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Prediction equation of drying shrinkage of concrete based on composite model

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Abstract

In this study, the prediction equation of drying shrinkage of concrete is obtained with two-phase composite model as aggregate and matrix. In order to obtain the input values for this prediction equation easily, the experimental formula of drying shrinkage and Young's modulus of cement paste are obtained, and the estimation method of Young's modulus of aggregate are proposed with easy test using cement paste, mortar and concrete. According to the experimental results, this equation can predict the drying shrinkage at any age in error by less than about 100 μm.

Keywords: Drying; Shrinkage; Prediction equation; Concrete; Elastic modulus

1. Introduction

The drying shrinkage of concrete is one of the main causes of the cracks generated in the RC structures. However, with regard to this point in the present concrete works, only the maximum value of the unit water content (185 kg/m^3) is specified in the JASS5, which is not considered to be sufficiently controlled. This is partly because of the lack of confirming the amount of drying shrinkage strain for the concrete used in an ordinary construction, as the drying shrinkage test (JIS A 1120) takes long time and many procedures.

As alternatives of the direct measuring by test, many researchers proposed prediction equations of drying shrinkage such as ones proposed by Bazant and Panula [1], by Branson [2] (ACI-209 equation), in CEB-FIP-70, 78, 90 equations. [3–5], and by Sakata [6]. These equations are practical in a sense that the drying shrinkage can be predicted from the figures written in mix proportion table, and are also useful for the preliminary study at the design stage because the external factors such as the relative humidity, and dimensions, shape of the member, or the age are considered. However, the accuracy of those predicted results are not very good and it is even reported to be around plus and minus 40% [7]. The reasons are considered to be that most of the prediction equations are empirical equations derived from the measured data which involves some errors generated in its statistical processing, and that those equations do not consider the effects of the material properties of which data is difficult to be obtained, in order to enhance its practicability.

Meantime, as a different approach from the above, many researchers proposed theoretical models in which the concrete or mortar was considered as two-phase material and its mechanism of drying shrinkage was derived from combination of the drying shrinkage of aggregate and that of matrix. The advantage of this approach is the clear rationale and the drying shrinkage strain can be accurately estimated by considering the impacts by the material properties only if necessary data were obtained. However, it is obviously distinguished from those practical and generic prediction equations in the following points. Those are that (1) three

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types of material including fine aggregate and coarse aggregate cannot be considered because of the assumption of two-phase material, that (2) it is not a type of equation to directly consider the external factors or the age, and that (3) the input values for the theoretical equation cannot be obtained easily.

The ultimate goal of this study is developing the complex model to a practical prediction equation. Within the scope of this paper, as the first step, the internal factors of the concrete, i.e., factors regarding the mix proportion or material properties, are taken, and a prediction equation of the drying shrinkage is proposed under the condition that the temperature, humidity, and the dimension or shape of the member are kept constant. This becomes the core of the prediction equation to which the external factors will be added in the future. For the development of the prediction equation, problem (1) described above is intended to be solved by applying the complex model stepwise, first to the mortar component in the concrete, and second to the concrete as a whole. For problem (2), a time-dependent prediction equation is proposed, and for problem (3), the method of measuring the factors of the prediction equation, such as the drying shrinkage strain of the cement paste or the Young's modulus of aggregate, is studied.

2. Estimation of drying shrinkage strain by stepwise application of complex model

2.1. Application method of complex model

As the complex models for drying shrinkage strain were proposed by Ohno [8], Pickett [9], Shiire [10], Hobbes [11], or Baba, the equation proposed by Kishitani and Baba [12], which the authors consider to give the most accurate answer, is used here:

$$\frac{\varepsilon_{sc}}{\varepsilon_{sm}} = \frac{[1-(1-mn)V_a][n+1-(n-1)V_a]}{n+1+(n-1)V_a} \quad (1)$$

where $n=E_a/E_m$, $m=\varepsilon_{sa}/\varepsilon_{sm}$, ε_s: drying shrinkage strain, E: Young's modulus (N/mm^2), V_a: aggregate volume ratio. The suffixes c, a, m, stand for the two-phase material, aggregate, matrix, respectively.

