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In situ measurement of coefficient of thermal expansion in hardening concrete and its effect on thermal stress development

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HIGHLIGHTS

- ▶ A time-dependent variation of CTE in hardening concrete was examined in situ.
- ▶ A particular device called impervious non-stress cylinder was used.
- ▶ The CTE at setting time was about twice as high as the CTE in the stabilized stage.
- ▶ The time-dependent CTE may be important for assessments of early-age cracking potential.

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ABSTRACT

It is well known that the coefficient of thermal expansion (CTE) has substantial effects on behavior and performance of concrete structures. In this study, a time-dependent variation of CTE in hardening concrete was examined based on a series of field experiments using a device called impervious non-stress cylinder (INC). The results showed consistent trends: (1) the CTE at the time of setting is about twice as high as the CTE in the stabilized stage and (2) after the CTE's initial sudden drop, it starts to slightly increase for a certain period of time and then stabilizes. The present study also quantitatively investigated the effect of time-dependent CTE variation on thermal stress developments. The results revealed that the effect of CTE's time-dependent variation is non-negligible; rather, it may be of great importance for accurate assessments of early-age cracking potential and the later-age behavior and response of concrete structures.

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1. Introduction

Cast-in-place concrete experiences significant volume changes, especially at early ages, due to variations in temperature and internal relative humidity (RH) [1–4]. In cement-based materials with a low water-to-cementitious ratio (w/cm) such as high-performance concrete (HPC) and ultra high-performance concrete (UHPC), additional volume changes can occur because of self-desiccation [5]. If these volume changes are internally and/or externally restrained, surface microcracking and visible macrocracking can take place in concrete structures [2,3,6]. These cracks could be detrimental to these structures' durability and performance because deleterious ingredients such as sulfate, acid, and salt can penetrate the hydrated cement matrix and steel reinforcement through the crack opening, which can lead to various types of deterioration such as corrosion of reinforcement, sulfate attack, carbonation, and frost attack [7].

Among the factors causing load-independent volume changes in concrete—thermal, hygral, and autogenous shrinkage—the thermal effect is believed to be the dominant influence in the early-age cracking tendency of normal-strength concrete structures. This influence results from the significant thermal fluctuations concrete undergoes at early ages due to liberation of hydration heat and its dissipation into environment, along with a rapid material stiffness evolution [2,3,6]. Also, the thermal effect may affect the post-cracking behavior of concrete structures as a cracked concrete member subjected to successive daily temperature variations experiences incompatible movements at the interface between the steel reinforcement and the surrounding concrete [8,9].

In realistically predicting the time-dependent behavior and structural response of concrete structures under temperature loading, characterizing a coefficient of thermal expansion (CTE) is of great importance because an instantaneous stress buildup due to temperature changes is in proportion to concrete's CTE. Previous research studies indicated that the CTE of cement-based material was influenced by several factors. Meyers [10], Sellevold and Bjøntegaard [11], Grasley and Lange [12], and Yeon et al. [13]

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found that the CTE was significantly affected by the internal RH of cement paste and concrete. The findings from these studies were nearly consistent in that the maximum CTE occurred around 70% RH, which coincided well with the research performed by Bažant [14]; the effect of RH on thermal expansion is primarily due to the hygrothermic dilation mechanism in pore structures and it reaches maximum at approximately 70% RH. The research by Wittmann and Lukas [15], Bjøntegaard and Sellevold [16], Kada et al. [17], Cusson and Hoogeveen [18], Choktaweekarn and Tangtermsirikul [19], Loser et al. [20], Richardson et al. [21], and Maruyama and Teramoto [22] showed that the CTE of cement-based materials was strongly affected by its age. The results from these studies agreed that the CTE varies considerably within the first few hours after the final setting, but the trends were contrary to each other. Kada et al. [17] and Loser et al. [20]'s works indicated that the CTE at the time of setting was greater than at the later stage while the other researchers' findings [15,16,18,19,21,22] showed that the CTE at the setting time was at its minimum and kept increasing over time thereafter. Helmuth [23], Wittmann and Lukas [15], and Emborg [6] discovered the definite hysteresis loop in temperature-strain curve between heating and cooling paths. This phenomenon may be explained by the contribution of delayed thermal deformation caused by variations in moisture distribution during and after the temperature changes [11,13,14,23–25]. Also, research [15] indicated that the CTE of hardened cement paste was influenced by the temperature. The experimental results showed that the CTE had a minimum value around the freezing point. Yang et al. [26] revealed that the CTE measurement was eventually affected by the measurement system and specimen's shape. Their findings showed that the CTE of a prismatic specimen was about 19–23% higher than that of a cylindrical specimen. Moreover, a difference of approximately 19% was observed in CTE depending on the type of measurement device used, even though the same specimen was used in the testing.

