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Ways of formulating wind speed in heat convection significantly influencing pavement temperature prediction

Yinghong Qin · Jacob E. Hiller

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Abstract This paper investigates the influences of wind speed and of heat-convection coefficient on the temperature prediction of a slab. Numerical calculation of a slab temperature found that wind speed varies the slab temperature in a degree of 2–10 °C. More varying degrees occur at midday and in sunny day but less, at midnight and in a cloud day. These degrees also depend on the used heat-convection coefficients, which have different values in different models. Special emphases are paid to unearth the correlation between different heat convection coefficients and find the best alternative in the slab-temperature prediction.

1 Introduction

Concrete pavements are subject to diurnal temperature variations through its depths. Temperature profiles of the pavement depend on the time of day and on local environmental conditions including solar radiation, air temperature, wind velocity, and other factors. Experimental tests and numerical methods have been widely used to study the temperature distribution through concrete slabs, in order to provide a reasonable pavement-layer design. In situ measurements are accurate for short-term readings but cannot be used to interpret all the site-specific conditions influencing heat transfer between the slab and the surrounding environment. To circumvent this problem and extrapolate to other locations, numerical models are popular to simulate the temperature through the pavement slabs [1, 2].

Temperature distributions within a slab are usually predicted by use of a one-dimensional heat transfer model. To accurately predict thermal changes in the slab, this model must include the contributions of solar radiation, air temperature, wind speed, etc. on the pavement-temperature distribution. Wind speed plays a key role on the temperature distribution of a slab because it directly influences the heat convection at the pavement surface. Currently the heat convection coefficient in existing models can be computed by use of several solutions [1, 3–5]. Available heat convection coefficients are thus greatly different because they may be regressed from different experiment setups. It is thereby necessary to examine the impact of these differing solutions on the slab-temperature profile predictions and to find a communication between these different heat-convection coefficients.

The objective of this paper is to investigate whether wind speed significantly influences pavement temperature prediction and to present to which degree the computation of heat convection coefficient affects the temperature development of a slab. A one-dimensional heat transfer model is proposed to predict the temperature profiles of the pavement layers. The heat convection coefficient in the proposed heat-transfer model is computed on the basis of the Blasius solution, which is modified by combining the heat convection coefficients at free and forced convections. The modified Blasius solution and the other empirical solutions are entered the heat-transfer model to

Y. Qin (✉)
College of Civil Engineering and Architecture,
Guangxi University, 100# University Road,
Nanning 530004, Guangxi, China
e-mail: yinghong231@gmail.com

J. E. Hiller
Department of Civil and Environmental Engineering,
Michigan Technological University, 1400 Townsend Drive,
201F Dillman Hall, Houghton, MI 49931, USA

predict temperature profiles of a slab, respectively. The predicted temperatures are respectively compared with field observed temperatures, to highlight the influence of formulating wind speed in heat convection on the slab-temperature calculation. Special emphasis is paid to unearth the correlation between different heat-convection coefficients and to advocate the use of modified Blasius solution.

2 Numerical model

2.1 Numerical simulation of temperature regime on JPCP slabs

A one-dimensional heat transfer model is proposed to predict temperature profiles of a concrete slab and its underlying layers. It considers the thermal conduction dominating the heat flow within the pavement and its lower layers. The heat convection within the ground may occur due to water and vapor migrations but can be neglected because the local thermal conductivity is several orders greater than the mass diffusivity within the pavement lower layers.

Pavement temperatures are mainly controlled by the heat fluxes from the ground surface and, to a lesser degree, from the deep ground. Heat flux at the upper boundary condition comes from the combined effects of solar radiation, convection, and thermal irradiation (Fig. 1a). The temperature at deep ground is mainly affected by the heat flow from the interior of the earth and therefore exhibits less variation. The depth of the zero annual temperature amplitude ranges approximately from 10 to 20 m below the surface [6, 7]. This study selects 20 m beneath the bottom of the pavement's base layer as the lower boundary in order to accurately predict the ground temperature for different site-specific conditions.

