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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).

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

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

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

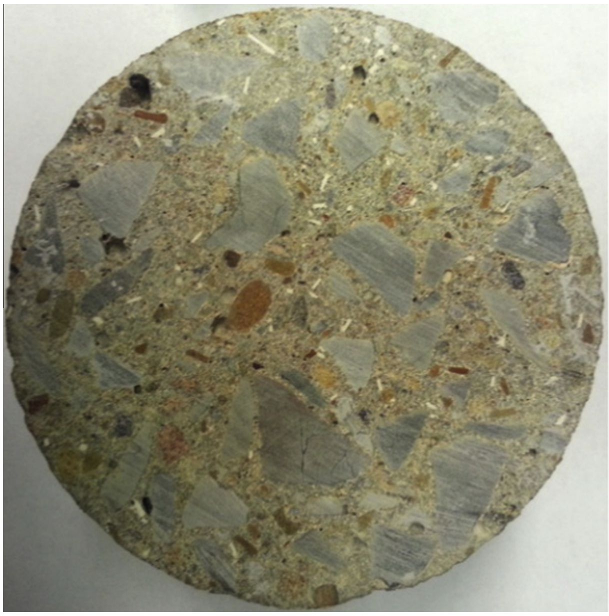

Fig. 1. Hardened cement concrete.

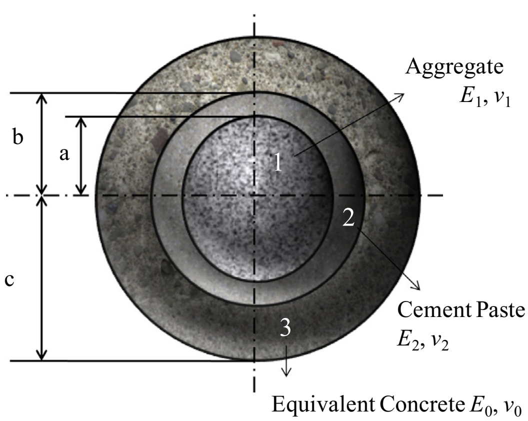

Fig. 2. Sketch of aggregate–cement paste-equivalent concrete medium.

stress at the surface between cement paste and the equivalent concrete in the radial direction.

The size of the equivalent concrete medium surrounding aggregate particle is much larger than aggregate itself, i.e., $c \gg b$, therefore, Eq. (2) can be simplified as

$$\frac{1-\nu_2}{E_2}\frac{3a^3}{2(b^3-a^3)}p + \left\{\frac{1}{E_2}\frac{1}{2(b^3-a^3)}[-a^3-2b^3+(4b^3-a^3)\nu_2] - \frac{1}{E_0(a)}\frac{1+\nu_0}{2}\right\}q - \propto_0(a)\Delta T + \propto_2\Delta T = 0 \tag{3}$$

Integration of the radial strain throughout aggregate and cement paste gives the total deformation in the radial direction:

$$u(a) = \int_0^a \epsilon_{1r}dr + \int_a^b \epsilon_{2r}dr \tag{4}$$

Macroscopically, the deformation of aggregate and cement paste also can be expressed as:

$$u(a) = b * \Delta T * \propto_0(a) \tag{5}$$

Then

$$B * \Delta T * \propto (a) = \int_0^a \epsilon_{1r}dr + \int_a^b \epsilon_{2r}dr \tag{6}$$

With Eqs. (1) and (3), the radial stresses, p and q, can be obtained. Then considering the geometric information of the composite (Fig. 2), the radial strains in the aggregate and the cement paste can be reached. Substituting the solution of radial strains into Eq. (6) yields

$$\left\{\frac{2\nu_1-1}{E_1}a + \frac{1}{2E_2}\frac{1}{a^2+ab+b^2}[(2a^3-ab(b+a)) - (4a^3+ab(a+b))\nu_2]\right\}p + \frac{1}{2E_2}\frac{1}{a^2+ab+b^2}\left\{[-2b^3+ab(a+b)] + [4b^3+ab(a+b)]\nu_2\right\}q - b\Delta T\propto_0(a) + [a\alpha_1+(b-a)\alpha_2]\Delta T = 0$$

