Measurement 85 (2016) 222–231

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

# A new approach for determination of the coefficient of thermal expansion of asphalt concrete

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ARTICLE INFO

*Article history:*
Received 22 October 2014
Received in revised form 30 October 2015
Accepted 19 February 2016
Available online 27 February 2016

*Keywords:*
Coefficient of thermal expansion
Asphalt concrete
Strain gauge
Climate change
Civil infrastructure
Transportation system

ABSTRACT

A new approach for determining the coefficient of thermal expansion (CTE) of asphalt concrete (AC), based on thermoelasticity and using a distributed thermocouple and strain gauge apparatus, is proposed. The thermoelastic model for an instrumented hollow cylindrical AC specimen was established. Experiments were conducted with six scenarios of thermal flux for simulating different levels of heating on AC pavement. Three approaches for interpreting the CTE according to the readings of the thermocouple and strain gauge are provided, with different CTE measurements expected and observed. Terms associated with strain measuring accuracy derived from thermoelasticity are defined. The thermal calibration of instrument readings was shown to be necessary for obtaining accurate CTE readings for AC specimens. The CTE readings obtained in this study showed strong agreement with values reported in the literature. The proposed measuring approach is shown to be simple to install and theoretically founded.



## 1. Introduction

Global warming indirectly influences the quality and service life of transportation infrastructure. For example, preliminary reports indicate that climate change has caused noticeable impacts on the Qinghai-Tibet Highway [1]. The growing thermal absorption of asphalt pavement has led to an increased deterioration of roads. Mills et al. argued that anthropogenic climate change challenges the assumption of a static climate on which current design criteria have primarily relied [2]. Asphalt-based materials absorb heat and moisture at a faster rate than other construction materials such as concrete do, and the viscoelastic nature that governs their mechanical properties is highly temperature sensitive. This may lead to significant changes in material moduli, strengths and some others, which ultimately alter the performance of asphalt under regular service loading [3,4]. Several studies have indicated that the deterioration rates of pavement are altered by climate change, and the associated factors that affect the material properties should be considered accordingly [2–5].

The coefficient of thermal expansion (CTE) is one of the primary parameters in designing the quality and performance of asphalt concrete (AC) pavement. Numerous studies have measured the CTE of metals and alloys [6]; however, relatively scant effort has been exerted in measuring the CTE of AC materials. The approaches for measuring the CTE of AC in laboratories include dilatometry [7–9], optical heterodyne interferometry [10–13], digital image correlation (DIC) [14–16], and strain gauge measurement [17–22]. For dilatometry, the test chamber in a push-rod dilatometer system generally consists of a tubed thermal drive such as a furnace, cryostat, or liquid bath for uniformly heating or cooling the sample material at a controlled rate along its longitudinal dimension. However, measuring the CTE by using a dilatometer is a delicate and

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http://dx.doi.org/10.1016/j.measurement.2016.02.035
0263-2241/

demanding task, rendering it more suited for the materials of a scientific laboratory than for a typical experimental stress analysis facility [20]. Optical heterodyne interferometry has been shown to be capable of attaining the high-precision requirements for measuring the CTE of dimensionally stable materials at room temperature [10,12,13]. However, such a high-precision apparatus is considered excessively expensive for AC because its CTE is generally two to four digits. DIC is an emerging noncontact approach capable of sensing small strains that are then used for computing the CTE of solid materials [14–16]. The noncontact feature enables DIC to be performed under severe conditions (e.g., over 600 °C) [14,15]; however, it usually experiences convergence difficulties, particularly when a small strain measurement is required.

