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Development of pavement temperature predictive models using thermophysical properties to assess urban climates in the built environment

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ABSTRACT

This study developed pavement temperature predictive models based on the characterized thermophysical properties of different pavements to assess urban climates in the built environment. A database comprising of six pavement types including conventional and modified asphalt, and cement concrete mixtures was available with their thermophysical properties: specific heat capacity, thermal conductivity and material density. Models were developed to predict temperature at the surface, and at 40 mm depth using the measured thermophysical properties, and recorded climatological parameters: air temperature, wind speed, and relative humidity. The two predictive models were robust and rational depicted by low bias and high precision. An increase in heat capacity increased pavement surface temperature indicating that higher energy is required to raise the pavement temperature, and also be able to release as much energy as stored, which would be best suitable at different times of the day to counter urban heat island (UHI) effects. An increase in thermal conductivity decreased pavement temperature illustrating that the pavement would store more heat within the system for a longer duration, and may release this heat at a particular timeframe changing the urban climate at that moment. An increase in wind speed by about 1 m/s increased pavement temperature by 1 °C, and this may increase UHI if there is already higher temperature in the environment. Overall, based on rational correlations between model predictions and actual field measurements it is recommended that the pavement temperatures of the systems be comfortably predicted for pavements using the developed models.

1. Introduction

It is of great concern that a global rise in the human needs due to an ever-increasing world's population has mutated rural setups into urbanized and industrialized expanses requiring higher demand for energy and resources (United Nations, 2013). Urbanization entails a need for better infrastructure, including new facilities in the built environment and transportation related activities. In the framework of transportation infrastructure, paved surfaces encompassing highways, streets, and parking lots cover anywhere between one-fourth and one-half of the urban built-up areas (Gui, Phelan, Kaloush, & Golden, 2007). An important effect due to pavement infrastructure development is the Urban Heat Island (UHI) phenomenon that generates a temperature differential between the rural setup and the built urban environment/city (Oke, 1987; Pomerantz, Akbari, Chen, Taha, & Rosenfeld, 1997; Gartland, 2008). A rational way to reduce UHI effects and change the course of regional urban climates is to engineer pavement systems by modifying the material ingredients within them. One of such engineered pavement systems is "cool pavement" technology defined as a mix range of established and emerging materials and technology (U.S. Enviromental Protection Agency, 2008).

Cool pavement materials and technologies have been efficient in reducing pavement surface temperature and also are effective in storing less heat within the system as in other words have been found to release less heat to the atmosphere. Several parameters such as solar energy and reflectance (albedo), thermal emittance and permeability have affected pavement temperatures in a significant manner. Researchers (Gui et al., 2007; Pomerantz et al., 1997; U.S. Enviromental Protection Agency, 2008; ACPA, 2002; Levinson & Akbari, 2002; Pomerantz, Akbari, Chang, Levinson, & Pon, 2003; Akbari, Menon, & Rosenfeld, 2009; Sarat & Eusuf, 2012; Maria, Rahman, Collins, Dondi, & Sangiorgi, 2013; Guntor, Din, Ponraj,

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& Iwao, 2014) have recommended modification of key thermal properties such as albedo and thermal conductivity in order to design a cool pavement system. These studies have considered the thermophysical properties to design cooler systems by means of accounting only one of the parameters individually but not in a comprehensive interactive manner.

Previously, UHI mitigation strategies focused on cool roof structures with a variety of new designs and materials. However, with the increased development in pavement infrastructures, the contribution of pavements on UHI has also been significant in that the perviousness of the natural ground has transformed into an impervious one that fundamentally stores excess heat due to increase in thermal mass. This has resulted in an increase in the surface and near surface air temperatures, which are deemed very vital in augmenting UHI effects. Therefore, there is a need to investigate and quantify the contribution of roads on UHI phenomenon by understanding all of the major thermophysical properties of pavement materials. But then, a limited research (Gui et al., 2007; Yavuzturk, Ksaibati, & Chiasson, 2005) is available that investigates the thermophysical properties and relates these parameters with pavement temperature which ascribe to that of UHI. The principle behind these models is based on a transient energy balance of the pavements, which includes heat transfer by convection, conduction, and solar and infrared radiation.

