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Predicting concrete coefficient of thermal expansion with an improved micromechanical model

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HIGHLIGHTS

- An improved micromechanical prediction model for the CTE of cement concrete.
- Model validated by a hierarchical approach (cement paste–mortar–concrete).
- The improved model provided better prediction on concrete CTE.
- Aggregate type was found to be the most important factor affecting concrete CTE.
- Finer aggregate gradation increased CTE; whereas, *w*/*c* had little impacts.

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ABSTRACT

The coefficient of thermal expansion (CTE) is a very important property of cement concrete. Concrete CTE represents the thermal expansion and/or contraction sensitivity of concrete, which highly relates to thermal cracks in concrete infrastructures, such as concrete dams and concrete pavements. The values of concrete CTE can be measured through laboratory testing or predicted using empirical models. While laboratory testing is time- and labor-consuming, the current concrete CTE prediction models are mainly based on empirical relationships. In this study, an improved micromechanical model was proposed to predict concrete CTE based on thermal mechanical analysis in which concrete was seen as a composite material. The original model developed by the authors can be found elsewhere. The improved CTE model was validated using a hierarchical approach with CTE measurements of cement paste, mortar, and concrete. The result indicates that the improved model was able to provide a better prediction on CTE values than the original model. Factors affecting concrete CTE were investigated utilizing the developed CTE prediction model. It was found that aggregate type was a major factor affecting concrete CTE, whereas water cement ratio did not have a significant effect on concrete CTE.

1. Introduction

1.1. Research background

When excessive temperature differences occur in a concrete structure or its surroundings, the disequilibrium of the potential volumetric changes inside the structure, when restrained, introduces internal tensile stresses. When these tensile stresses exceed the in-place concrete tensile strength, thermal cracks occur. The hairline thermal cracks could not be easily found and may not affect concrete performance immediately. However, thermal cracks could be a durability problem for concrete infrastructures. Through these cracks, moisture and ions such as chloride and sulfate can evade into concrete. Sulfate attack (if exists) [1–3], chloride attack (if exists) [4,5], and freeze–thaw phenomenon [6] significantly accelerate the deterioration of concrete. In general, thermal cracks shorten the service life of concrete infrastructures, decrease the serviceability, and increase the maintenance cost.

The thermal expansion sensitivity of concrete can be reflected by its basic characteristic, the coefficient of thermal expansion (CTE). CTE, defined as the rate at which concrete contracts or expands as temperature changes, affects thermal cracking development in concrete. Ceylan et al. [7] found concrete CTE significantly

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influences faulting, transverse cracking, and international roughness index (IRI) of concrete pavement. Numerous studies investigated the CTE of Portland cement concrete (PCC) and its impact on concrete infrastructures was found to be significant [8–11].

It has been reported that concrete CTE depends upon many factors, such as the CTE values of raw materials, aggregate type [9,10,12,13], moisture [13–16], age [13,14,17], and other factors.

There are two major approaches to obtain concrete CTE, i.e., laboratory tests and prediction models. Currently, AASHTO T336-09 [18] is adopted for measuring the concrete CTE by the transportation professionals in the United States. In the test, a saturated concrete specimen is placed vertically in a water bath. The change in the specimen length caused by temperature change is measured to calculate CTE. Nevertheless, it was found that the test results are greatly influenced by the accuracy and stability of the length changes at low and high temperature boundaries [19]. Other CTE test methods were also proposed but received less attention, such as CRD-C 39-81 [20], sealed beam-air heating method [15], fiber optic sensors [21,22], vibrating wire extensometer method [23]. On the other hand, some concrete CTE prediction models were developed by researchers, as shown in Table 1. Variables included in these models were also listed. It is noted that most of the existing concrete CTE prediction models are based on the rule-of-mixtures, i.e., concrete CTE is the weighted average of its components' CTEs.

Laboratory testing for concrete CTE [18] requires expensive apparatus and is time-consuming. Furthermore, different laboratory tests usually provide different concrete CTE values due to the variations in testing conditions. On the other hand, the prediction models in Table 1 empirically evaluate concrete CTE values from physical and mechanical parameters based on the-rule-of mixtures [13,25,26]. However, the mechanism of the thermal expansion of concrete was barely investigated in these models from a view of micromechanics. Additionally, an important factor, aggregate gradation, has never been considered in these models to show its effect on concrete CTE.

