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Application of a PCM-rich concrete overlay to control thermal induced curling stresses in concrete pavements

Naser P. Sharifi *, Kamyar C. Mahboub

Department of Civil Engineering, University of Kentucky, Lexington, KY 40506, USA

HIGHLIGHTS

- The weather conditions cause curling stresses in concrete pavements.
- Because of their cyclic nature, they cause fatigue damage in pavements.
- The induced cumulative fatigue Damage Index could be up to 0.22 in a concrete slab.
- Using a thin PCM rich concrete overlay can mitigate this deterioration mechanism.

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ABSTRACT

This study aims to evaluate the application of a Phase Change Material (PCM) rich concrete overlay to reduce curling stresses in concrete pavements. Curling stresses are the results of temperature gradient in pavements, and are comparable to the stresses that are induced by traffic loads. The weather conditions, which have a cyclic nature, are the source of curling stresses, and they cause cyclic tensile and compressive stresses in pavements. This phenomenon causes fatigue damage in concrete pavements and reduces their service life. The PCMs have a high latent heat of fusion and can increase the thermal inertia of concrete. When PCM is used in a concrete overlay, it tends to moderate the temperature gradient in the slab, and thus mitigate the curling stresses. The efficiency of the proposed PCM-rich overlay was evaluated under the real climatic conditions of three different cities in the US. The findings of this research demonstrated that the cumulative fatigue Damage Index (DI) resulted from repetitive curling stresses can be up to 22% in a concrete slab with the service life of 35 years. However, using a 7.6 cm bonded concrete overlay with 25 vol% PCM can moderate the curling stresses so much that the effect of curling induced fatigue damage would be virtually negligible.

1. Introduction

In recent decades, a large number of studies have evaluated the application of Phase Change Materials (PCMs) to improve the thermal performance of buildings and pavements [1,2]. PCMs are substances with high latent heat of fusion, which can go through phase transition cycles without chemical degradation [3]. They can absorb and release a relatively high amount of thermal energy during solid-to-liquid and liquid-to-solid phase transitions; and thus they can work as passive thermal energy storage systems. Various types of PCMs, with a wide range of phase transition temperatures, are industrially available [4]. Their high latent heat of fusion, along with their compatibility with construction and pavement materials have made PCMs desirable additives to improve thermal properties of these materials [5].

In buildings, incorporation of PCMs in walls and roofs have been reported to be an effective strategy to decrease energy usage for heating and cooling [6,7]. Obviously, less energy usage contributes to a decrease in the emissions such as CO_2 [8]. On the other hand, since the incorporation of PCMs can enhance the thermal inertia of pavement materials, they have been used for different purposes in pavements. Generally, PCMs have been used in pavements in order to decrease freeze/thaw damage in concrete and asphalt pavements [2,9], to assist with melting of ice and snow on concrete pavements [10], and to prevent rutting in asphalt pavements [11]. They have also been used in concrete and asphalt pavements to mitigate the urban heat island effect in large cities [12,13].

Although intensive studies have evaluated different aspects of incorporating PCMs in pavements, the application of PCMs to control curling stresses in concrete pavements has not been studied. Curling

* Corresponding author.
E-mail addresses: npsharifi@uky.edu (N.P. Sharifi), kc.mahboub@uky.edu (K.C. Mahboub).

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refers to the bending of concrete pavements caused by a temperature gradient [14]. It not only generates bending stresses in the pavement, but also may cause loss of support at slab edges and corners [15]. The magnitude of the thermally induced stresses are comparable to the magnitude of the stresses that are generated in the pavements because of traffic loads [16,17]. However, because the source of curling stresses is the cyclic daily temperature fluctuations, it has a repetitive nature, and the cyclic changes in the induced stresses cause fatigue damage in concrete pavements. Therefore, the goal of this article is to report the findings of a study which investigated the fatigue damage induced in concrete pavements due to curling stresses, and evaluated the effectiveness of PCMs to moderate this type of fatigue damage mechanism.

To do so, the following tasks were carried out: first, real climate data such as air temperature and solar radiation were extracted from TMY3 database [18], and a mathematical model was adopted to calculate surface temperature of concrete pavements for an entire year for various locations with different climatic regions. Second, a 2-D finite element heat transfer model was generated using COMSOL Multiphysics® software package to calculate temperature profile through the cross-section of a pavement. Using these calculations, the most optimum arrangement to incorporate PCMs in the pavement layers was determined. Third, a 3-D finite element stress analysis model using COMSOL software was generated to calculate curling stresses induced in the concrete slab as a result of temperature gradient. Finally, a fatigue damage model for concrete slabs was employed to calculate the fatigue damage induced by the curling stresses over the course of a pavement's service life, and the effectiveness of a PCM-rich concrete overlay to control this damage mechanism was evaluated.