Thus, there is a definitive need to characterize the chief thermophysical properties of different pavement materials and hence quantify the contribution of each of those parameters in a comprehensive manner. This process is best achieved through the development of mathematical models that can assess thermal behavior of pavement materials and is able to recommend suitable systems as UHI mitigation strategies. In one of the previous studies conducted on UHI related to buildings and environment, the modeling process adopted was of similar algorithm but limited to small scale modeling (or region specific) methodology (Mirzaei & Haghighat, 2010). Thus, the main objective of this research study conducted as part of (Shashwath, 2015) was to establish diurnal pavement temperature predictive models for different pavement systems based on the characterized thermophysical properties, which will help assess urban climates in a comprehensive manner. The scope of the effort included: (i) Assemblage of the estimated thermophysical properties of the different mixtures; (ii) Development of pavement temperature predictive models using thermophysical properties; (iii) Establishment of laboratory—field correlations for different pavement systems; (iv) Validation of the predictive models using field pavement sections and properties; and (v) Assessment of urban climates based on quantified thermal behavioral properties of different pavement materials.

It would be worthwhile to integrate the models developed in this study with the model(s) already available within the literature in the larger ambit of buildings and environment, thus including pavement parameters to build sustainable cities in a greener society.

2. Data collection

The database assembled to develop pavement temperature predictive models comprised of the measured/calculated thermophysical properties for six pavement mixtures produced in the laboratory, which included: (a) AROPEN: asphalt-rubber open graded with 18% air voids and 9% asphalt content; (b) ARGAP: asphalt-rubber gap graded with 8% air voids and 7% asphalt content; (c) DGAC1: conventional dense graded asphalt with 4% air voids and 4.5% asphalt content; (d) DGAC2: conventional dense graded asphalt with 7% air voids and 4.5% asphalt content; (e) CPCC: conventional dense cement concrete with 15% cement content; and (f) PERVCC: pervious concrete with 20% air voids and 18.86% cement content by volume. Note that three cylindrical samples of 150 mm diameter and 150 mm height were prepared for each mix to determine specific heat capacity (C_p) as per (ASTM, 1999) and thermal conductivity (k) as per the modified version of (ASTM, 2006a) and used in (Carlson, Bhardwaj, Phelan, Kaloush, & Golden, 2010). Three slab samples of 500 mm × 400 mm × 75 mm were prepared for each mix to measure albedo (α) which followed (ASTM, 2006b); and pavement temperature (T_p) at the surface and 40 mm depths for 24 h.

A total of 36 sample data points were used to determine C_p and k; and 60 slab sample data points were available for the determination of α and T_p. All of the thermophysical properties that were determined in the laboratory and are reported in (Mirzaei & Haghighat, 2010); the pavement temperature measurements were conducted in the field on the same sample mixtures. Table 1 provides summary of the thermophysical properties of the six pavement mixtures.

T_p at the surface and at a depth of 40 mm for each mix were determined along with the recording of climatological data such as wind speed, humidity and air temperature in the field area where samples were placed. The difference between air and pavement surface temperatures was in the range of 10 to 30 °C depending on the mix type.

3. Development of pavement temperature models

3.1. Selection of factors

Pavement temperature is a function of various climatic and thermophysical properties. The climatological properties mainly include wind speed, relative humidity, and air temperature; thermophysical properties encompass specific heat capacity, thermal conductivity, and density. T_p of different pavement types in this study were collected at the surface and at 40 mm below the surface of the pavement. The wind speed was measured using an anemometer, the relative humidity was measured using a hygrometer, and the air temperature was measured using a thermocouple, which was connected to the data logger. Two pavement temperature predictive models were developed to predict pavement surface temperature and temperature at 40 mm depth below the surface. The models were developed using least square regression technique which relies on minimizing the sum of squared errors between the observed and predicted values. Further, the models were assessed for their robustness using sensitivity analyses and validated based on field studies.

Table 1
Summary of thermophysical properties of six pavement mixtures.

Pavement type	Specific heat (J/kg/°C)	Thermal conductivity (W/m/K)	Thermal diffusivity (m^2/s)	Albedo	Density (kg/m^3)
AROPEN	664	0.51	3.87E − 07	0.07	2003.985
ARGAP	863	0.77	3.87E − 07	0.07	2309.688
DGAC1	933	0.88	3.87E − 07	0.07	2428.964
DGAC2	1039	0.96	3.92E − 07	0.07	2361.875
CPCC	1154	1.02	4.11E − 07	0.20	2148.725
PERVCC	1665	1029	3.87E − 07	0.15	2005.116

Table 2
Parameter coefficients of $T_{surface}$ predictive model.

Variables	Parameter coefficient	Std. Error	*t*-Value	*P*-value
(Constant)	−29.117	14.034	−2.075	0.039
Specific heat	0.016	0.008	2.051	0.042
Thermal conductivity	−26.505	9.462	−2.801	0.006
Wind speed	4.301	0.432	9.951	0.0001
Relative humidity	−0.115	0.072	−1.597	0.112
Air temperature	1.612	0.263	6.127	0.0001
Density	0.014	0.004	3.574	0.0001

Table 3
ANOVA summaries for $T_{surface}$ predictive model.