2.2 One-dimensional heat transfer model

The temperature T (°C) of the computational domain (Fig. 1b) can be described by the Fourier equation:

$$\rho c \frac{\partial T}{\partial t} = div(k \cdot gradT) + q \tag{1}$$

where k (W/m °C^{-1}) is the thermal conductivity of mediums; ρ (kg/m^3) and c (J/kg °C^{-1}) are the density and heat capacity of medium, respectively; q (W/m^{-2}) is the internal heat generation rate, for hardened concrete, $q = 0$. The thermal capacity, density, and thermal conductivity of concrete have been well documented by previous researchers [8–10]. These properties depend on concrete mixture characteristics, e.g., water-to-cement ratio, aggregate type, aggregate volume, and porosity of the concrete. Detailed values for these factors are site-specific but reasonably controllable parameters. This study uses the assumed parameter values and typical ranges in Table 1.

2.3 Heat flow at the pavement surface

The heat flux at the upper boundary consists of the combined heat flow from heat convection, thermal irradiation, and solar radiation absorption. The magnitude of the heat flow is a site-specific, but less-controllable parameter affected by factors such as the ambient air temperature, wind velocity, etc.

2.3.1 Solar radiation

Solar radiation propagates energy as a short wave arriving at the ground surface. The energy absorbed by the earth surface depends on the medium's thermal properties and the surface's color. McCullough and Rasmussen [15] proposed the following equation for the short-wave absorption of solar radiation q_{abs} (W/m^2):

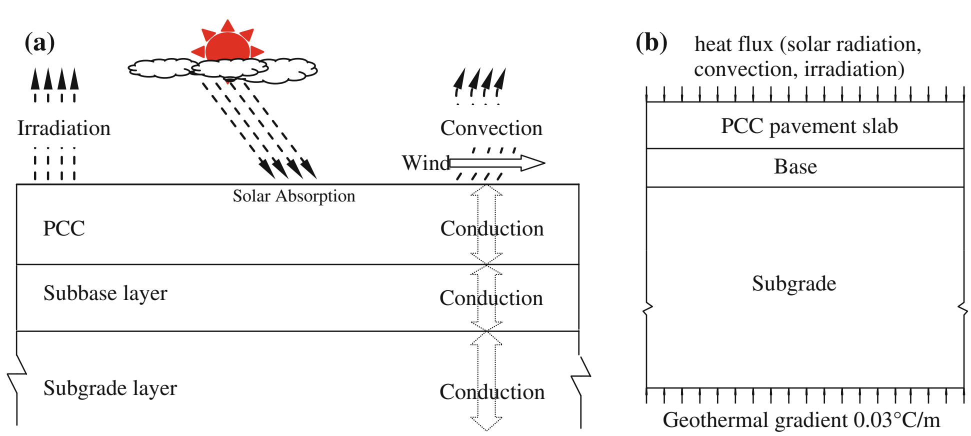

Fig. 1 Heat transfer model utilized showing; **a** a schematic showing the factors affecting heat transfer, **b** boundary conditions in computational domain

Table 1 Thermal parameters of the pavement and underlying layers

Stratum	k (W K^{-1} m^{-1})	c (KJ kg^{-1} K^{-1})	ρ (kg/m^3)
Slab[a]	2.5 (1.5–3.5)	1.0 (0.84–1.17)	2,350 (2,200–2,400)
Base[b]	1.8 (1.5–2.0)	0.9 (0.9–1.3)	2,210 (2,297–2,425)
Subbase[c]	1.8 (1.5–1.8)	0.9 (0.7–0.9)	2,210 (1,792–2,405)
Subgrade[d]	1.5 (0.5–2.0)	0.86 (0.8–0.9)	1,560 (1,380–1,600)