2. Methodology

2.1. Calculation of pavement surface temperature

The first step for calculating temperature profile through the pavement depth is calculating the surface temperature of the pavement. The surface temperature of a pavement is a function of air temperature, solar radiation, wind velocity, and humidity. Surface temperature profile can be drastically different from air temperature profile, and these two temperature profiles cannot be assumed to be the same. Therefore, in this study, a mathematical model was employed to calculate the surface temperature of concrete pavements as a function of climatic data.

Various equations have been proposed for calculating the pavement surface temperature from the climate data [19–21]. There are also some finite difference codes that predict the thermal response of cementitious composites [22]. The humidity of the environment has not been taken into account in many of the proposed equations, because it was found to have negligible effect on the pavement temperature. However, solar radiation has a considerable effect on pavement surface temperature, and has to be taken into account [20]. The adopted equation correlates the surface temperature to air temperature, solar irradiation, and wind velocity. In this correlation, the 24-h periodic temperature of the pavement surface can be calculated by Eq. (1)[1] [21]:

$$T(t) = T_M + T_V \times \frac{H}{\sqrt{(H+C)^2 + C^2}} \times \sin\left(0.262 \times t - \arctan\left(\frac{C}{H+C}\right)\right) \quad (1)$$

[1] Since all the parameters and constants presented in the reference of Eq. (1) are in the US customary units, the parameters, constants, and values presented in here and in Table 1 are also only in the US customary units.

where: T(t) = pavement's surface temperature, $^\circ F$; T_M = mean effective air temperature, $^\circ F$; T_V = maximum variation in surface temperature from mean, $^\circ F$; t = time from beginning of cycle, hr; H = h/k, ft^{-1}; h = $1.3 + 0.62 \times W^{0.75}$, surface convection heat transfer coefficient, $BTU/(ft^2 \cdot hr \cdot {}^\circ F)$; W = wind velocity, mph; k = thermal conductivity of the concrete slab, $BTU/(ft \cdot hr \cdot {}^\circ F)$; C = $\sqrt{0.131/D}$, ft^{-1}; D = $k/(C_p.\rho)$, concrete slab diffusivity coefficient, ft^2/hr; C_p = concrete slab specific heat, $BTU/(lb \cdot {}^\circ F)$; and ρ = concrete slab density, lb/ft^3.

In this equation, T_M and T_V can be calculated using the following equations [21]:

$$T_M = T_A + R, T_V = 0.5 \times T_R + 3 \times R \quad (2)$$

where: T_A = daily average air temperature, $^\circ F$; T_R = daily range in air temperature, $^\circ F$; R = $(0.67 \times \alpha \times I_0)/h$, average contribution to effective air temperature, $^\circ F$; α = concrete slab solar absorptivity coefficient, 1; and I_0 = maximum daily solar radiation, $BTU/(ft^2.hr)$.

In Eq. (1), $H/\sqrt{(H+C)^2 + C^2}$ is defined as the modification factor, F; and $\arctan(C/(H+C))$ is defined as the time lag between occurrence of the maximum air temperature and maximum slab's temperature, φ. Therefore, the equation can be rewritten as:

$$T(t) = T_M + T_V \times F \times \sin(0.262 \times t - \varphi). \quad (3)$$

The Eq. (3) approximates the pavement surface temperature by a sinusoidal function. All the physical and thermal properties of the concrete slab, as well as key climate parameters, are involved in this approximation. Therefore, there is a reasonable correlation between the observed and computed surface temperature using this equation [21].

The formulation presented by Eq. (3) was used to calculate the surface temperature of various locations in the US. For each location, air temperature, Global Horizontal Irradiation (GHI), and wind velocity were extracted from TMY3 database [18]. This open-access database has the hourly recorded weather data for 1020 locations in the US. It should be mentioned that in this study, thermal properties of the pavement were modified based on the PCM percentage. Therefore, for each case, the surface temperature of the pavement was calculated using the modified thermal properties of the pavement.

As a demonstration, the weather parameters of the month of November in Lexington, KY (shown in Fig. 1) were applied to a concrete pavement with the parameters presented in Table 1, and the surface temperature of the pavement was calculated. For each day, T_A, T_R, R, T_M, T_V were calculated, and Eq. (1) was used to calculate the surface temperature of the pavement. The comparison between air temperature and calculated pavement surface temperature is shown in Fig. 2. It is worthwhile to mention that for these parameters, φ has been found to be equal to $0.29 Rad$; which means the time lag between occurrence of maximum air temperature and maximum pavement temperature is equal to 66 min [21,23].

2.2. Calculation of temperature in the pavement layers

To calculate the temperature changes through the pavement layers, a 2-D finite element heat transfer model using COMSOL software was generated. The physics that were involved in the model were heat conduction, heat convection, and heat radiation. The model also included heat transfer in porous media, and heat transfer with phase change. The concrete slab was modeled as a porous medium so that the PCM could be incorporated inside its porosity. Details regarding the boundary conditions, initial conditions, meshing, etc., as well as the validation process of the model, are provided in another study [24]. In this study, to calculate the temperature profile through the pavement thickness, the thermal properties of the pavement were modified based on the utilized