Source	Sum of squares	DF	Mean square	*F*	Significance
Regression	39006.370	6	6501.062	418.815	0.0001
Residual	3337.341	215	15.523		
Total	42343.710	221			

3.2. *Pavement surface temperature predictive model,* $T_{surface}$

The surface of the pavement gets heated up to 10–20 °C higher than the air temperature since it is exposed to direct solar radiations and secondly by convection through the circulation of heated air. The higher surface temperature is known to adversely affect the serviceability of pavements which is also known to increase the UHI effect. The pavement materials being made up of different materials such as conventional and modified asphalt mixtures, and cement concrete have different thermophysical properties that affect the temperature distributions in a pavement (Table 1). The first pavement temperature model, namely, $T_{surface}$ predictive model for different pavement mixtures was developed using the six variables mentioned above. The correlation between the dependent and predictive variables was first studied using a correlation matrix. It was found that at 95% confidence level, $T_{surface}$ had high positive correlation with wind speed (+86.3% significance) and air temperature (+92.7% significance), and high negative correlation with relative humidity (−90.1% significance). Further, the thermophysical properties such as C_p and k showed inverse correlations of -14.1% and 13%, respectively with $T_{surface}$, while density (ρ) was about −9% negatively correlated with $T_{surface}$ property. The final $T_{surface}$ predictive model based on 222 (6 mixes × 37 temperature recordings) data points was given by:

$$T_{surface} = -29.117 + 0.016C_p - 26.505k + 4.301W_s - 0.115RH + 1.612T_{air} + 0.014\rho \quad (1)$$

where $T_{surface}$ is the pavement surface temperature, °C; C_p is the specific heat capacity, J/kg/°C; k is the thermal conductivity, W/m K; W_s is the wind speed, m/s; RH is the relative humidity, %; T_{air} is the air temperature, °C; ρ is the density, kg/m^3.

It has to be noted that, though albedo was measured in this study, it was not used in the formulation of the model due to an increase in the standard error of regression coefficients. The statistical significance of each parameter coefficient of the different predictive variables is shown in Table 2. The predictive variables had significant relations with $T_{surface}$ as indicated by very low *P*-value (i.e., <0.05) except relative humidity. This suggests that the variables used in this model were able to capture the variation in

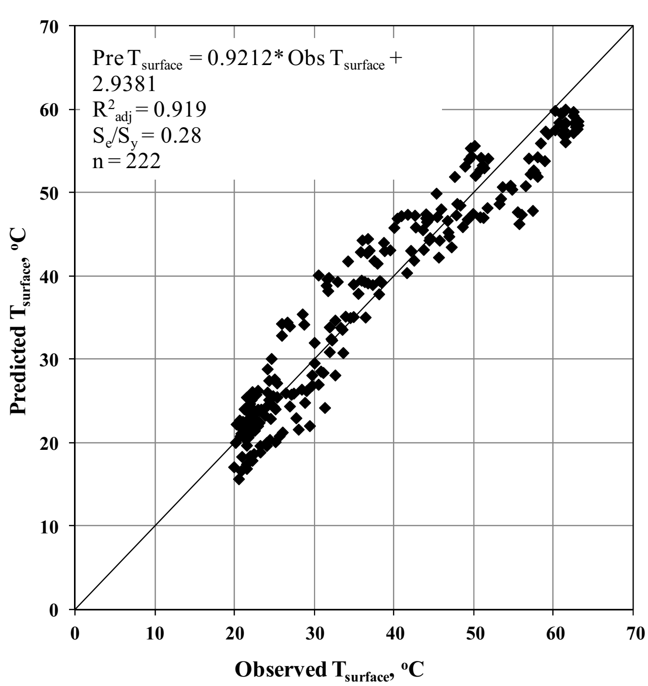

Fig. 1. Observed versus predicted $T_{surface}$.