Combining Eqs. (1), (3), and (7), $\propto_0(a)$ can be solved as:

$$\propto_0(a) = \left(D - \frac{BC}{A}\right)\frac{Aa+Cb-F}{(F-Cb)B-(G-Db)A}(\alpha_1-\alpha_2) - \frac{C}{A}(\alpha_1 - \alpha_2) + \alpha_2 \tag{8}$$

where $A = \frac{2\nu_1-1}{E_1} - \frac{1}{E_2}\frac{1}{2(b^3-a^3)}[b^3+2a^3+(b^3-4a^3)\nu_2]$; $B = \frac{1-\nu_2}{E_2}\frac{3b^3}{2(b^3-a^3)}$; $C = \frac{1-\nu_2}{E_2}\frac{3a^3}{2(b^3-a^3)}$; $D = \frac{1}{E_2}\frac{1}{2(b^3-a^3)}[-a^3-2b^3+(4b^3-a^3)\nu_2] - \frac{1}{E_0(a)}\frac{1+\nu_0}{2}$; $F = \frac{2\nu_1-1}{E_1}a + \frac{1}{2E_2}\frac{1}{a^2+ab+b^2}[(2a^3-ab(b+a)) - (4a^3+ab(a+b))\nu_2]$; $G = \frac{1}{2E_2}\frac{1}{a^2+ab+b^2}\left\{[-2b^3+ab(a+b)] + [4b^3+ab(a+b)]\nu_2\right\}$.

An approach [33] was used to determine the thickness of cement paste, i.e., b–a, as well as the volumetric factors of components in concrete were determined [26].

The elastic modulus of the equivalent concrete, $E_0(a)$ [40], is calculated as:

$$E_0(a) = \frac{E_2(1-n)(1-2\nu_0)}{x_1 - \frac{9E_1n(1-\nu_2)^2}{4E_2(1-2\nu_1)(1-n)+4E_1x_2}} \tag{9}$$

where n = volume of concentration of aggregate in concrete, $(a/b)^3$; $x_1 = 1/2 * n(1+\nu_2) + (1-\nu_2)$; and $x_2 = 1/2 * (1+\nu_2) + n(1-2\nu_2)$.

The CTE of the composite is influenced by many parameters such as temperature, aggregate size, cement paste thickness as well as elastic modulus, Poisson's ratio, CTE values of aggregate and cement paste. Every aggregate of a specified size gives its contribution to the overall CTE of the concrete. In order to take aggregate gradation into account, CTE of the concrete can be expressed as follows:

$$\alpha = \int_{a_{min}}^{a_{max}} \propto (a)dP(a) \tag{10}$$

where a_{min} = minimum aggregate radius; and a_{max} = maximum aggregate radius.

Since the integration is too complex, a numerical summation, as an approximation to the integration, is adopted, as in Zhou et al. [26].

4. Model validation

A hierarchical approach, starting with cement paste and progressing to mortar and concrete, was adopted to validate the CTE model in this study. As is well known, Portland cement concrete can be treated as a composite in which coarse aggregate particles are embedded in the cement mortar matrix. The cement mortar can be treated further as a composite consisting of fine aggregate particles embedded in the cement paste matrix. Such relationships are shown in Fig. 3. The validation approach for the CTE model started with measuring in the laboratory the CTE value of cement paste and using it as an input to predict the CTE values of cement mortar and concrete. Then the CTE values of cement mortar and concrete were tested and compared to the predictions from the

