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Innovative Chromogenic Materials for Pavement Life Extension: Modeling Study of Surface Temperature of Sustainable Asphalt Pavement

Jianying Hu[1], Xiong (Bill) Yu[1+], and Junliang Tao[1]

Abstract: Asphalt pavements are widely used in highways due to their good performance and relatively low construction and maintenance costs. However, the black color of asphalt induces that the sunlight is not reflected but absorbed, which raises the temperature of the asphalt pavement and impacts its long-term durability. Thermochromic materials are substances that can reversibly change their colors in response to temperature. This innovative is to incorporate thermochromic materials into asphalt to improve the durability of asphalt pavement. By fine-tunig the threshold temperature, the material can potentially produce a larger solar reflectance at high temperatures. Consequently, this will help reduce the temperature on the surface of asphalt pavement. The long term goal is to make pavement more reflective during summer and more solar absorptive during winter. In this paper, FEM simulation is conducted to study the influence of thermochromic materials on the surface temperature of asphalt pavement. The results show that the surface temperature of asphalt pavement doped with thermochromic materials is significantly lower compared to that of conventional asphalt pavement. In the meanwhile, conventional asphalt pavement underwent higher magnitude of temperature variations compared with thermochromic asphalt pavement. The decreased surface temperature and lower heat flux of thermochromic pavement both contribute to better pavement performance.

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Key words: *Asphalt pavement; Heat island effects; Sustainability; Thermal properties; Thermochromic.*

Introduction

Asphalt pavements are widely used in highways due to their good performance and relatively low construction and maintenance costs. However, the black color of asphalt has large solar absorption that lead to high temperature at the surface of asphalt pavement, which can be as high as 48-67 °C during summer [1-3]. The increased temperature impacts durability of asphalt pavement due to certain distress mechanisms (i.e., rutting, shoving, aging, fatigue damage, bleeding) associated with temperature [4]. One potential way to improve durability that has gained attention in the past years is the use of materials that present high reflectivity during the summer period [5-7].

Thermochromic materials are substances that can change their colors in response to temperature. Above certain temperature, they reflect solar energy (mainly infrared radiation); under that temperature, they mainly absorb solar energy. The specific temperature that causes the transition is called the "switching temperature". The reversible temperature-dependent transformation of thermochromic materials is attributed to the variations of the molecular structures associated with temperature, such as phase transition in a compound (e.g., in an organic chromophore), changes in ligand geometry, variation in the crystal field or the number of solvent molecules in the coordination sphere (e.g., in a pure transition metal complex that derives its color from crystal field effects), and more complex factors in multicomponent mixtures [8]. Thermochromic materials are characterized by high solar reflectance in summer and high solar absorption in winter. These properties were used in building materials to achieve energy efficiency and comfort [9, 10]. Ma and Zhu [11] prepared thermochromic cement by combining thermochromic materials with cement, which has potential to heat buildings during winter and avoid buildings overheating during summer.

In this paper, thermochromic asphalt was firstly prepared by mixing conventional asphalt with thermochromic materials. The thermal responses of pavement with thermochromic asphalt and conventional asphalt are studied by FEM simulations.

[1] Department of Civil Engineering, Case Western Reserve Univ., 2104 Adelbert Road, Bingham 203C, Cleveland, Ohio, USA.

[+] Corresponding Author: E-mail xxy21@case.edu

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Preparation of Thermochromic Asphalt

Organic thermochromic pigments made by Hali Industrial Coporation Ltd. were used to develop thermochromic asphalt. Red, blue and black thermochromic pigments were chosen and their switching temperature is 31°C. The pigments are microencapsulated with an average particle of 3 - 10 μm (shown in Fig. 1).

Thermochromic asphalt was prepared by mixing the thermochromic powders with pure asphalt by certain percentage. Above the switching temperature, thermochromic asphalt reflects solar energy (mainly infrared radiation); under that temperature, it mainly absorbs solar energy (shown in Fig. 2). Pavement made by thermochromic asphalt is called thermochromic asphalt pavement in this paper. Both of energy-reflecting and energy-absorbing properties of thermochromic asphalt help to keep pavement at an appropriate temperature range and therefore improve long-term performance of the pavement structure.