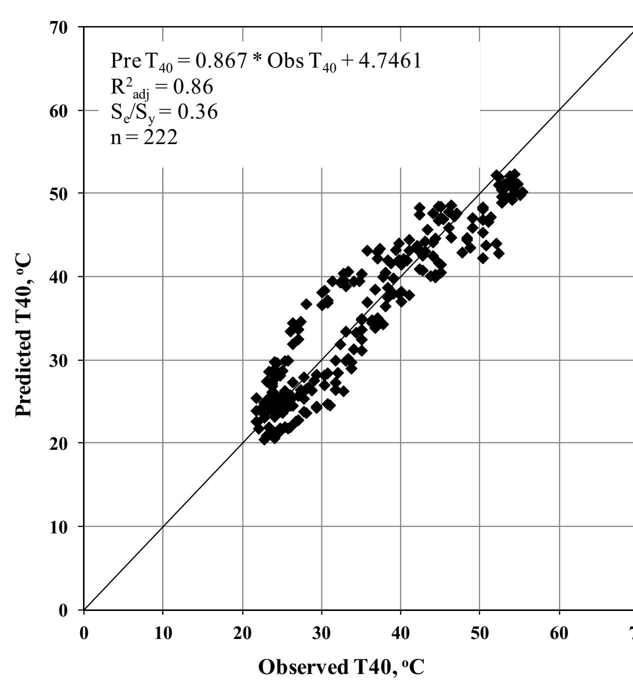

Fig. 2. Observed versus predicted T_{40}.

Table 4
Parameter coefficients of T_{40} predictive model.

Variables	Parameter coefficient	Std. Error	*t*-Value	*P*-value
(Constant)	−6.757	13.569	−0.498	0.619
Specific heat	0.019	0.007	2.551	0.011
Thermal conductivity	−26.508	9.150	−2.897	0.004
Air temperature	0.784	0.254	3.084	0.002
Density	0.015	0.004	4.072	0.001
Wind speed	3.024	0.418	7.234	0.001
Relative humidity	−0.208	0.070	−2.975	0.003

Table 5
ANOVA summaries for T_{40} predictive model.

Source	Sum of squares	DF	Mean square	*F*	Sig.
Regression	20472.978	6	3412.163	235.111	0.001
Residual	3120.289	215	14.513		
Total	23593.267	221			