As the extensive literature studies revealed, several parameters influence the CTE of cement-based materials. In this paper, an experimental study to evaluate the time-dependent variation of CTE in hardening concrete was carried out based on in situ free thermal deformation measurements using an apparatus called impervious non-stress cylinder (INC) developed by Choi and Won [27]. Furthermore, the contribution of time-dependent CTE variations to the structural responses of concrete structures was quantitatively investigated. This study distinguishes itself from previous research in that: (1) tested on concrete, while most of the former research used cement paste or mortar as testing materials; (2) used an in situ experimental method, which is more practical; and (3) investigated the impact of time-dependent CTE on the structural behavior of concrete structures, whereas the majority of previous research studies solely focused on the time-dependency itself.

It is expected that such an in situ approach will provide meaningful information that leads to a comprehensive understanding of the time-dependent behavior of concrete structures subjected to temperature loading, and thus will be helpful to develop a more reliable design of concrete structures.

2. Field experimental program

2.1. Testing sites

A series of field experiments were conducted in three different construction projects. Sections A and C were newly constructed Portland cement concrete pavements with different design concepts and dimensions: a 0.20 m thick typical continuously reinforced concrete pavement and a 0.23 m thick post-tensioned concrete pavement, respectively. Section B was a 0.15 m thick full-scale bonded concrete overlay placed over the existing asphalt pavement. Detailed information about the test sites is summarized in Table 1.

2.2. Materials

Three different concretes were investigated in this study. The concrete mixtures used in all test sections were the Class P concretes [28], typically used in concrete pavements in Texas. The mixture proportions and material properties of the concretes used are summarized in Table 2.

3. Experimental method

3.1. Concept of the experimental method and test apparatus

The measured total strain consists of four independent strain components, i.e., elastic strain, creep strain, shrinkage strain, and thermal strain. Those components are additively related and thus can be mathematically expressed as follows [1]:

$$\varepsilon(t) = \varepsilon^E(t) + \varepsilon^C(t) + \varepsilon^S(t) + \varepsilon^T(t) = \varepsilon^\sigma(t) + \varepsilon^0(t) \tag{1}$$

where $\varepsilon(t)$ is the total strain; $\varepsilon^E(t)$ is the elastic strain; $\varepsilon^C(t)$ is the creep strain; $\varepsilon^S(t)$ is the shrinkage strain; $\varepsilon^T(t)$ is the thermal strain; $\varepsilon^\sigma(t) = \varepsilon^E(t) + \varepsilon^C(t)$ is the stress-dependent strain; and $\varepsilon^0(t) = \varepsilon^S(t) + \varepsilon^T(t)$ is the stress-independent strain.

Because only thermal strain is related to the evaluation of CTE, separating the thermal strain from the measured total strain was essential. For this purpose, an INC was employed in the field testing (see Fig. 1a). The design concept of INC is to provide a small room within a concrete member, which is completely separated from the surrounding concrete, so that the concrete element inside the room could undergo thermal volume changes in a stress-free condition without any influence of surrounding concrete elements. Because the INC was designed not to allow moisture exchange with the surrounding concrete, the free strain measured from the concrete inside the INC represented only thermal strain at the depth of installation.

As shown in Fig. 1b, the dimensions of the INC adopted in the testing were 75.0 mm (inside diameter) × 237.5 mm (length). A hollow polyvinyl chloride (PVC) slip was used as the body of the INC and both ends of the PVC slip were capped with plastic caps. On the inner surface of each plastic cap, a 15 mm thick piece of Styrofoam was attached to allow volume expansion without restraint. Also, a single layer of soft fabric was glued onto the inner surface of the INC body to alleviate the friction between the concrete and INC as well as the radial pressure of concrete. To measure the strain of the concrete inside the INC, an embedment-type vibrating wire strain gage (VWSG) (Model 4200; Geokon) with a 153 mm of effective gage length, which is suitable for long-term strain measurement in a concrete member, was employed. The resolution of the VWSG used was 1.0×10^{-6} mm/mm and the accuracy was ±0.1% F.S. within the temperature range from −20 to 80 °C, which is precise enough for implementation in this study.

3.2. Validation of INC setup

In order to validate the INC testing setup, a laboratory experiment was carried out using a cracking frame [27]. The cracking frame is a device which is designed to measure the restrained stress development in early-age concrete by simulating a restraint condition using two rigid invar steels supporting two crossheads 1.0 m apart [2,3]. The insulated formwork, where the concrete specimen is placed, is located between the two crossheads and is equipped with a water circulating temperature controller so that a desired temperature history can be imposed to the concrete specimen in the frame.

For the validation testing, two different specimens were fabricated with the concrete material from the same batch; one was the free cylinder, which was placed and cured in a match curing box where almost identical temperature histories were maintained to those in the cracking frame member, and the other was the INC