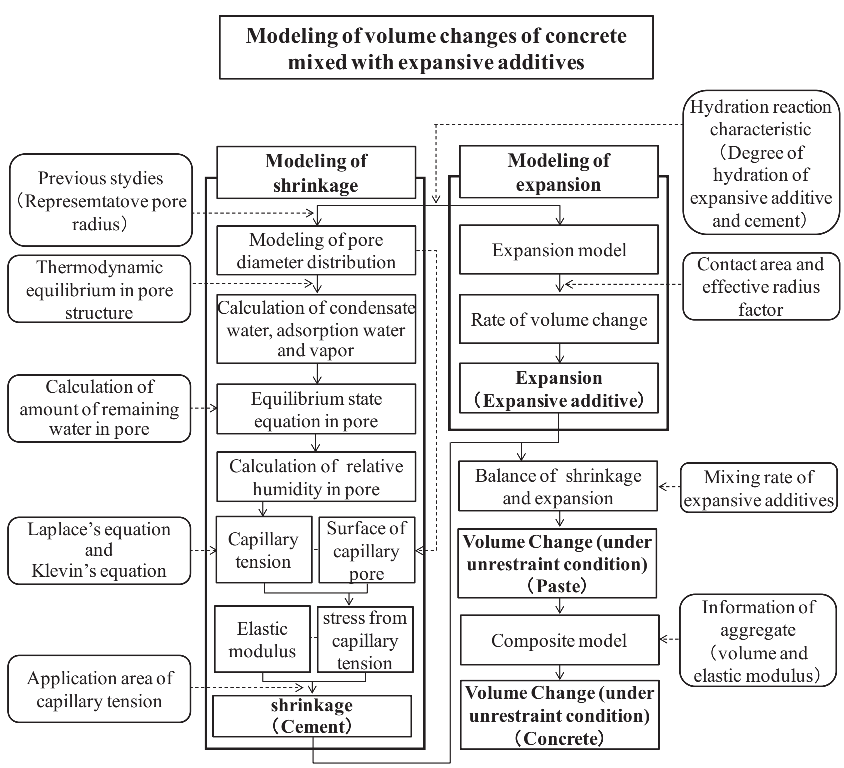

Fig. 1. Modeling of volume changes of concrete mixed with expansive additives.