Numerical Simulation

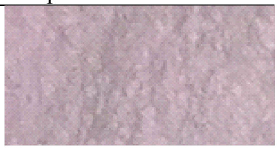
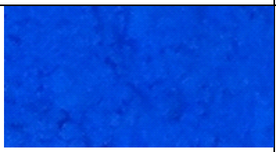
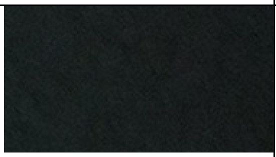
	Below the Switching Temperature	Above the Switching Temperature
Red		
Blue		
Black		

Fig. 1. Colors of Thermochromic Powders.

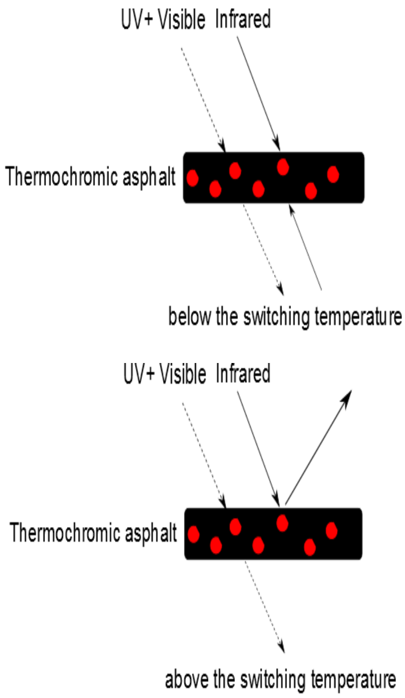


Fig. 2. Schematic of the Principle of Thermochromic Asphalt.

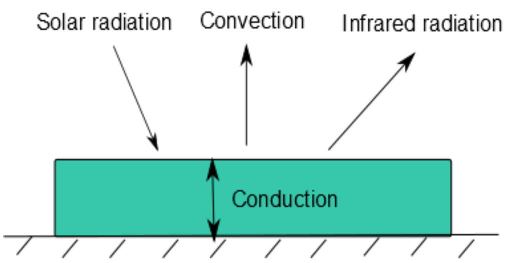


Fig. 3. Heat Transfer Mode between Asphalt Pavement and its Surroundings.

As the width and length of asphalt pavement is far greater than its thickness. Pavement temperature is mainly controlled by solar exchange and heat flux at its surface. Therefore, a one-dimensional heat transfer model provides reasonable prediction of the temperature distribution with depth in the pavement layer. The computational model used to simulate the pavement responses is based on a transient energy balance of the pavement, including convection, conduction and solar and infrared radiation, as shown in Fig. 3.

One-dimensional Heat Transfer Model

The one-dimensional transient heat conduction equation for the pavement is expressed as:

$$\rho c \frac{\partial T(x,t)}{\partial t} = k \frac{\partial^2 T}{\partial x^2} \tag{1}$$

where k (W/(m·K) is the thermal conductivity of the pavement; ρ (kg/m^3) and c (J/(kg·K)) are the density and the heat capacity of the pavement, respectively; T (K) indicates temperature of the pavement; x (m) and t (s) are coordinate and time, respectively.

Heat Flux at the Pavement Surface

Radiation Heat Transfer.

There are two solar radiation heat transfer modes at the pavement surface, i.e., absorption of solar radiation and infrared radiation. The effective incident solar radiation arriving at pavement surface can be described by the Eq. (2) [12]:

$$q_{sun} = (1-\gamma)I \tag{2}$$

where q_{sun} (W/m^2) is the short-wave absorption of solar radiation; γ is the solar reflectivity of the pavement surface; I (W/m^2) is the solar radiation.