2. Objective and Scope

This paper is a continuation of a previous work by Zhou et al. [26]. Although the micromechanical model [26] can give a reasonable prediction on concrete CTE values, generally 17–20% lower than the measured ones, considering its significant effects on concrete performance [7–10,27,28], it would be meaningful if the model can be improved for more accurate prediction on concrete CTE. The objective of this study is to improve the micromechanics-based concrete CTE model proposed by Zhou et al. [26]. Thermal stress/strain analysis was performed according to a physical model consisting of aggregate and cement paste. An improved micromechanical model was developed for predicting concrete CTE with aggregate gradations considered. The improved CTE model was validated through a hierarchical approach utilizing CTE values of cement mortar and cement concrete from laboratory tests. Major factors affecting concrete CTE were also investigated. Compared to Zhou et al. [26], this paper adopted a more precise calculation on concrete stiffness and a new and practical assumption for calculation of concrete CTE. Also, a hierarchical approach was employed for the validation of the CTE micromechanical model. These improvements led to a more accurate and reliable model on prediction of concrete CTE.

3. CTE Model Development

Particulate filled composite theory recently has been adopted in analyzing properties of pavement materials, especially asphalt materials, such as dynamic shear modulus [29,30] and stiffening mechanisms [31] of asphalt mastic, volumetric coefficient [32], elastic modulus [33–35], tensile and resilient modulus [36], shear modulus [37], dynamic modulus [38–44], creep behavior [45]. Similar to asphalt concrete, hardened cement concrete consists of aggregate particles and hydrated products of cement paste, which can be treated as a particulate filled composite material. Equivalent concrete medium is assumed to encircle such particulate filled composite material as shown in Fig. 1. Macroscopically, it can be seen as a homogenous material. The sketch of an aggregate–cement paste-equivalent concrete medium is shown in Fig. 2. Cement concrete and its components are assumed to be linear elastic. E_i, υ_i, and $\propto_i$ are Young's modulus, Poisson's ratio, and CTE value, respectively ($i = 0$ equivalent concrete; $i = 1$ aggregate; $i = 2$ cement paste). Aggregate particles are assumed to be spherical in shape. As shown in Fig. 2, an aggregate particle with a radius a is coated with cement paste b–a thick, which is further embedded in an equivalent concrete medium c–b thick. The Poisson's ratio of concrete is quite stable, independent of temperature and moisture [46]. A constant value of 0.20 was used.

When a temperature change ΔT occurred, the stress–strain relationship inside the composite (Fig. 2) was investigated [26] and shown in Eqs. (1) and (2).

$$\left\{\frac{2\upsilon_1-1}{E_1}-\frac{1}{E_2}\frac{1}{2(b^3-a^3)}[b^3+2a^3+(b^3-4a^3)\upsilon_2]\right\}p + \frac{1-\upsilon_2}{E_2}\frac{3b^3}{2(b^3-a^3)}q+(\propto_1-\propto_2)\Delta T=0 \tag{1}$$

$$\frac{1-\upsilon_2}{E_2}\frac{3a^3}{2(b^3-a^3)}p+\left\{\frac{1}{E_2}\frac{1}{2(b^3-a^3)}[-a^3-2b^3+(4b^3-a^3)\upsilon_2] - \frac{1}{E_0(a)}\frac{1}{2(c^3-b^3)}[2b^3+c^3+(c^3-4b^3)\upsilon_0]\right\}q-\propto_0(a)\Delta T+\propto_2\Delta T=0 \tag{2}$$

where p is the interaction stress at the surface between aggregate particle and cement paste in the radial direction; q is the interaction

Table 1
Summary on concrete CTE prediction models.

	Emanuel and Hulsey [24]	Neville and Brooks [25]	Mukhopadhyay et al. [12]
Variables included in the models	(1) The proportions of individual components, (2) The CTEs of individual components, (3) Moisture, (4) Age, (5) Temperature	(1) The CTEs of individual components (2) The stiffness ratio of cement paste to aggregate, (3) The volume fractions of aggregate	Step1: aggregate CTE (1) Calculated weight percentages, (2) Pure mineral CTEs, (3) Aggregate elastic moduli Step2: concrete CTE (1) Aggregate CTE (2) Mortar CTE (3) Volume fractions of components, (4) Elastic moduli of components