The values within the bracket are a rough range of the medium's thermal properties; the exact value is site-specific. [a] [11]; [b] [12]; [c] [13]; [d] [14]; Density for sub-base is dry density

$$q_{abs} = \gamma_{abs} \times I_f \times q_{solar} \tag{2}$$

where γ_{abs} is the solar absorptivity of the pavement surface; I_f is the intensity factor accounting for the sun's angle during a 24-h day; and q_{solar} is the daily peak solar radiation. The solar absorptivity γ_{abs} relies on the ground-surface color. For concrete slabs, γ_{abs} ranges from 0.5 to 0.9 for new and older concrete, respectively. The solar radiation intensity I_f strongly depends on the atmospheric conditions, the time of day, and the incident angle of the sun's ray on the ground surface. During nighttime conditions, solar radiation is negligible. During the daytime, I_f is assumed to follow a sinusoid function varying with the time of day and ranging from zero at both sunrise and sunset to a peak value at midday [4, 16]. The daily peak solar radiation q_{solar} depends on the sky conditions, e.g., cloud cover. According to McCullough and Rasmussen [15], q_{solar} is 1,000 W/m^2 on a sunny day, 700 W/m^2 on a partly sunny day, and 300 W/m^2 on a cloudy day.

2.3.2 Thermal irradiation

Thermal irradiation propagates a long-wave heat flow from the natural ground surface to the ambient air when the temperature at the material's surface is higher than the surrounding environment. Irradiation depends on the ground-surface conditions, such as vegetation covering, pavement surface color, etc. The total irradiation emitted is expressed by the Stefan–Boltzman law. The thermal radiation-induced heat flow, q_{irr} (W/m^2), between the pavement surface and the sky is expressed as:

$$q_{irr} = \varsigma \times \varepsilon \times (T_{sky}^4 - T_s^4) \tag{3}$$

where T_s is the temperature at slab's surface, (°K). ς (W m^{-2} K^{-4}) is the Stefan–Boltzman constant, $\varsigma = 5.669 \times 10^8$, T_{sky} (°K) is the effective sky temperature, and ε is the ground surface's emissivity. $\varepsilon = 0.90$ is used in this study and others [5, 17] when the pavement temperatures are evaluated. Bentz [4] used the following formula to predict T_{sky}:

$$T_{sky} = \varepsilon_{sky}^{0.25} \times T_a \tag{4}$$

where T_a (°K) is the air temperature; ε_{sky}, the sky emissivity, is given by:

$$\varepsilon_{sky} = 0.754 + 0.0044 \times \mathrm{T_{dp}} \tag{5}$$

where T_{dp} is the local dew point, °C.

2.3.3 Convection

The heat convection q_{conv} (W/m^2) at the pavement surface is given by:

$$q_{conv} = h_{conv}(T_a - T_s) \tag{6}$$

where h_{conv} is the heat convection coefficient, W/m °C^{-1}. The magnitude of h_{conv} is a function of the local wind Reynolds number Re, the thermal conductivity of the air K_{air} (W K^{-1} m^{-1}), the air's Prandtl number, and the characteristic length (which is used to calculated the Re number) [18]. According to traditional heat-transfer theory [17, 18], h_{conv} consists of two parts: natural (free) convection and forced convection. The heat convection coefficient of free air convection on a flat plane is approximately 5.6 W/m °C^{-1} [18]. According to the Blasius solution [18], the coefficient of forced convection of a flat plane is $0.332Re^{0.5}Pr^{1/3}K_{air}/L$ if the airflow is at low speed (e.g., <6 m/s). Therefore, the heat convection coefficient, i.e., the modified Blasius solution, is expressed as:

$$h_{conv} = 5.6 + 0.332Re^{0.5}Pr^{1/3}K_{air}/L \tag{7}$$

where for the air, $K_{air} = 0.027$, $Pr = 0.7$. For the airflow on a infinite flat plate, $L = 0.15$ m [18]. The Reynold number Re is:

$$Re = vL/\mu \tag{8}$$

where v is the local wind velocity, μ is the air's kinematic viscosity and usually is 16.01 × 10^{-6} m^{2}s^{-1} [18].

The total heat flux at the pavement surface can then be calculated as:

$$q_{total} = q_{conv} + q_{abs} + q_{irr} \tag{9}$$

2.4 Simulation information and the reliability of the model

To assess thermal profiles in the pavement structure, the computational domain is discretized by 23 three-node elements, with 10 elements for the slab, 3 elements for the base, and 10 elements for the sub-grade. The thickness of the slab is 29.2 cm over a 10.2 cm thick base. It is noteworthy that either a gravel base, an asphalt treated base, or other base type will not notably vary the temperature prediction of the slab and sub-layer because these materials have very similar thermal properties for conduction (Table 1).