The solar radiation strongly depends on the atmospheric conditions, time of day, and incident angle of the sun's ray one the ground surface. At night, the solar radiation is negligible. At daytime, the solar radiation intensity is approximated to a sinusoid function that alters with daytime and covers from zero at both sunrise and sunset to a peak value at midday [13, 14]. Moreover, according to McCullough and Rasmussen [15], the peak value of solar radiation is 1000 W/m^2 for a sunny day, 700 W/m^2 for a partly sunny day, and 300 W/m^2 for a cloudy day. In this study, the time of the peak value is assumed at 12:00. The solar radiation is expressed as:

$$I = \begin{cases} 0 & t < 6 \\ 1000 \sin\left[\frac{2\pi}{24}(t-6)\right] & 6 \le t \le 18 \\ 0 & t > 18 \end{cases} \tag{3}$$

where t (h) time.

Infrared radiation, q_{rad} is a long-wave heat flux between the natural ground surfaces and the sky. The total infrared radiation follows the Stefan-Boltzmann law and is described as

$$q_{rad} = \varepsilon\sigma\left(T_s^4 - T_{sky}^4\right) \quad (4)$$

where q_{rad} (W/m^2) is the emitted irradiation; ε is the pavement surface emissivity; σ (W/(m^{2}K^4)) is the Stefan-Boltzemann constant and equal to 5.669×10^{-8}; T_s (K) is pavement surface temperature; T_{sky} (K) is the effective sky temperature. According to Tang and Meir [16], T_{sky} could be evaluated by

$$T_{sky} = \left(0.754 + 0.0044T_{dp}\right)^{0.25}T_\infty \quad (5)$$

where T_∞ (K) is ambient temperature; T_{dp} (K) is the dew point. For comfortable environment, T_{dp} is generally in 13–16°C. In this simulation, the temperature of dew point is assumed to be 289.15 K. The ambient air temperature varies as a cosine function of time according to recorded temperature data.

Convection Heat Transfer

The pavement exchanges heat with air by the convective heat transfer at its surface:

$$q_{conv} = h_\infty\left(T_s - T_\infty\right) \quad (6)$$

where q_{conv} (W/m^2) is convection heat flux; h_∞ (W/(m·K)) is the convection coefficient. The convection coefficient was determined based on the wind speed available in the weather database and the following equations used in the commercially available FEMMASSE system [17]:

$$h_\infty = 5.6 + 4.0v_{wind} \quad for \quad v_{wind} \le 5 \quad m/s \quad (7)$$

$$h_\infty = 7.2 + 4.0v_{wind}^{0.78} \quad for \quad v_{wind} > 5 \quad m/s \quad (8)$$

In this simulation, v_{wind} is 3.5 m/s and so h_∞ is 19.6 W/(m^2·K).

Therefore, the total heat flux at the pavement surface can be expressed as:

$$q_{total} = q_{sun} - q_{rad} - q_{conv} \quad (9)$$

Simulation Information

The input parameters for the thermophysical properties of asphalt pavement used in the computer modeling include density (2300 kg/m^3), specific heat (1800 J/(kgK)), and thermal conductivity (1.8 W/(mK)). These parameters are assumed to be constant independent of temperature. The pavement thickness is 20 cm. Emissivity and solar reflectivity of pavements with black, blue and red thermochromic asphalt as well as pure asphalt is shown in Table 1. The initial temperature of the pavement is assumed to be 25°C. Air temperature and sky temperature use the above-mentioned data.

Results of Computational Simulations

FEM is used to simulate the thermal responses of pavement under solar radiation. The mechanisms such as solar absorption, solar reflection, emissivity, and heat exchange by convection are considered in the FEM model. The goal is to evaluate the effect of thermochromic asphalt on the surface temperature and heat flux of asphalt pavement under different ambient temperatures. In summer, the ambient temperature T_∞ (°C) is assumed to be $T_\infty = 30 + 10\cos\left[\frac{2\pi}{24}(t-12)\right]$. In winter, the ambient temperature is assumed to be $T_\infty = 10 + 10\cos\left[\frac{2\pi}{24}(t-12)\right]$. The results of model simulations are shown in Fig. 4(a) and 4(b) for summer conditions and Fig. 5(a) and 5(b) for winter conditions.