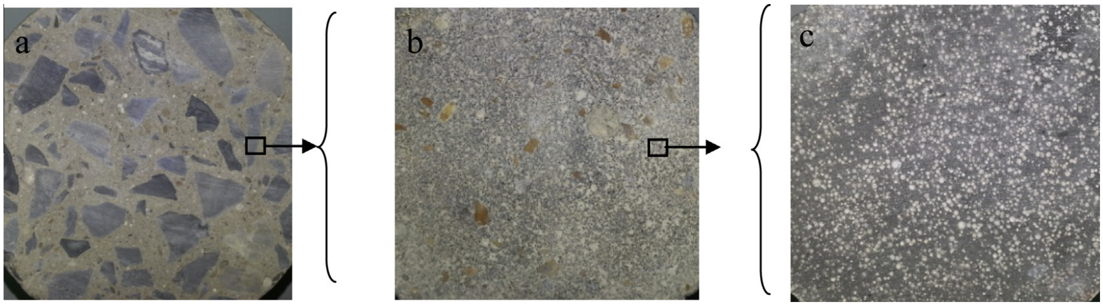

Fig. 3. Cement concrete (a) mortar (b) paste (c).

CTE model. It should be noted that the measured CTE of mortar can not only be compared with the predicted values, but also be used as an input for predicting the concrete CTE.

4.1. Laboratory determination of CTE values

In order to validate the CTE model, CTE values of cement paste, mortar, and concrete were tested in the laboratory. Type I Portland cement was employed to make the cement composites. A local siliceous sand and a local limestone from Memphis, Tennessee were used as fine aggregate and coarse aggregate in cement mortar and/or concrete. The gradation and specific gravity values of sand and aggregate are summarized in Table 2. The mixture proportions of concrete are listed in Table 3.

Three 10×20 cm cylinders were fabricated at four water cement ratios, i.e., 0.32, 0.38, 0.44, 0.48, for cement paste and mortar. Three 15×30 cm concrete cylinders were prepared at a water cement ratio of 0.44. The specimens were stored in the curing room for 26 days and then were sawed into a length range of 17–21 cm, which is the requirement for CTE testing according to AASHTO T336-09 [18]. These specimens were then saturated in a lime water tank for at least 48 h. Finally, the saturated specimens were tested for their CTE values. The measured CTE values are summarized in Table 4.

Additionally, the measured concrete CTE values in Alabama [10] were utilized to validate the CTE model too. Concrete with two types of coarse aggregates, i.e., dolomitic limestone (DL) and granite (GR) were utilized in this paper. Siliceous sand was used for fine aggregate in all of concrete. In each type of concrete, three water cement ratio (0.32, 0.38, 0.44) and three volumetric ratios of coarse aggregate to fine aggregate (60:40, 55:45, 50:50) were adopted. Therefore, there are totally nine different concretes with DL coarse aggregate, as well as nine concretes with GR coarse aggregate. The inputs such as aggregate gradation and bulk specific gravity of each material and the measured concrete CTE values can be found in Zhou et al. [26].

Table 2
Gradation and bulk specific gravity of raw materials for concrete in Memphis, Tennessee.

Sieves	Mass% passing sieves		
	Limestone		Siliceous
	#4	#67	Sand
1.5″ (37.5 mm)	100	100	100
1″ (25.0 mm)	27.9	99.4	100
3/4″ (19.0 mm)	3.1	70	100
3/8″ (9.5 mm)	0	5.2	100
#4 (4.75 mm)	0	0.3	99
#8 (2.36 mm)	0	0.1	92
#16 (1.18 mm)	0	0	80
#30 (0.6 mm)	0	0	50
#50 (0.3 mm)	0	0	15
#100 (0.15 mm)	0	0	5
#200 (0.075 mm)	0	0	0
Bulk specific gravity	2.62	2.63	2.61

4.2. Inputs for the CTE model

The inputs of cement paste, aggregate and natural sand [47,48] are listed in Table 5, including CTE values, elastic moduli, and Possion's ratios. It should be mentioned that CTE values of cement paste were assumed to be the same with the ones obtained in the laboratory above, since the same type of cement was used in Sakyi-Bekoe [10].

4.3. Validation on the CTE model with cement mortar

The measured CTE values of cement mortar were compared with the predicted ones from the CTE model, as shown in Fig. 4. Since the CTE values of raw materials such as limestone varied, as shown in Table 5, the predicted CTE values of cement mortar fell into a range, as well as the ones for concrete. It can be seen that a very good agreement was reached between the predicted results and the measured results with no more than 5% variation. Slight

Table 3
Mixture proportions of concrete in Memphis, Tennessee (kg).