The proposed heat transfer model is solved by the finite element method, which is based on the framework of the weak Galerkin formulation. The Crank-Nicolson method is applied to implicitly solve the differential Eq. (1). The time step size used is 6 min to ensure the convergence of the simulation in realistic time. The initial temperature profiles for the pavement structure and its underlying layer are obtained by use of the ground temperature profile from the preceding date. This date's temperature profile is gained by the repeated use of the local air annual mean temperature to simulate until the difference between the temperature profiles on any specific date in the previous and subsequent year is <0.001 °C.

The proposed heat transfer model is validated by the documented data presented by Yu et al. [19]. This data was measured from a concrete pavement slab in the westbound driving lanes of I-70 (near the Kansas-Colorado border) on July 12, 1994. Climatic conditions are obtained from the NOAA database as input parameters for the model including the following:

- Average wind speed, 2.2 m/s;
- Daily peak solar radiation, 500 W/m^2;
- Slab short-wave surface absorptivity, 0.68.

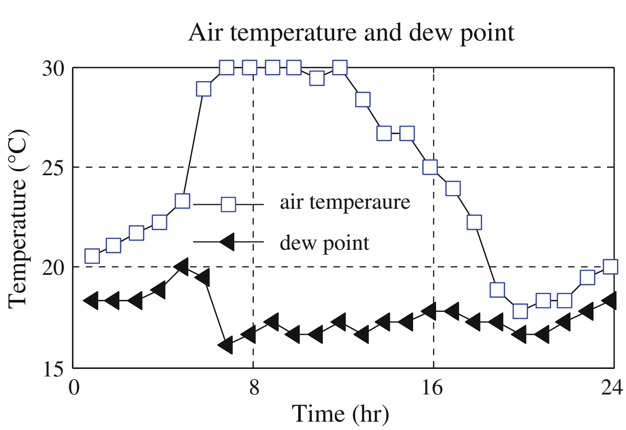

Fig. 2 Air temperature and dew point on July 12 for westbound driving lanes of I-70 (near the Kansas-Colorado border)

- Dew point and air temperature throughout the day are shown in Fig. 2.

The thermal properties of the pavement slab and its underlying layers are tabulated in Table 1 (the values outside the bracket). The thermal parameters of the sub-grade are obtained from the United States Department of Agriculture (USDA) [20].

The numerical results computed from the proposed heat transfer model coincide well with the in situ observed data (Fig. 3). The maximum temperature difference between the numerical result and in situ observation is 2.5 °C. The mean error and standard error were −0.17 and 1.24 °C, respectively. A more elaborate data set to validate the proposed heat transfer model can be found elsewhere [21].

3 Results and discussion

The validation (Fig. 3) does not infer the level of significance of the influence of wind speed on slab-temperature development. To confirm this influence, this study simulates the slab temperature by using those weather conditions and thermal parameters that have been utilized to validate the observed temperature in Fig. 3. The simulation respectively considers 0 and 6 m/s wind speed, in order to distinguish the influence of wind speed on the temperature development of the slab. For convenience, the following simulation uses the thermal parameters in Table 1 and adopts all the weather parameters in the above section, unless otherwise noted.

3.1 Wind speed significantly affects pavement temperature prediction

Wind speed exerts a significant influence on the slab's temperature profile, as illustrated in the predicted 24-h temperatures through the depth of the pavement under no wind and a 6 m/s wind (Fig. 4). The pavement slab becomes noticeably cooler as the wind speed increases, especially during the daytime (hours 8 through 20). During the daytime, the airflow on the slab's surface draws more heat away from the pavement because the difference between the ambient and surface temperatures is relatively large.