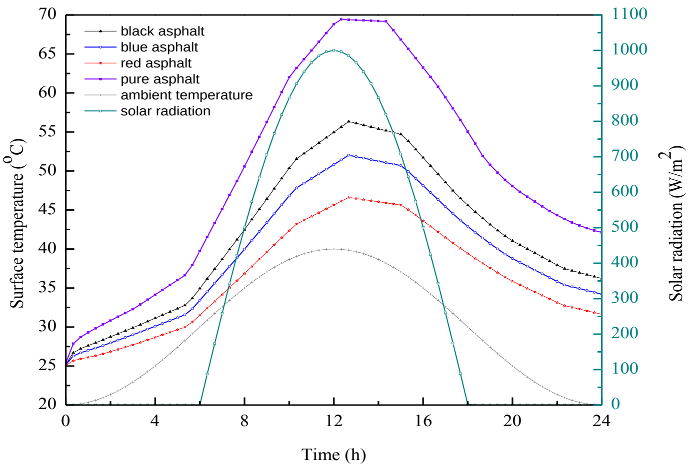
Fig. 4 summarizes the simulated pavement surface temperature in a typical summer day (with higher ambient temperature). Fig. 4(a) presents the influence of thermochromic materials on the surface temperature of asphalt pavement. Conventional asphalt pavement responds with highest surface temperature, with peak surface temperature of 68 °C. While the surface temperatures of thermochromic asphalt pavement are significantly lower than that of conventional asphalt pavement. The reduces of peak surface temperature compared with conventional asphalt pavement is 10 °C, 12 °C and 15 °C for black, blue and red by thermochromic asphalt pavement, respectively. The peak of the pavement surface temperature appears at around 13:00, which is related for one hour since the peak value of the solar radiation and ambient temperature is set at 12:00.

Fig. 4(b) shows the impact of thermochromic materials on the heat flux at the surface of the asphalt pavement. It can be seen that conventional asphalt pavement undergoes higher heat-loss and -gain cycles compared with thermochromic asphalt pavements. During the nighttime, conventional asphalt pavement experience less heat loss. The peak value of total heat flux occurs at around 13:00. After that time, total heat flux declined. At higher ambient temperature, the magnitude of heat loss of black, blue and red asphalt pavement is about 59.5, 74.8 and 93.1 W/m^2 less than pure asphalt pavement. The reduced heat flux across pavement surface also means the temperature variation of thermochromic pavement will be more moderate than conventional pavement.

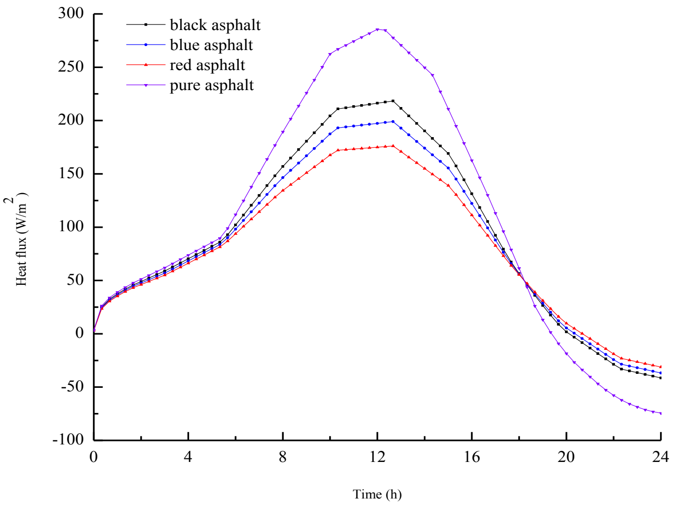
Fig. 5 summarizes the simulated pavement surface temperature in a typical day with low ambient temperature of 10 °C. Fig. 5(a) presents the influence of thermochromic materials on the surface temperature of asphalt pavement. The maximum decrease in the

Table 1. Emissivity and Solar Reflectivity Used in the Simulation.