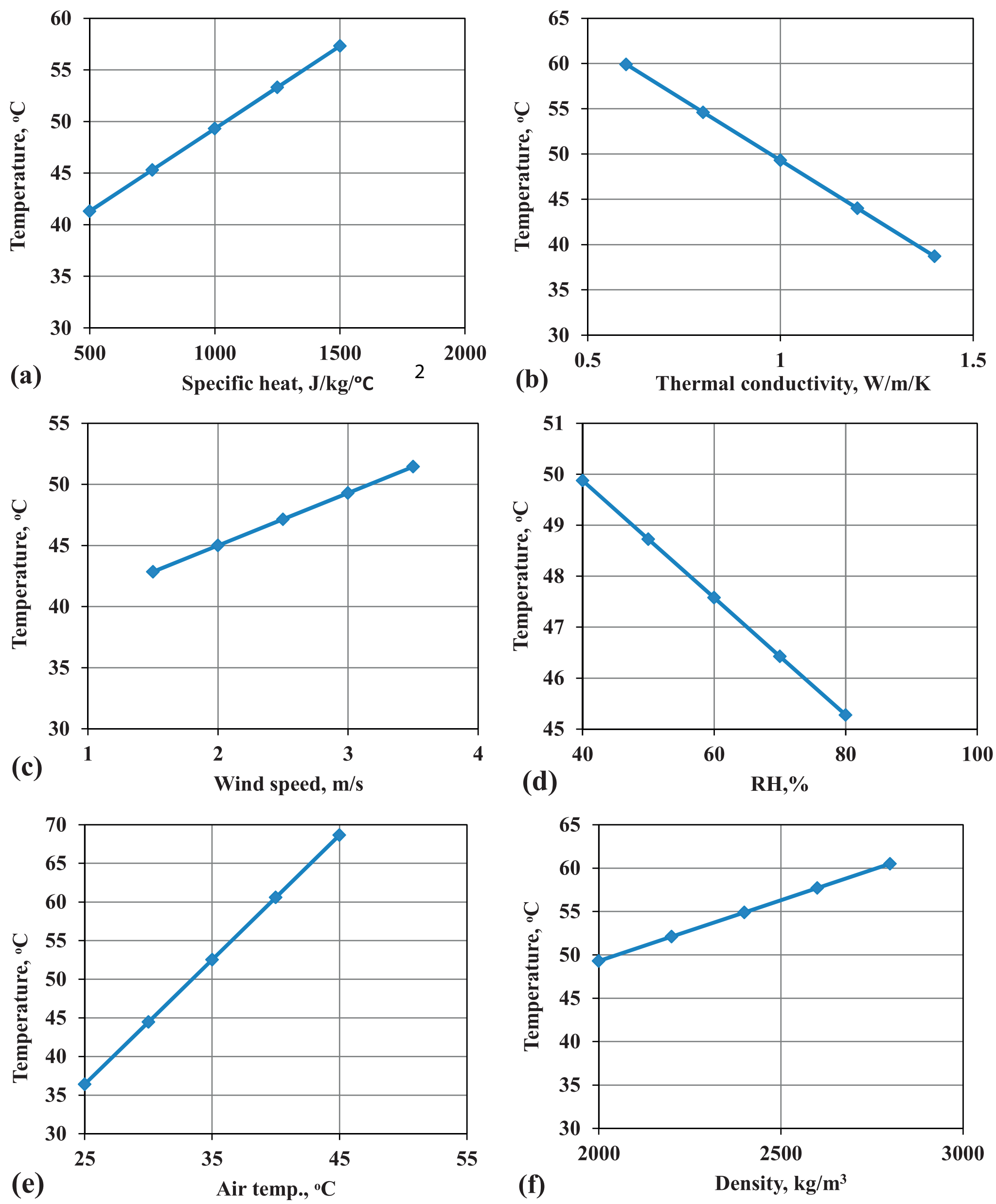

Fig. 3. Model parameters' sensitivity analyses.

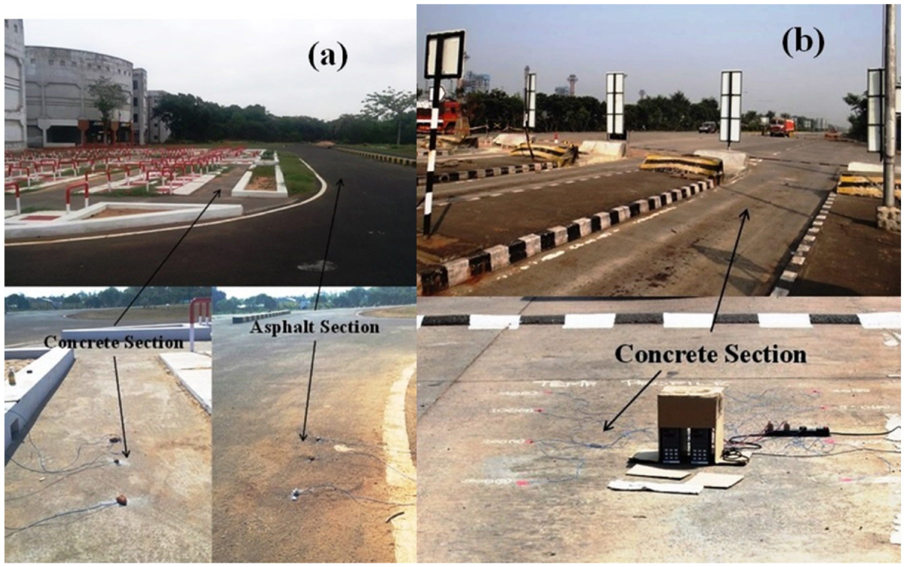

Fig. 4. Model validation sites: (a) Nalanda location, Indian Institute of Technology Kharagpur campus; (b) National Highway NH 60 toll plaza.

$T_{surface}$ of different pavement types. The model was rational since the increase in specific heat capacity, air temperature, and density increased the surface temperature. The materials with higher specific heat require more heat energy to increase its temperature by 1 °C, and hence higher $T_{surface}$. Though the above two findings are contradictory, it will only be wise if other factors are also considered and studied simultaneously to understand the concept better.

In continuation, with decrease in thermal conductivity and relative humidity, there was an increase in $T_{surface}$ since the material with lower thermal conductivity would take more time to conduct heat to lower layers, and hence would show higher surface temperature. In order to investigate the robustness of the model, Analysis of Variance (ANOVA) was carried out and the result is as shown in Table 3. The ANOVA results showed a significant difference from the null hypothesis that was indicative of the rationality of the model. Further, the observed values of the $T_{surface}$ of pavement were compared with the model predicted values and shown in Fig. 1. The correlation was excellent ($R^2{}_{adj} \geq 0.90$) with low bias and high precision (illustrated by the points that were closer to the equality line) with $S_e/S_y \leq 0.350$.

One of the limitations of the model is that it does not consider moisture effects. Also, it is noteworthy that the model developed in the study is not related to any basic assumptions of heat transfer and therefore, may not utilize charts and theory of heat transfer applications.