The increase in airflow helps mitigate the nonlinear temperature gradients across the slab. This gradient can be roughly estimated from the density of the temperature contours shown in Fig. 4. The slab experiencing an airflow of 6 m/s has temperature contours that are more evenly spaced (Fig. 4b) than those under no wind (Fig. 4a), indicating less non-linearity in temperature gradients in the

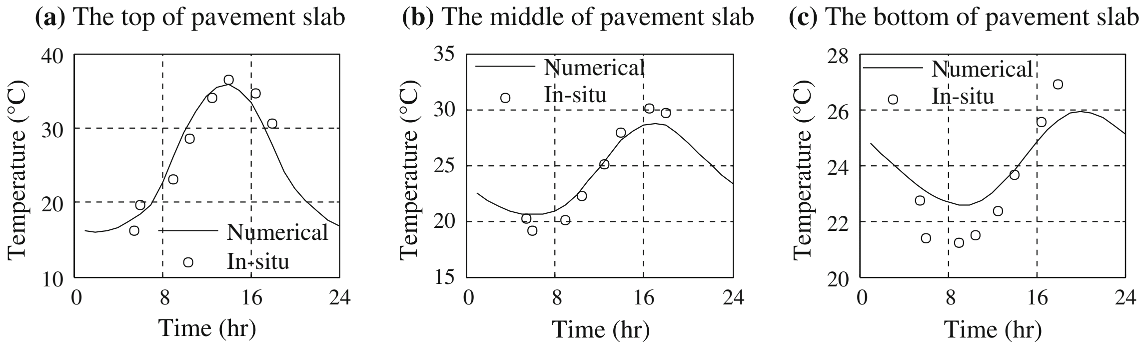

Fig. 3 Predicted versus in situ observed temperature using modified Blasius solution as the heat convection coefficient (*dotted data* reproduced from Yu et al. [19])

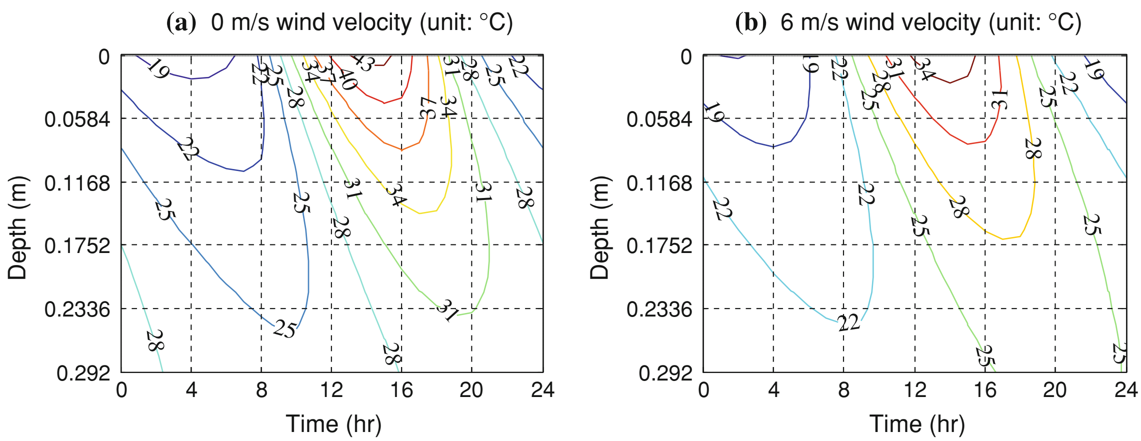

Fig. 4 Temperature contours (in °C) of a slab experiencing different wind speeds. *Note*: coordinate system is considered positive downward and measured from the slab's top

slab. A greater temperature difference in the slab develops more curling stress; the level of non-linearity increases the self-equilibrating stresses, which results from the constraints of compatibility of the slab [22].

Wind speed variations may influence a slab-temperature prediction in a more pronounced manner if the slab experiences a sunny day and/or if the slab has greater short-wave absorptivity (>0.68, i.e., worn pavement). This is because the pavement will absorb more solar radiation than the example shown in Fig. 4. For example, during a sunny day, the daily peak solar radiation is 1,000 W/m^2, twice as high as the radiation used in the predicted temperature profiles (Fig. 4). This strong instantaneous solar radiation will increase the slab surface temperature as well as the level of non-linearity of the temperature profile in the slab. The increase of available solar radiation therefore enlarges the difference between air temperature and slab-surface temperature. This also facilitates convection from wind speed by drawing more heat from the surface and magnifying the influence of wind speed on the slab-temperature distribution.