Asphalt Sample	Black Asphalt		Blue Asphalt		Red Asphalt		Pure Asphalt
	Colored	Colorless	Colored	Colorless	Colored	Colorless	
	Phase	Phase	Phase	Phase	phase	phase	
γ	0.36	0.47	0.46	0.58	0.60	0.71	0.08
ε	0.90	0.88	0.88	0.85	0.86	0.82	0.93



(a)

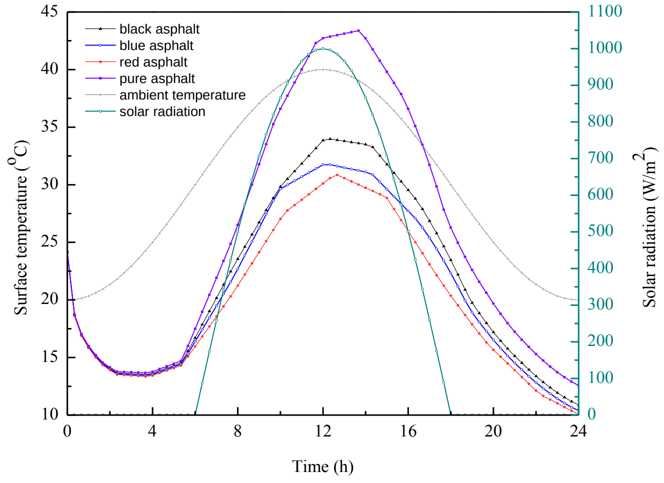


(b)

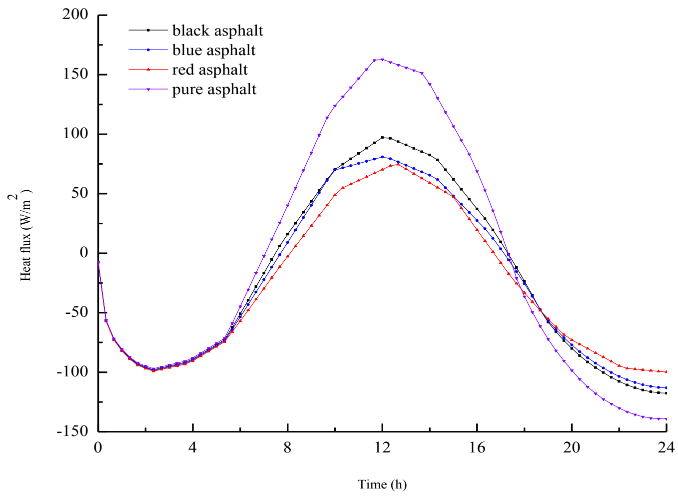
Fig. 4. Responses of Different Types of Pavement (Thermochromic versus Conventional Asphalt) to Typical Solar Radiation in Summer: a) Surface Temperature, b) Heat Flux.

pavement surface temperature is 9°C, 12°C and 13°C for black, blue and red asphalt pavement compared with traditional asphalt pavement, respectively. The reduced temperature is attributed to the reflection of sun light by thermochromic materials. The reduced temperature is attributed to the reflection of sun light by thermochromic materials. The reduced temperature and kept appropriate temperature range helps to improve long-term performance of asphalt pavement.

Fig. 5 shows the corresponding impact of thermochromic materials on the heat flux at the surface of the asphalt pavement. At this ambient temperature, the magnitudes of heat loss in the black, blue and red thermochromic asphalt pavement are about 66.1, 83 and 88.3 W/m^2 less than traditional asphalt pavement. The possible reason includes the differences in the solar absorption and infrared radiation at the pavement surface.



(a)



(b)

Fig. 5. Response of Different Types of Pavement (Thermochromic versus Conventional Asphalt) to Typical Solar Radiation in Winter: a) Surface Temperature, b) Heat Flux.

Conclusions

This paper describes a sustainable asphalt pavement made by incorporation of thermochromic asphalt. The influence of thermochromic materials on thermal responses of asphalt pavement was studied by FEM simulation. The simulation results indicated that the surface temperature of thermochromic asphalt pavement can be significantly lower than that of conventional asphalt pavement. The maximum decrease in the pavement surface temperature can be as high as 15°C by thermochromic materials in a sunny summer day with high ambient temperature. Besides, the heat exchange between pavement and air is also significantly reduced by use of thermochromic pavement materials. Both the reduced surface temperature and reduced amplitudes of heat-gain and –loss cycles of asphalt pavement help to improve its durability.

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