3.3. *Pavement temperature at 40 mm depth predictive model,* T_{40}

Pavement temperature at 40 mm below surface (T_{40}) is important to understand the structural behavior of the pavement layers in the system. Most of the design guidelines use pavement temperature at 40 mm depth as an input for characterizing the thermal behavior of pavements. The second model which predicts pavement surface temperature at 40 mm depth below the surface was also developed with the same six variables described before. The correlations between the predictor variables and the dependent T_{40} variable revealed the following. At 95% confidence level, T_{40} had high positive correlation with wind speed (+83.1% significance) and air temperature (+90.0% significance), and high negative correlation with relative humidity (−88.6% significance). Further, the thermophysical properties such as C_p and k showed inverse correlations of −10.0% and −8.4%, respectively with T_{40}, while density (ρ) was about +11.2% positively correlated with T_{40}. The final T_{40} predictive model based on 222 (6 mixes × 37 temperature recordings) data points was given by:

$$T_{40} = -6.757 + 0.019C_p - 26.508k + 0.784T_{air} + 0.015\rho + 3.024W_s - 0.208RH \quad (2)$$

where T_{40} is the pavement temperature at 40 mm depth below surface, °C; C_p is the specific heat capacity, J/kg/°C; k is the thermal conductivity, W/m/K; W_s is the wind speed, m/s; RH is the relative humidity, %; T_{air} is the air temperature, °C; ρ is the density, kg/m^3.

The significance of the parameter estimates are shown in Table 4, including the *P*-value that is indicative of the model's rationality. The summary showed that the variables chosen to predict T_{40} are all significant at 95% confidence level similar to that seen in the previous model which can be seen in Table 2. Additionally, in order to check the overall robustness of the model, ANOVA test was carried out as shown in Table 5, which indicated that the model was robust to explain the variation in T_{40}. The observed and predicted values of the T_{40} were plotted as shown in Fig. 2. The correlation between the observed and predicted values showed that there was low bias and high precision, and thus can be recommended to be used to rationally predict T_{40} for various types of pavement systems given the thermophysical properties and climatological parameters. Note that though albedo is an important parameter in defining thermal behavior of pavements; since it is only a surface property that depends on smoothness and texture of the pavement surface, it was not considered in the development of the two pavement temperature predictive models.

3.4. *Model sensitivity analyses: Discussion*

Sensitivity analyses were carried out on the developed pavement temperature predictive models to understand the significance of different thermophysical properties and climatological parameters on pavement temperatures. Fig. 3 presents the variation of pavement temperature due to different properties and parameters. An increase in C_p increased the T_p, which indicated that higher energy would be required to raise the temperature of a pavement system (Fig. 3(a)). It is expected that the pavement material that has the highest C_p by virtue of its material properties may be able to release as much energy as it has stored and would be best suitable at different times of the day to counter UHI effects,