Cement	#67 limestone	#4 limestone	Siliceous sand	Water	Air entrainer	Water reducer
312	610	488	748	136	0.74	1.11

Table 4
Measured CTE values for cement paste, mortar, and concrete in Memphis, Tennessee.

	Cement Paste				Cement Mortar				Concrete
w/c ratio	0.32	0.38	0.44	0.48	0.32	0.38	0.44	0.48	0.44
CTE (10^{-6}/°C)	11.2	10.8	10.4	10.3	11.6	11.2	11.0	11.0	8.7

Table 5
CTE values, elastic moduli and Poisson's ratios of concrete components.

Properties	DL	GR	Siliceous sand	Cement paste		
				0.32	0.38	0.44
CTE range (10^{-6}/°C)	7–10	7–9	11–13	–	–	–
Medium CTE (10^{-6}/°C)	8.5	8	12	11.2*	10.8*	10.4*
Elastic modulus (GPa)	20	60.0	20	20.87	18.42	15.97
Poisson's ratios	0.20	0.20	0.20	0.20	0.20	0.20

* Measured CTE values of cement paste in laboratory aforementioned.

decreases were observed on CTE values when water cement ratio increased. However, this trend was not significant on a *t*-test at 5% significant level.

4.4. Validation on the CTE model with cement concrete

The concrete CTE can be predicted either directly from measured CTE of cement paste or from measured CTE of cement mortar. Both approaches were used to predict the CTE value of the concrete with 0.44 water cement ratio in Memphis Tennessee. Fig. 5 shows the comparison between predicted and measured concrete CTE values. It indicates that the predicted concrete CTE deviated no more than 15% and 10% from the measured concrete CTE when measured cement paste CTE and measured cement mortar CTE were used as inputs for the CTE model, respectively.

In order to further verify the proposed CTE model, a group of measured concrete CTE values from Alabama [10] were compared with the predicted CTE values, as shown in Fig. 6. It can be seen that the upper limits of aggregate CTE values provided the maximum values of concrete CTE, while the lower limits provided the minimum values of concrete CTE. Between the maximum and minimum values were the concrete CTE values predicted from other combinations of aggregate CTE values. The differences between the predicted and measured concrete CTE values were no more than 15%.

Comparing to the old micromechanical model [26], the improved model can predict concrete CTE values 5–10% closer to the measured concrete CTE. Considering the great impact of concrete CTE on concrete performance, the improved micromechanical model for concrete CTE prediction may bring significant improvement for more precise concrete structural designs. Better agreement between the predicted and measured CTE values of cement mortar and concrete indicates that the improved CTE model was valid for predicting concrete CTE. Better prediction could be reached on concrete CTE when the measured CTE of cement mortar was used as an input.

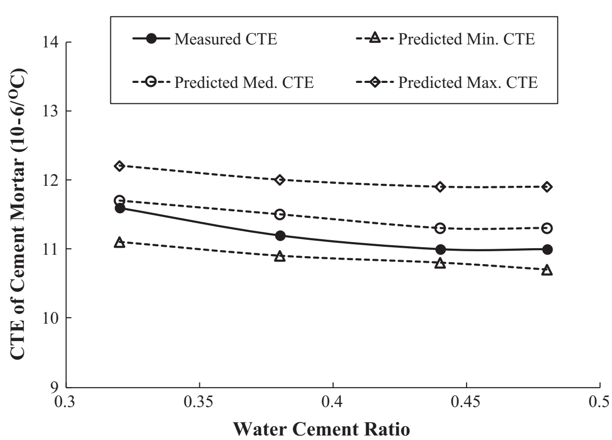

Fig. 4. Comparison of measured and predicted CTE values of cement mortar.