3.2 Formulation of wind speed in heat convection coefficients

3.2.1 *Models to compute the heat convection coefficients*

Because wind speed exert a considerable influence on the pavement temperature, it is critical to properly account for the heat convection coefficient in the prediction of pavement temperature profiles. This section compares the calculated heat-convection coefficients used in different documented literatures.

The coefficient used in the Enhanced Integrated Climatic Model (EICM), a sub-model embedded in the Mechanistic-Empirical Pavement Design Guide (MEPDG), is computed by Eq. (10):

$$h_{conv} = 122.93 \times \left[0.00144 T_m^{0.3} v^{0.7} + 0.00097 (T_s - T_a)^{0.3}\right] \tag{10}$$

where T_m (°K) is the average of the surface and air temperatures [23]. Setting wind velocity to $v = 0$ in the EICM model, the h_{conv} is close to zero since $0.00097(T_s - T_a)^{0.3}$ is minimal. Therefore, use of Eq. (10) results in a reliance on free convection condition (no wind velocity) at the ground surface with only a small capacity for convection. This free convection condition is one order of magnitude lower than that computed from the accepted heat transfer theory (5.6 W/m °C^{-1}) [18], which can be regarded as a standard solution. The most unreliable factor in Eq. (10) is that the slab's surface temperature must be higher than the air temperature, otherwise h_{conv} would be a complex number. While not common, this event does occur with fast changing weather patterns and during nighttime hours.

Priestley and Thurston [24] recommended a simple, empirical solution to evaluate the heat convection coefficient as follow:

$$h_{conv} = 13.5 + 3.88v \tag{11}$$

Equation (11) indicates that the free convection at ground surface is 13.5 W/m^2 °C, which is approximately twice the value (6.855 W/m^2 °C) computed in traditional heat transfer theory [18]. This equation also implies that the heat convection linearly increases with the wind velocity. However, a linear relationship between h_{conv} and v results in a higher influence on v than the classical approximation method [18], in which h_{conv} linearly increases with the square root of wind speed.

Different from a linear correlation, Bentz solution [4] is an alternative to compute the heat the heat convection coefficient for concrete:

$$h_{conv} = \begin{cases} 5.6 + 4.0 \times v, & |v \leq 5m/s \\ 7.2 \times v^{0.78}, & |v > 5m/s \end{cases} \tag{12}$$

in Eq. (12), the free convection at the pavement surface is 5.6 W/m^2 °C and thus is in the range of the ground-surface free convection coefficient according to traditional heat transfer theory [18]. However, the increasing rate of $v^{0.78}$ makes the computed coefficient more sensitive to wind speed than the square root of wind speed does. Application of Eq. (12) therefore would potentially overestimate the convection of the ground surface, especially in windy regions.

3.2.2 *Heat convection coefficient effect on slab temperatures*

The difference between the utilized heat-convection coefficients is distinguished by comparing these coefficients from the Bentz solution, the EICM solution, the Priestley and Thurston solution, and the modified Blasius solution. The heat convection coefficient computed from the EICM model is appreciably lower than the other three at free and forced convection (Fig. 5a).

To study this impact of a reduced heat convection coefficient, this study performs a simulation by using the weather data and location described in Fig. 2, except for assuming a partly sunny day (daily peak-solar radiation intensity of 700 W/m^2) in order to better differentiate results. The predicted results confirm that heat convection coefficient used notably influences the slab's temperature prediction (Fig. 5b). As the local air temperature ranges from 20 to 30 °C (Fig. 2), the maximum predicted slab temperature in a partly cloudy day ranging from 30 to 45 °C is more in line with expected results. Under these local weather conditions, a maximum predicted slab temperature ranging from 51 to 55 °C may be unreasonable, particularly with the daily mean wind speed of 6 m/s (Fig. 5b). As the wind speed dissipates heat from the slab surface, the use of EICM indicates an extremely high slab temperature prediction because the EICM adopts a negligible convection compared to the other models. In contrary, the impact of the heat convection computed from the Bentz solution on a slab's temperature prediction is more pronounced than that from the modified Blasius solution. This is because the former solution has a greater increasing rate of the heat convection coefficient than the latter.