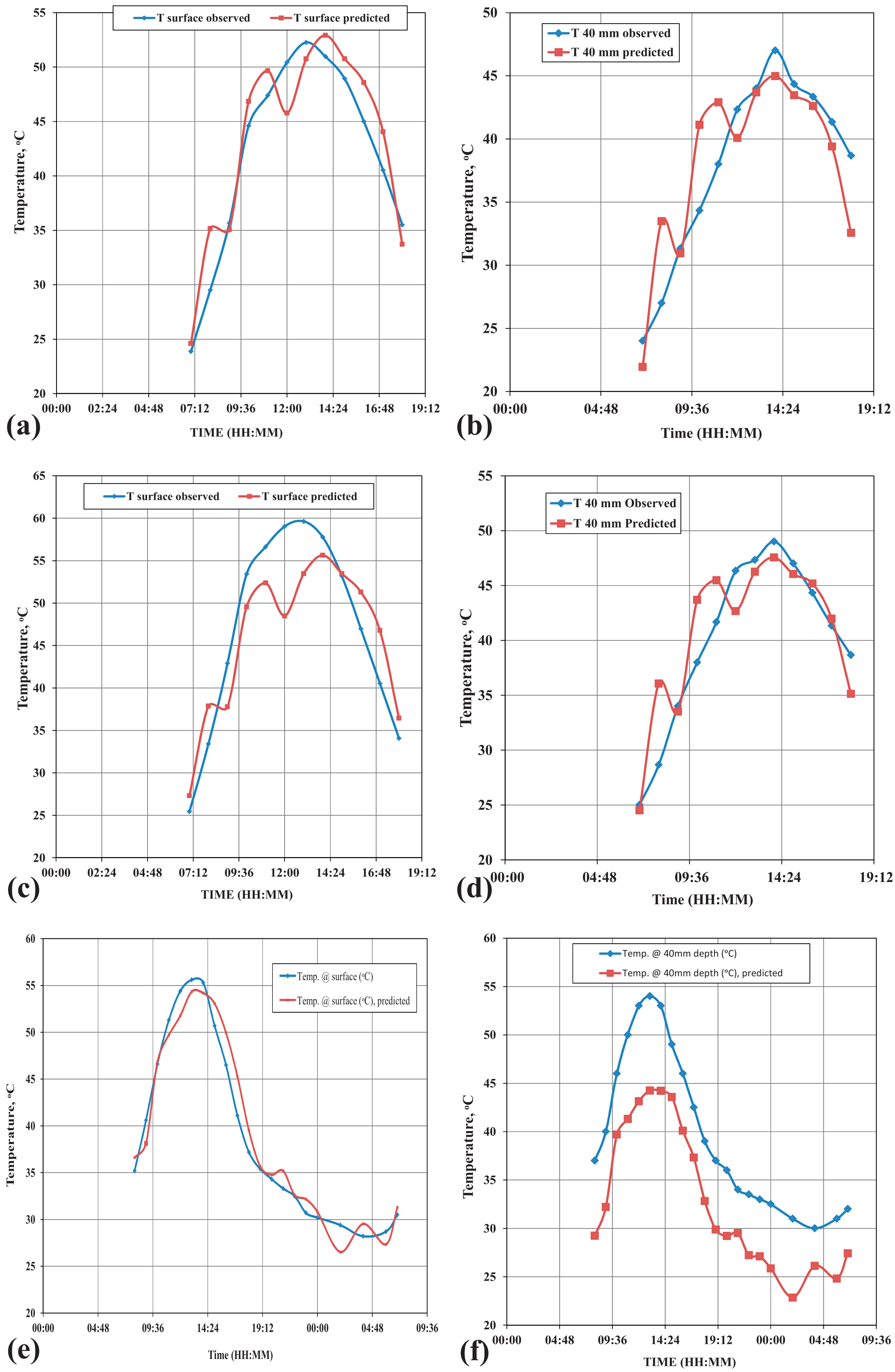

Fig. 5. Measured versus models predicted for: (a) T_p of CC, IITKGP; (b) T_{40} of CC, IITKGP; (c) T_p of AC, IITKGP; (d) T_{40} of AC, IITKGP; (e) T_p of CC, NH 60; and (f) T_{40} of CC, NH 60.

which require accurate designs. It is also evident from Fig. 3(b) that an increase in k decreased T_p. It is important to note that k is a parameter which describes the rate of heat transfer across the pavement system and into the ground. Therefore, a material with lower k would store higher heat within the system for a longer duration, and is expected to release this heat at a particular timeframe possibly changing urban climate at that period of time. Therefore, designers must be skillful to balance the effects of C_p and k for UHI effects.

From Fig. 3(c), one can observe that with the increase in W_s by about 1 m/s and keeping all other parameters constant, T_p increased by 1 °C. Therefore, it is expected that higher W_s would possibly increase UHI if there is already higher temperature in the environment. But, higher W_s increasing the T_p would occur due to its material properties such as pavement's C_p and k as discussed earlier. A combination of higher W_s and T_p would render the atmosphere to be warmer. One of the other possible reasons for increase in the T_p due to an increase in the W_s is as follows: the air which gets heated up by the mid-day is lighter due to a reduced moisture content in the air. This hot air, which is not heavy, could be easily carried away by the wind at a greater speed. Further, the same hot air would transfer the heat to the pavement surface by the convection process.

An increase in RH decreased T_p as observed in Fig. 3(d). This correlation calls for further investigation of other properties of pavement systems that get cooler due to additional moisture in air, sometimes called the evaporative cooling effect. In fact, the evaporative cooling effect parameter would help the material to lower the temperature within the system and is a benefactor in mitigating UHI effects. Further, an increase in air temperature by about 5 °C increased the T_p by about 10 °C (Fig. 3(e)). This is a well-studied phenomenon and also observed by measurements in this study. Both T_{air} and T_p have always correlated positively to each other with T_p being higher than T_{air} owing to different material properties of the pavements. The increase in ρ (a material property) increased T_p as observed in Fig. 3(f). It is obvious that pavement material's higher ρ would make the mix to have higher temperature release rate as there is less scope for heat absorption within the system. Based on the various correlations, it is just not straightforward to state which material would be best suited for obviating UHI effect, but a careful but skillful design would help the local atmosphere less affected by pavements and vice versa.

4. Model validation

The efficiency of the two pavement temperature predictive models developed was tested by validating the models against the field data collected as part of the investigations. In order to validate the models, two sites were considered:

- Nalanda complex on-campus Indian Institute of Technology Kharagpur (IITKGP), West Bengal, India: is an open area (Fig. 4(a)) comprising of conventional asphalt concrete (AC) and conventional cement concrete (CC) pavement surfaces, and
- National Highway NH 60 (Fig. 4(b)): about 25 km from IITKGP campus that constituted cement concrete (CC) pavement section.