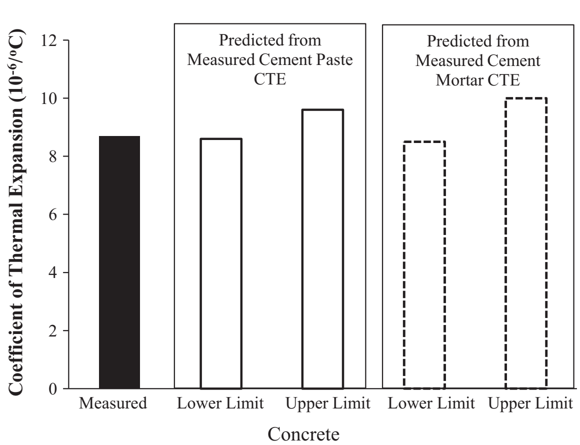

Fig. 5. Comparison between predicted and measured concrete CTE values in Memphis, Tennessee.

5. Sensitivity analysis

As mentioned earlier, many factors may have significant effects on concrete CTE. The effects of these factors must also be investigated. The following factors were considered in this study: water cement ratio, aggregate type, and aggregate gradation. The CTE data of the Alabama concrete was utilized to evaluate the effects of different factors on concrete CTE using the CTE model.

5.1. Water cement ratio

Within the range of water cement ratio from 0.32 to 0.44, it is observed that there were no obvious changes in concrete CTE. However, according to the test results in Table 3, the cement paste CTE decreased as water cement ratio slightly increased. Since the cement paste accounts only for a small volumetric portion of cement concrete and its CTE value does not exhibit a significant difference from those of aggregates, no significant variation was observed for the concrete CTE under different water cement ratios.

5.2. Aggregate type and gradation

In order to investigate the influences of aggregate type and gradation on concrete CTE, five types of coarse aggregate were selected. They fall into the following categories: marble (CTE: 4–7 × 10^{-6}/°C), basalt (CTE: 6–8 × 10^{-6}/°C), granite (CTE: 7–9 × 10^{-6}/°C), dolomitic limestone (CTE: 7–10 × 10^{-6}/°C), and quartzite (CTE: 11–13 × 10^{-6}/°C). Siliceous sand (CTE: 13 × 10^{-6}/°C) was used as fine aggregate. The water cement ratio in all concrete mixtures was assumed to be 0.32. All coarse aggregate types followed the size distribution as granite in Zhou et al. [26] and fine aggregate followed the size distribution of siliceous sand in Table 2 as well. The change of the proportions of coarse aggregate and fine aggregate affected the mixture gradation, as shown in Fig. 7.

The predicted concrete CTE values are summarized in Table 6, including the upper and lower limits of concrete CTE values corresponding to the minimum and maximum values of coarse aggregates. It can be seen that as the aggregate gradation became finer, the concrete CTE slightly increased. As for aggregate type, the concretes made with low-CTE aggregates (such as marble and basalt) showed lower CTE values than the concrete made with high-CTE aggregates (such as quartzite). However, the CTE values of different concrete were very close when their raw materials had similar CTE values but different Young's moduli (e.g., marble and granite with the same CTE value of 7 × 10^{-6}/°C). It indicates

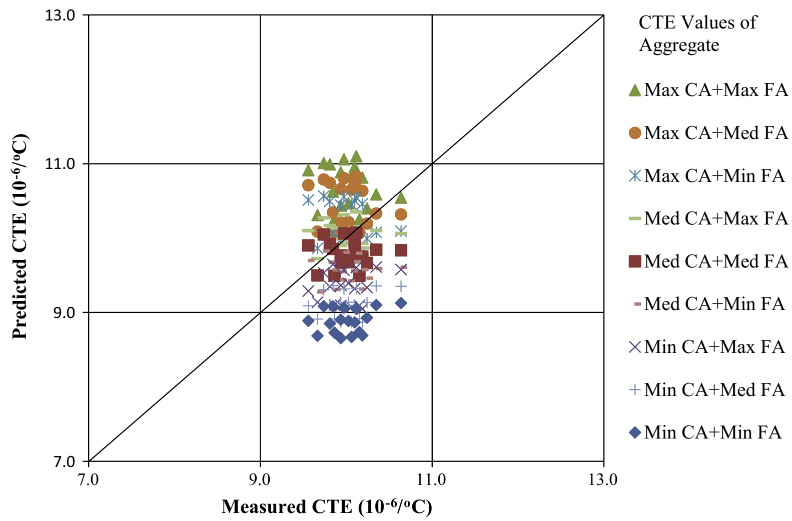

Fig. 6. Comparison between predicted and measured concrete CTE values in Alabama.

