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A systematic optimization technique for the coefficient of thermal expansion of Portland cement concrete

Md Sarwar Siddiqui [a,*], David W. Fowler [b,1]

[a] *Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, 10100 Burnet Road, PRC 18B, Austin, TX 78758, United States*
[b] *Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, 301 E. Dean Keeton St. Stop C1747, Austin, TX 78712, United States*

HIGHLIGHTS

- First systematic approach to optimize concrete CTE.
- CTE can be reduced by replacing high-CTE aggregates with low-CTE aggregates.
- CTE can be reduced by reducing cement paste volume.
- A step-by-step concrete CTE optimization technique.

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ABSTRACT

The coefficient of thermal expansion (CTE) of concrete is one of the important concrete properties that is responsible for the deterioration of concrete pavements and structures. A significant savings in repair and rehabilitation cost can be achieved by optimizing the CTE of concrete according to the need of the concrete pavements and structures. CTE reduction also improves the durability and longevity. CTE of concrete is dependent on the CTE of its constituents. Replacing high-CTE aggregates with low-CTE aggregates can significantly reduce the CTE of overall concrete. In addition, concrete CTE can be reduced by reducing the cement paste volume. This study presented systematic guideline to select the concrete constituents to achieve a target CTE.

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1. Introduction

The coefficient of thermal expansion (CTE) of concrete is responsible for deformations in unrestrained concrete structures whenever concrete is subjected to temperature change. Thermal stresses occur when the deformations are restrained. The magnitude of thermal stress depends on change in temperature, CTE, modulus of elasticity of the materials, and degree of restraint of the concrete members. If the developed thermal stresses are greater than the tensile strength of the concrete, cracks occur. At early age, concrete is more prone to thermal cracking due to low strength [1]. In addition, a high amount of early-age relaxation may occur. Higher CTE generates higher thermal stress at a given temperature difference. Reducing the CTE of concrete is likely to reduce the distress potential of concrete structures. According to Mallela et al. [2] it might not be cost effective to reduce the concrete CTE by changing the constituents of concrete mixtures. However, optimizing the CTE of concrete according to the need of a given structure can result in a significant savings in repair and rehabilitation cost and increases the durability and longevity of the concrete structures.

This study will present the potential to reduce CTE of concrete by blending low-CTE aggregates with high-CTE aggregates and reducing cement paste volume. Finally, a systematic CTE optimization technique will be presented.

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[*] Corresponding author. Tel.: +1 785 320 0743.
E-mail addresses: mssiddiqui@utexas.edu (M.S. Siddiqui), dwf@mail.utexas.edu (D.W. Fowler).
[1] Tel.: +1 512 232 2575.

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2. Background

The CTE is the strain development due to a unit change in temperature. Thermal stress is one of the major causes of pavement distresses, including slab cracking, joint faulting, punchouts, and delamination. A small variation in CTE can significantly affect the design pavement thickness by the Mechanistic-Empirical Pavement Design Guide (MEPDG) [2–6]. Mallela et al. [2] and Tanish et al. [6] studied the effect of concrete CTE on slab cracking, joint faulting, and ride quality of jointed plain concrete pavements (JPCP). They both agreed that CTE significantly affected pavement performance. Won and coworkers [7,8] identified CTE as the major reason of CRCP horizontal cracking. Agencies like the Texas Department of Transportation (TxDOT) have recognized the thermal incompatibility between cement paste and aggregates as one of the major causes of continuously reinforced concrete pavement (CRCP) distresses for some time. Many TxDOT districts have limited the CTE of CRCP concrete to avoid pavement distresses. Spalling has significantly reduced after the Houston District limited the CTE of CRCP concrete [9]. Recently, TxDOT started to implement a statewide CTE maximum of 5.5×10^{-6} strain/°F (9.9×10^{-6} strain/°C) on CRCP concrete. Moreover, the Houston district has a lower CTE limit for CRCP aggregates, with a maximum of 5.0×10^{-6} strain/°F (9.0×10^{-6} strain/°C). Coarse aggregate sources that produce concrete, which have CTE higher than the specified limit are no longer accepted in CRCP projects in Texas. Although TxDOT is the first agency to impose CTE as an acceptance criterion for pavement concrete to reduce CRCP distresses, other transportation agencies in the U.S. and around the world might adopt this acceptance criterion for pavement concrete in near future to reduce pavement distresses. In addition to CTE, incompatibility of Young's modulus between the concrete constituents also has influence on the overall concrete CTE [10,11].