$T_{surface}$ and T_{40} were measured half-hourly for 12-h duration at the first site and for 24 h at the second site. Further, the climatological data including W_s, RH and T_{air} were also recorded. Field cores were not taken from the sites but thermophysical properties such as C_p and k were assumed suitably from actual measurements on laboratory samples corresponding to pavement types. All the variables were used to predict $T_{surface}$ and T_{40}, and are shown in Fig. 5(a)–(f) for corresponding sites and respective pavement types. As observed, the predictions matched well with the observed pavement temperatures validating the robustness of the models. There is a small discrepancy in the observations made in Fig. 5(f). This may be attributed to the improper placement of thermocouples used for temperature measurements. However, the trends of both measured and predicted profiles of temperature are similar. It is recommended that $T_{surface}$ and T_{40} be comfortably predicted for both asphalt and cement concrete mixture types of pavements using the models developed in the study.

5. Conclusions and recommendations

The main objective of this research study was to establish pavement temperature predictive models for different pavement systems based on the characterized thermophysical properties, which will help assess urban climates in a comprehensive manner. The database assembled to develop the predictive models comprised of the measured thermophysical properties for six pavement mixtures produced in the laboratory, including conventional and modified asphalt and cement concrete mixtures with varying properties. A total of 96 sample data points were available from measurements of thermophysical properties: C_p, k and ρ. Two pavement temperature predictive models were developed to predict $T_{surface}$ and T_{40} using measured thermophysical properties and recorded climatological parameters such as T_{air}, W_s, and RH. Based on the findings, the salient conclusions and recommendations of the study are under:

- $T_{surface}$ predictive model was mathematically robust and excellent with $R^2_{adj} \geq 0.90$; $S_e/S_y < 0.35$; low bias and high precision. The model was rational since the increase in C_p, T_{air}, and ρ increased $T_{surface}$ during heating and could be different during pavement cooling. The materials with higher C_p require more heat energy to increase its temperature by 1 °C, and hence higher $T_{surface}$. In continuation, with decrease in k and RH, there was an increase in $T_{surface}$ since the material with lower k would take more time to conduct heat to lower layers, and hence would show higher $T_{surface}$. T_{40} predictive model was also mathematically robust and depicted low bias and high precision ($R^2_{adj} \geq 0.85$; $S_e/S_y = 0.36$), and thus can be recommended to be used rationally to predict the T_{40} for different types of pavements.
- Sensitivity analyses of the predictive models with respect to different thermophysical properties and climatological parameters were performed to understand their influence on UHI effects. (a) An increase in C_p increased T_p, which indicated that higher energy would be required to raise the temperature of a pavement system. It is expected that the pavement material that has the highest C_p by virtue of its material properties may be able to release as much energy as it has stored and would be best suitable at different times of the day to counter UHI effects. (b) An increase in k decreased T_p. It is noteworthy that k is a parameter which describes the rate of heat transfer across the pavement system and into the ground or back into the atmosphere. Therefore, a material with lower k would store higher heat within the system for a longer duration, and is expected to release this heat at a particular timeframe possibly changing urban climate at that period of time. (c) With the increase in W_s by about 1 m/s and keeping other parameters constant, T_p increased by 1 °C. Therefore, it is expected that higher W_s would possibly increase UHI if there is already higher temperature in the environment. A combination of higher W_s and T_p would render the atmosphere to be warmer. (d) An increase in T_{air} by about 5 °C increased T_p by about 10 °C. (e) Further, an increase in ρ increased T_p. It is obvious that pavement material's higher ρ would make the mix to have higher

temperature release rate as there is less scope for heat absorption within the system.

- The model predictions were also validated using field studies on actual pavement sections and were found to be correlating well with the measured pavement temperatures based on thermo-physical and climatological parameters. It is recommended that $T_{surface}$ and T_{40} be comfortably predicted for both asphalt and cement concrete pavement types using the models developed in the study.
- *Future scope of study*: One of the limitations of the developed models is that they do not consider moisture effects. Therefore, future studies must incorporate this parameter to understand the effects of moisture on pavement temperature variations. Further, the process of heat transfer in pavements is entirely different from those observed in other structures. In this direction, it is recommended that future models must consider establishing heat transfer charts and equations for pavements. Finally, it would be worthwhile to integrate the models developed in this study with the model(s) already available within the literature in the larger ambit of buildings and environment, thus including pavement parameters to build sustainable cities in a greener society.

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