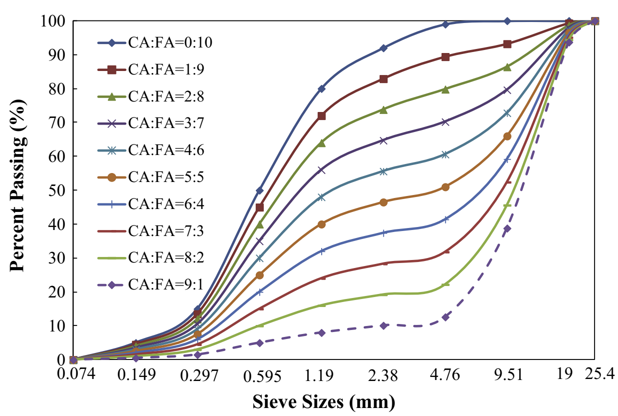

Fig. 7. Aggregate gradations used in sensitivity analysis.

that the CTE values of raw materials played a significant role in determining concrete CTE value. It is found that concrete CTE was not sensitive to the stiffness of raw materials.

6. Summary and conclusions

A micromechanics-based model was improved from a previous study [26] to better predict the CTE of concrete while concrete was seen as a composite material. The CTE data of cement paste, mortar, and concrete measured in the laboratory and collected from the published literature were utilized to validate the CTE model on cement mortar and cement concrete. Sensitivity analyses was performed to investigate the effects of factors influencing concrete CTE. The following conclusions can be drawn from the study:

- The improved CTE model was validated using a hierarchical approach on cement paste, mortar and concrete. The difference between measured and predicted CTE values of cement mortar was no more than 5%. With measured CTE values of cement paste and cement mortar as inputs, the predicted concrete CTE values were no more than 15% and 10% different from measured concrete CTE, respectively.
- Compared to the original micromechanical model developed by the authors, the improved model could predict concrete CTE values 5–10% closer to the measured ones.
- The aggregate type, i.e., the aggregate CTE value, was the most important factor that affects concrete CTE. Higher CTE values of raw materials led to higher concrete CTE values.
- Concrete CTE tended to increase as the aggregate gradation became finer.
- Within the range of water cement ratio from 0.32 to 0.44, it is found that there were no obvious changes in concrete CTE.

Table 6
CTE values of concrete with different types of coarse aggregate.

Coarse aggregate:fine aggregate	Coarse aggregate type									
	Marble		Basalt		Granite		DL		Quartzite	
	4*	7*	6*	8*	7*	9*	7*	10*	11*	13*
0:10	7.4	9.2	8.6	9.8	9.2	10.4	9.2	11.0	11.6	12.8
1:09	7.4	9.2	8.6	9.8	9.2	10.4	9.2	11.0	11.6	12.7
2:08	7.4	9.2	8.6	9.8	9.2	10.4	9.2	10.9	11.5	12.7
3:07	7.4	9.2	8.5	9.7	9.2	10.3	9.1	10.9	11.5	12.7
4:06	7.4	9.1	8.5	9.7	9.1	10.3	9.1	10.9	11.5	12.7
5:05	7.4	9.1	8.5	9.7	9.1	10.3	9.1	10.9	11.5	12.6
6:04	7.3	9.1	8.5	9.7	9.1	10.3	9.1	10.8	11.4	12.6
7:03	7.3	9.1	8.5	9.6	9.1	10.2	9.1	10.8	11.4	12.5
8:02	7.3	9.1	8.5	9.6	9.1	10.2	9.0	10.8	11.3	12.4
9:01	7.3	9.1	8.5	9.6	9.1	10.2	9.0	10.7	11.3	12.3

* CTE values of coarse aggregates, 10^{-6}/°C.

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