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A developed method of analyzing temperature and moisture profiles in rigid pavement slabs

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HIGHLIGHTS

- A one-dimensional heat and moisture transfer model using Crank-Nicolson finite difference method.
- The impacts of coupling effect of temperature and moisture along the slabs at early age.
- The feasibility of using thermal conductivity (K) and moisture diffusivity (D) in the developed numerical mode.
- The goodness of fitting between the predicted and measured temperature and moisture values.

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ABSTRACT

This study proposes a developed method to compute the temperature and moisture distribution along the depth of the rigid pavement slab via a one-dimensional heat and moisture transfer model using Crank-Nicolson finite difference method. The components of thermal conductivity (K) and moisture diffusivity (D) are added to the existing numerical model, and their effects are evaluated by comparing numerical results with field measurements via an ATEK Concrete Maturity Meter (ACMM) system. The results section presents from the following aspects: (1) the impacts of coupling effect of temperature and moisture on pavement temperature and moisture distribution along the slabs at early age, (2) the feasibility of using thermal conductivity (K) and moisture diffusivity (D) in the developed numerical model, and (3) the goodness of fitting between the predicted and measured temperature and moisture values. The subsequent discussion concentrates on whether the predicted results of the numerical model can be used to develop similar conclusions both in the laboratory and field. The discussion also focuses on the boundary-formulation differences between the proposed model and the field test model for concrete slabs, which is highlighted in terms of how these models characterize the impact of temperature and moisture profile inside of pavement slab.

1. Introduction

Significant thermal stresses are induced through the depth of the in-service concrete pavements, which are subject to internal temperature gradients [1–3]. The surrounding temperature and humidity boundary conditions play a crucial role in the developed slab temperature and moisture profile. Moisture variations also induce development of critical stress and distress in concrete pavement, such as cracking and drying shrinkage, especially at early age. It is also reported that moisture gradients may raise tensile stress and cause slab warping and associated cracking [4].The slab temperature and moisture profiles are concomitantly affected by other weather conditions such as wind speed and solar radiation. Accounting for all these factors in a systematic manner makes it is necessary to develop a numerical model capable of reasonably characterizing their roles.

Numerical modeling of temperature distribution inside of pavements has been widely developed [5–9], However, with respect to early age concrete, these documented models yield unsatisfactory results since they ignore the impact of heat of hydration and evaporation at the pavement surface on the temperature and moisture profile at the time of setting. Of course, the Enhanced Integrated Climatic Model (EICM) incorporated into the Mechanistic-Empirical Pavement Design Guide (MEPDG), was never intended

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to represent early-aged hardening or the heat of hydration and evaporation on the resulting profile [10]. An engineering software tool named as HIPERPAV has been developed to predict early-age behavior of concrete pavements [11–13]. In HIPERPAV model, the moisture profile along the pavement depth follows a linear relationship. Since the complexity and nonlinear nature of moisture transport phenomena, this linear model may underestimate the moisture content along the depth of slabs. Some researchers also developed a moisture model and associated program for enhancing HIPERPAV predictions [14]. However, few of these models address temperature together with moisture or curing boundary conditions very well.

This paper describes a tool to represent the impact of heat of hydration and evaporation on the set gradient in hardening concrete pavement slabs. A one-dimensional heat and moisture transfer model is proposed to predict the temperature and moisture distribution of slabs. The proposed model distinguishes itself from the documented models in following critical aspects: (1) the impact of heats of hydration and vaporization on pavement temperature distribution through the slabs at early age, (2) the numerical thermal and moisture profile results dependence on the correlation between temperature and humidity. An ATEK Concrete Maturity Meter (ACMM) system is used to verify the validity of temperature and moisture in different layer of slab. The associated discussion highlights the difference between the proposed model and field test.

2. Numerical model

2.1. Numerical simulate the temperature profile of pavement slab

Since pavement temperatures are primarily controlled by the heat flux at the top, a one-dimensional heat transfer model is thus adequate to predict the temperature distribution of a slab. To simplify the model, the following assumptions were made:

(1) Heat conduction is the dominant heat transfer process in the pavement structure and the underlying layers. The heat convection within the ground and the pavement slab is neglected.
(2) The occurrence of moisture transport inside of the slab does significantly affect the thermal properties of the fresh concrete pavement. Therefore, the thermal conductivities, heat capacities, and degree of hydration are changed with temperature variation.

