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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 (m²/s)	Albedo	Density (kg/m³)
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