In order to further confirm the influence of heat convection coefficient on the temperature prediction of a slab, Eqs. (10–12) are used to validate Yu et al.'s observed data throughout a given day. The validation illustrates that use of the EICM potentially overestimates the slab temperature and results in these predicted temperatures diverting significantly from the observations. Uses of the other three heat convection coefficients yield good correlations between the predicted and observed surface temperatures, having R-squared values over 0.91 (Fig. 6).

4 Discussion

The comparison between the observed and predicted temperatures cannot reach a definitive conclusion that one of these heat convection coefficients is better than other solutions. This is because the simulation uses a 2.2 m/s wind speed, making the heat convection coefficients relatively undistinguishable. Therefore, more discussion is needed to determine which formulation should be more appropriate to properly characterize the heat convection coefficient.

The EICM does not provide an appropriate solution to compute the heat convection coefficient. It embedded an assumption [Eq. (10)] that the surface temperature must be higher than the air temperature in order to avoid the heat convection becoming a complex number. Furthermore, the EICM results in zero free convection at the pavement surface and thus goes against traditional heat transfer theory from which natural convection at ground surface is about 5–6 W/m °C^{-1} (Fig. 6).

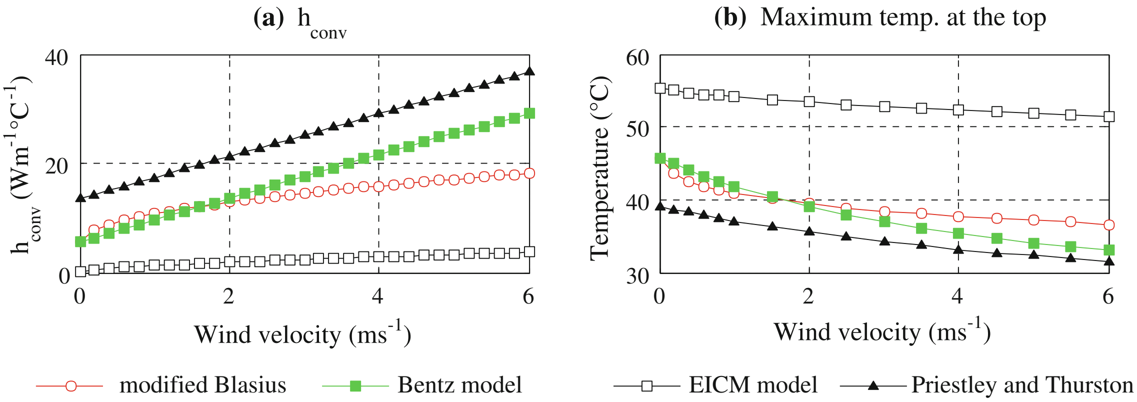

Fig. 5 Difference in heat convection coefficients and their impact on the surface temperature of a concrete slab

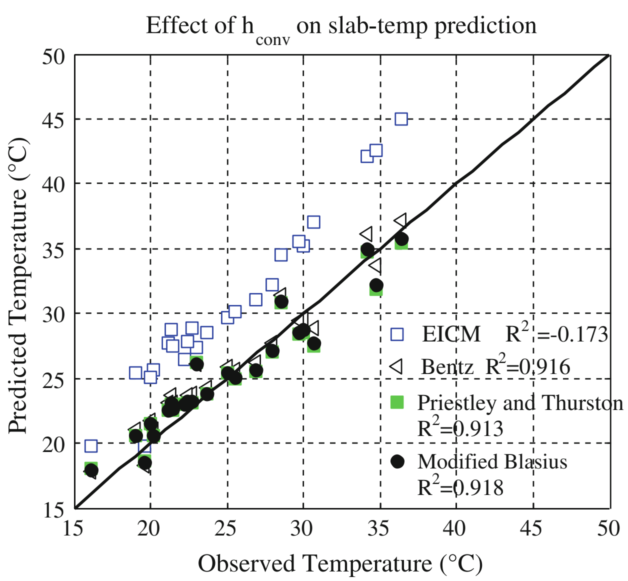

Fig. 6 Validating observed concrete surface temperatures using different heat-convection coefficients