Strain gauges have been widely used for mechanical tests of materials. They are applicable to various types of matter, geometry, and anisotropy and do not require expensive instruments, making them an economic alternative for measuring CTEs [20–22]. Ratanawilai et al. compared the CTEs of printed circuit boards measured using Moiré interferometry and an electric resistance strain gauge. They reported that consistent CTE measurements can be obtained with the difference being less than 0.8 ppm/°C [11]. De Strycker et al. investigated the CTEs of S235, SS304, and SS409 stainless steels measured using DIC and strain gauges, and similar results at temperatures lower than 120 °C were obtained [14]. All these preliminary studies have suggested that strain gauges are suitable for accurately measuring the CTE of AC over its operating temperature range in the field (room temperature to 120 °C). In addition to being economical and accurate, the strain gauge approach is preferred over other approaches because it requires less operation space for small strain measurements of objects. This study employed a strain gauge apparatus to measure the CTE of AC based on thermoelasticity theory. A simplified thermoelasticity model (hollow cylinder) was first derived. Similar to ASTM dilatometry [7], the use of hollow cylinders in this study enables us to uniformly heat the sample material at a controlled rate along its longitudinal dimension, and thus simplify the investigation of CTE of AC. The thermal probe and multi-strain-gauge experimental set-up was established and testing procedures were conducted, and the measured thermal strains of AC hollow cylinder specimens were then calibrated accordingly and used for interpreting the corresponding CTE and the coefficient of thermal contraction (CTC). Furthermore, the results obtained were compared with values from the literature to determine their validity and applicability. It should be mentioned that bonding strain gauges to nonhomogenous materials such as AC requires sophisticated preparations including the selection of proper gauge length, proper use of the adhesives, and prior processing of the bonding surface (typically, polishing).

## 2. Theoretical models

The thermoelasticity models used in this study were primarily for objects with a hollow circular cylindrical geometry with finite longitudinal ($z$) and radial ($r$) boundaries. Several assumptions were made as per rational considerations:

1. Cylindrical coordinates ($r$, $\theta$, $z$) and displacement fields ($u$, $v$, $w$) are used.
2. Materials are homogeneous, isotropic, and linear elastic, and the properties are temperature independent.
3. The surface forces (if any) along the longitudinal direction are constant; in other words, stresses and strains are independent of the longitudinal coordinate.
4. Torques are not present on the two ends of the cylinder; the shear stresses and shear strains in the longitudinal direction are zero (i.e., $\tau_{rz} = \tau_{\theta z} = \gamma_{rz} = \gamma_{\theta z} = 0$).
5. Temperatures are constant along the longitudinal direction; the thermal field is merely a function of the radius (i.e., $T = T(r)$).
6. Displacements are functions of the radial coordinate only; the generalized plane strain model can be simplified as a one-dimensional plane-strain problem (i.e. $\varepsilon_z = \varepsilon_0 = \text{constant}$).
7. The stresses are below the yield limits.
8. The initial thermal field is constant ($T = T_R$, where $T_R$ is the reference temperature), and thermal stresses are analysed on the basis of prescribed boundary conditions $T(r_i) = T_i$ and $T(r_o) = T_o$.

### 2.1. Thermal conduction of circular hollow cylinders

For a circular hollow cylinder that enables only one-dimensional (radial coordinate) steady-state heat transfer (Fig. 1), the equation of the thermal field in cylindrical coordinates can be expressed as [23]

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dT}{dr}\right) = 0. \tag{1}$$

By integrating Eq. (1) and applying the boundary conditions $T(r_i) = T_i$, $T(r_o) = T_o$, the temperature distribution can be obtained as follows:

$$\Delta T = \Delta T_o - (T_o - T_i)\frac{\ln(r/r_o)}{\ln(r_i/r_o)} \tag{2}$$

where $\Delta T = T - T_R$, $\Delta T_o = T_o - T_R$, and $T_R$ = reference temperature.

### 2.2. Thermal strains of circular hollow cylinders

For the one-dimensional steady-state plane-strain ($\varepsilon_z = \varepsilon_0$) thermoelasticity problem, the displacement fields can be simplified as $u = u(r)$. Furthermore, by assuming that no forces are present on the inner and outer surfaces (i.e., free surfaces, $\sigma_r(r_i) = \sigma_r(r_o) = 0$), thermal stresses can then be expressed as [23]

$$\sigma_r = \frac{\alpha E(T_o - T_i)}{2(1-\mu)}\left[\frac{\ln(r/r_o)}{\ln(r_i/r_o)} - \frac{(r_o/r)^2 - 1}{(r_o/r_i)^2 - 1}\right] \tag{3a}$$