2.2. One-dimensional heat transfer model

Based on the literature has been present in detail in the past [15], one-dimensional heat transfer model can be described by the Fourier equation:

$$K\frac{d^2T}{dx^2} + Q_{Net} = c_p\rho\frac{dT}{dt} \tag{1}$$

Temperature Boundary Conditions

$$-K\nabla T + q_c + q_r - q_s - q_h + q_v = 0 \quad \text{surface}$$

$$-K\nabla T = 0 \quad \text{bottom}$$

where, K is the thermal conductivity of medium, ρ (kg/m^3) and c_p (J/kg/°C) are the density and the heat capacity of mediums, respectively; K can be expressed by the following equation $K = e^{A+B\alpha^2+CT}$ and α is the degree of hydration, which can be calculated by maturity of concrete; A, B and C are constants, $A = 4.0773213; B = 15.281914; C = 2.99826 \times 10^{-5}$; q_c (W/m^3) is heat flux due to convection; q_r (W/m^3) is heat flux due to irradiation; q_s (W/m^3) is solar radiation absorption; $q_h$is heat of hydration; q_v (W/m^3) is heat of vaporization; $\triangledown$ is operation, and it is unit dir. of heat flow.

2.3. Heat flux at the pavement surface

The heat flux at the upper boundary is affected by the solar radiation, convection, irradiation, heat of hydration and evaporation.

2.4. Convection

Convection heat transfer occurs between a wind flow in motion and top surface of a concrete slab when they have different temperatures. The temperature on a region of fluid above the slab will vary from Ts at the surface of slab and Tao f the ambient air temperature. The heat convection at the pavement surface is given by [16,17].

$$q_c = h_c(T_s - T_a) \tag{2}$$

where, qc is convective heat flux (W/m^2) and T_s is surface temperature (°C); T_a is ambient temperature (°C); h_c is the convection coefficient, W/m^2/°C. An empirical formulae was suggested to relate convection heat transfer coefficient to wind velocity and roughness of slab surface [18]. So h_c can be expressed as:

$$h_c = 6 + 3.7 \times v \tag{3}$$

where, 6 W/m^2/°C represents an average slab surface roughness without wind effects. And the heat transfer coefficient increase with the increase of wind speed proportionally.

2.5. Thermal irradiation

Differ from conduction and convection requires a material medium, irradiation transfers heat energy by electromagnetic waves. Thermal irradiation is a long-wave heat flux between the natural ground surfaces and the sky. The total irradiation emitted q_r (W/m^2), follows the Stefan–Boltzmann law and is expressed as [19,20]:

$$q_c = \varepsilon\sigma(T_s^4 - T_{sky}^4) \tag{4}$$

where, ε is surface emissivity of concrete = 0.88 [4,5]; 1 for a black body; σ is Stefan-Boltzmann constant = 5.67 × 10^{-8}; T_{sky} is sky temperature which can be evaluated by Eq. (5) [21]:

$$T_c = \varepsilon_{sky}^{0.25} \times T_a \tag{5}$$

where Ta (K) is air temperature; ε_{sky}, the sky emissivity, is given Eq. (6) [22]:

$$\varepsilon_{sky} = 0.754 + 0.0044 \times T_{dp} \tag{6}$$

where T_{dp} is the dew point.

2.6. Radiation

Solar radiation contributes to a temperature gradient through the depth of a concrete pavement which consists of direct and indirect components. Solar radiation q_s (W/m^2) propagates energy as a short wave arriving at the ground surface, which can be evaluated by Eq. (7) [18]:

$$q_s = \alpha_s\left[I_d\sin\theta + I_i\left(\frac{1+\cos\gamma}{2}\right)\right] \tag{7}$$

where, α_s is the solar absorptivity of the pavement surface; the solar absorptivity cabs is highly-dependent on the ground surface color. α_s can range from 0.5 to 0.9 for new and older concrete, respectively. This study uses α_s = 0.6 to mimic a rigid pavement slab that has become darkened after opening to traffic. I_d is direct solar