The modified Blasius solution, the Bentz solution, and Priestly and Thurston solution generally produce similar results. At any specific wind speed, the heat convection coefficient computed from the modified Blasius solution is closely equal to those from the Bentz solution. Both coefficients, however, are roughly 10 W/m $°C^{-1}$ lower than the coefficient estimated from the Priestly and Thurston model when the wind speed ranges from 0 to 6 m/s. Because the monitored wind speed is different at different height level, the inputted wind speed in each heat-convection coefficient solution may refer to the wind speed at different height. That is, each model may specify a different wind speed as the input, even though the wind speed is recorded from the same weather station. In the Blasius solution [Eq.(7)], the inputted wind speed is recorded from either the weather stations or local airports, being collected at 9 m above a flat ground surface. The speeds in Eqs. (11) and (12) are based on laboratory or empirical regression; they are recorded at approximately 0.5 m above the concrete specimen surface. One can estimate the wind speed at 0.5 m above ground surface by transforming the weather-station collected wind speed by use of Eq. (13) [25].

$$w = w_{rec}(z/z_{rec})^{1/7} \quad (13)$$

where w_{rec} is the recorded wind speed provided by a weather station; z_{rec} (m) is the height at which the wind speed is measured by weather stations, $z_{rec} = 9$; and z (m) the height of the required wind speed w thus $z = 0.5$. Equation (13) thus becomes:

$$w = 0.662 w_{rec} \approx 2/3 w_{rec} \quad (14)$$

Equation (14) indicates that the recorded wind speed provided by a local weather station is roughly one and half times higher than the wind speed at 0.5 m above the ground surface. This means that the heat convection coefficient would be overestimated if the wind speed recorded from weather station is directly used in the EICM [Eq. (10)], Priestley and Thurston solution [Eq. (11)], and Bentz solution [Eq. (12)].

Use the transformed wind speed to compute the heat convection coefficient result in a better agreement between the Bentz solution and the Blasius solution; whereas the Priestley and Thurston solution potentially overestimates the heat convection coefficient (Fig. 7). This transformation decreases the h_{conv}-increasing rate of the Bentz solution to more closely match the increasing rate of the Blasius solution. The transformation also reduces the h_{conv}-increasing rate of the Priestley and Thurston solution, yet the relatively-large free h_{conv} of this solution results in h_{conv} still higher than the other solutions.

5 Conclusions

The development of a heat transfer model for pavement applications is described to account for both free and

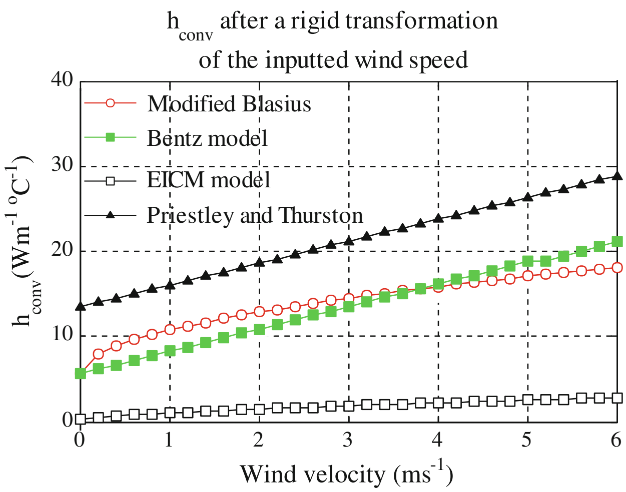

Fig. 7 Comparison of heat convection coefficients after making a transformation (transformation in *X*-axis) of the inputted wind speed

forced convection of the pavement surface, among other features. Studying the effects of convection, the computation of the heat convection coefficient can highly influence the temperature prediction of a concrete slab to a degree of 0–10 °C depending on the heat-convection solution utilized. One such model (the EICM model) potentially overestimates the pavement slab's temperatures due to the lack of convection cooling with increased wind speed.

There exists a rigid transformation between the inputted wind speed of the empirical heat-convection model and the wind speed recorded from local weather stations. To better account for this effect, a heat convection coefficient should utilize this transformed wind speed to more accurately reflect the wind speed conditions nearest the pavement surface. The use of this transformed wind speed promises more rational heat-convection coefficients for use in a heat transfer model.

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