Krauss and Rogalla [12] studied the early-age cracking of bridge decks in the U.S. They observed over 10,000 bridge decks that exhibited early-age cracking. Early-age cracking has a detrimental effect on the long-term performance of concrete bridges. One of the reasons of early-age cracking is thermal loading [1]. Temperature change influences the girder axial force, girder moment, pile lateral force, pile moment, and pile head movement [13]. Bridge joint and bearing distresses can also occur from thermal movement [14]. Several bridge failures were reported due to a lack of design consideration to accommodate thermal movement [15,16]. Im and Chang [17] studied thermal stress development in a composite box-girder bridge and observed that daily temperature cycles can generate significant tensile and compressive stresses.

Mass concrete can experience significant temperature rise due to the heat of hydration of cementitious materials. Bentz et al. [18] presented a real world problem where severe cracking occurred in mass concrete due to excessive temperature rise generated from heat of hydration. Cracking potential in mass concrete due to heat of hydration can be reduce by reducing the CTE of concrete.

It can be concluded from the previous discussions that thermal stress plays a major role on the durability and longevity of concrete pavements and structures. Optimizing the CTE of concrete can diminish these unwanted thermal distresses and improve the service life of the structures, and reduce the repair cost. Emanuel and Hulsey [19] presented a model based on the rule of mixtures to predict the CTE of concrete from its constituents, which can be presented as:

$$\alpha_c = f_T(f_M f_A \beta_p \alpha_s + \beta_{FA}\alpha_{FA} + \beta_{CA}\alpha_{CA}), \tag{1}$$

where α_c, α_s, α_{FA}, and α_{CA} are the linear CTE of concrete, saturated hardened cement paste, fine aggregate, and coarse aggregate, respectively; f_T is correction factor for temperature alteration; f_M is correction factor for moisture; f_A is correction factor for age; β_p, β_{FA}, and β_{CA} are proportions by volume of hardened cement paste, fine aggregate, and coarse aggregate respectively. So,

$$\beta_p + \beta_{FA} + \beta_{CA} = 1 \tag{2}$$

In this study, the CTE was measured for saturated samples in a controlled environment at an age between 2 and 3 months. As a result, $f_T = f_M = f_A = 1$ and Eq. (1) becomes,

$$\alpha_c = \beta_p\alpha_s + \beta_{FA}\alpha_{FA} + \beta_{CA}\alpha_{CA} \tag{3}$$

From Eq. (3) it is evident that the CTE of concrete can be reduced by reducing the CTE of coarse and fine aggregate. Typically, the CTE of cement paste is higher than the CTE of most of the aggregates. Therefore, CTE of concrete can also be reduced by reducing the cement paste volume. Eq. (3) was developed based on the assumption that there is only one type of cement, one fine aggregate, and one coarse aggregate in a concrete mixture. It was a valid assumption at that time, because there was no need for blending multiple aggregates and/or multiple cement sources. Blending aggregate from multiple sources is gaining acceptance due to depletion of good quality aggregate sources and unavailability of acceptable aggregates in or near the construction site. Moreover, blending aggregate from multiple sources is necessary to reduce the CTE of concrete. Therefore, concrete with one type of cement and multiple coarse and fine aggregates the Eq. (3) can be written as:

$$\alpha_c = \beta_p\alpha_s + \sum_{i=1}^{n}\beta_{FAi}\alpha_{FAi} + \sum_{j=1}^{m}\beta_{CAj}\alpha_{CAj} \tag{4}$$

where $\sum$ is the operator for summation; n and m are the number of fine and coarse aggregates in concrete, respectively; α_{FAi} and α_{CAj} are the linear CTE of ith fine aggregate and jth coarse aggregate, respectively; β_{FAi} and β_{CAj} are proportion by volume of ith fine aggregate and jth coarse aggregate, respectively.

3. Optimizing concrete CTE

Concrete consists of cement paste and aggregates that can be divided into two components, coarse and fine. The CTE of concrete constituents affect the CTE of concrete. Reducing the CTE of each component will reduce the CTE of concrete. This section will discuss laboratory observation regarding the influence of the CTE of each constituent on the overall CTE of concrete.

3.1. Materials

An ASTM C 150 [20] Type I/II cement was used for all concrete mixtures. A total of 4 coarse and 4 fine aggregates were used in this study. Table 1 presents the mineralogy, specific gravity (SG), and absorption of these coarse and fine aggregates. To determine the effect of cement content on the CTE of concrete, 7 aggregate blends were used. Further details on the aggregate blends can be found in previous studies [21,22].

3.2. Test procedure

Three optimization techniques were evaluated in this study, including blending low-CTE coarse aggregate with high-CTE coarse aggregate, blending low-CTE fine aggregate with high-CTE fine aggregate, and reducing cement content. For the first two observations concrete mixtures were proportioned with a cement, fine

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