When the equation shown above is rewritten for the mortar component in the concrete (two-phase material consisting of fine aggregate and cement paste), and for the concrete (two-phase material consisting of coarse aggregate and mortar), the following equations (Eqs. (2), and (3), respectively) are derived.

$$\frac{\varepsilon_s(V'_s,0)}{\varepsilon_{sp}} = \frac{[1-(1-m_1n_1)V'_s][n_1+1-(n_1-1)V'_s]}{n_1+1+(n_1-1)V'_s} \quad (2)$$

$$\frac{\varepsilon_s(V'_s,V_g)}{\varepsilon_s(V'_s,0)} = \frac{[1-(1-m_2n_2)V_g][n_2+1-(n_2-1)V_g]}{n_2+1+(n_2-1)V_g} \quad (3)$$

where, $n_1=E_s/E_p$, $n_2=E_g/E\ (V'_s,0)$, $m_1=\varepsilon_{ss}/\varepsilon_{sp}$, $m_2=\varepsilon_{sg}/\varepsilon\ (V'_s,0)$, ε_s: drying shrinkage strain, E: Young's modulus (N/mm^2), V'_s: fine aggregate volume ratio (to the volume of mortar), V_g: coarse aggregate volume ratio (to the volume of concrete). The suffixes s, g, p stand for the fine aggregate, coarse aggregate, and cement paste, respectively.

In this study, Eq. (3) is applied to the concrete and the drying shrinkage strain $\varepsilon_s(V'_s,V_g)$ is predicted. At this time, the value of the factor $\varepsilon_s(V'_s,0)$ is estimated by applying Eq. (2) to the mortar component. This approach, the stepwise application of Eqs. (2) and (3), becomes the basis of the prediction equation to be proposed by the authors in Section 4 (these two equations together are called as the basic equation, hereinafter).

Fig. 1 shows the summary of the factors for the basic equation. Although these values have to be obtained in advance in order to predict the drying shrinkage strain, detail discussion will be made in Section 3 with regard to the drying shrinkage strain and the Young's modulus for the cement paste. The estimation method for the Young's modulus of the aggregate will be presented in Section 5.

2.2. Outline of verification experiment

In order to verify the reasonableness of the stepwise application of the complex model, an experiment was conducted by taking a concrete sample under the condition of the drying shrinkage test in accordance with JIS A 1129 (temperature of 20 °C, humidity of 60%, and specimen size of 10×10×40 cm), as an object for prediction.

2.2.1. Drying shrinkage test

In order to obtain data for verification of the basic equation, the drying shrinkage strain was measured for the concrete specimens (series I) and the mortar specimens (series II). The experimental parameters were the water–cement ratio at three levels, 30%, 45%, and 60%, and the aggregate volume ratio at five levels, in a range between 0 and 0.5, as shown in Table 1. It was executed in accordance with JIS A 1129 (dial gauge method) as shown in Table 2, and the size of specimens were 10×10×40 cm for the concrete and 4×4×16 cm for the mortar.

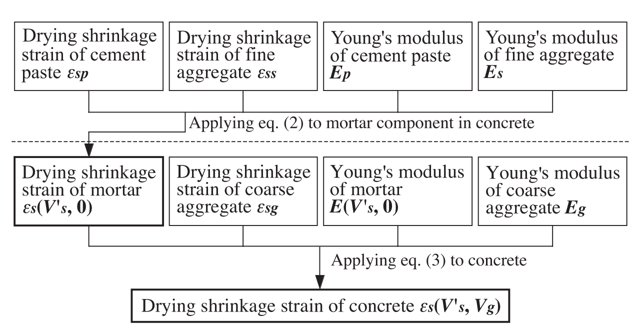

Fig. 1. Flow chart of prediction of drying shrinkage strain for concrete.