Modification of AC Thermal Properties to Mitigate UHI Effects

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ABSTRACT

An analysis of the asphalt concrete (AC) pavement material properties that affect surface temperatures is presented. These properties affect the contribution to the urban heat island (UHI) effects. Its goal is to analyze the effect of various alternative aggregate materials, such as limestone, silica, polymer, glass, and graphite, have on asphalt concrete pavement surface temperatures under various environmental conditions. Pavement surface temperatures were analyzed for two extreme weather locations in the USA, namely South Texas and Northern Minnesota. LTPP weather data over a year-long period, were analyzed for each location using the computer model TEMPS. Average and range of pavement temperatures were compared at a depth of 0.01 meter. It was concluded that the higher the coefficient of thermal conductivity, the heat capacity and the albedo of the pavement surface layer, the lower the average and maximum surface temperatures are during the summer months. Graphite was shown as a promising limestone aggregate substitute producing significant reductions in AC surface temperatures.

Keywords: Pavement, asphalt concrete, heat capacity, heat conductivity, graphite.

1. INTRODUCTION

Asphalt concrete (AC) paved surfaces act as heat sinks during hot weather due to their dark color and heat absorption characteristics. This results in elevated ambient temperatures in urban environments, known as the Urban Heat Island (UHI) effect. The UHI effect has been documented as the leading cause of elevated temperatures in urban areas by the Environmental Protection Agency [1]. As a result, the air temperature in large cities during day time may be 1-3°C higher than that in rural areas, while it can be 7-12°C higher during night time [2]. The reason for the higher ambient temperatures in the evening is that structures (i.e., pavements and buildings) emit the heat they stored during the day. The technical challenges of mitigating the UHI effect are many. This paper tackles one of them, namely the cooling of AC pavement surfaces by considering alternative innovative materials as substitute to conventional aggregates. The objective of this paper is to compare pavement surface temperature predictions for various materials that could be used as substitutes to limestone aggregates in ACs. The materials considered include silica, polymer, glass, and graphite.

2. BACKGROUND

A schematic of the heat components defining pavement surface temperature are given in Fig. 1. In general, the net heat q_{net} entering or leaving the pavement surface is expressed as [3]:

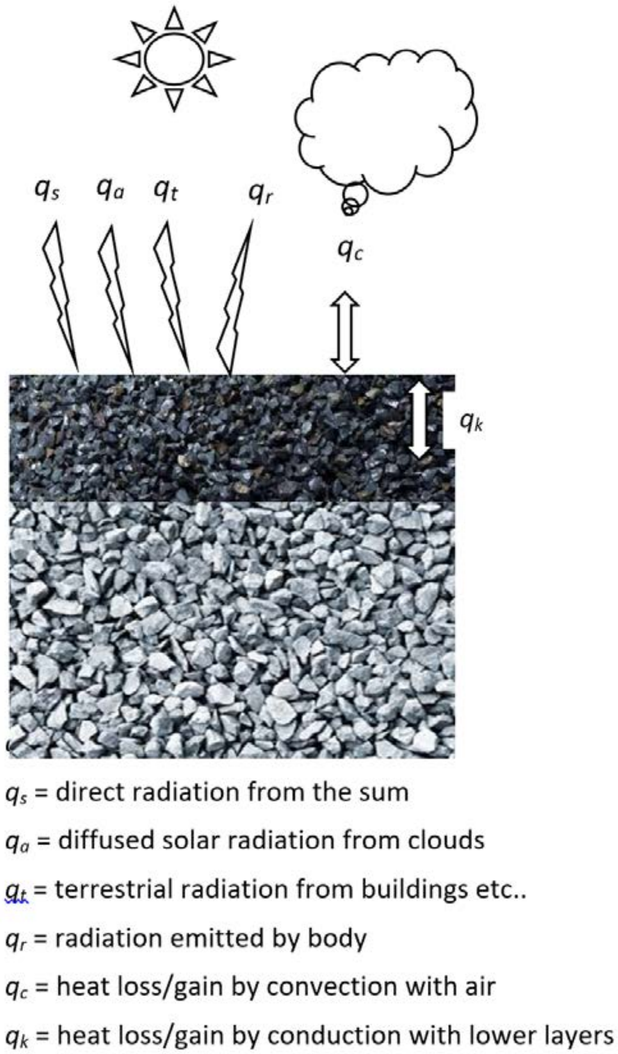

Figure 1 Heat Flux Components in Pavements

$$q_{net} = q_s + q_a + q_t \pm q_c \pm q_k - q_r \tag{1}$$

The variables in this equation are defined in Fig. 1. Some of the heat components could either reduce the heat entering the pavement surface, hence indicated as negative, or increase it, hence marked as positive. Considering that q_t is negligible, this equation can be simplified as:

$$q_{net} = q_s + q_a \pm q_c \pm q_k - q_r \tag{2}$$

The direct solar radiation q_s absorbed by the surface is a function of the albedo of the surface, denoted by α, expressed as:

$$q_s = (1 - \alpha) R_o \tau_a \,\mathrm{m} \cos i \tag{3}$$

where, R_o is the solar radiation constant (1394 W/m^2), τ_a is the atmospheric heat transmission coefficient per unit mass (i.e., ranges between 0.62 and 0.81 depending on the amount vapour in the air), m is the relative air mass (i.e., the ratio of the length of the actual transmission path divided by the length of the shortest path) and i is the angle between the direction of the solar radiation and the vertical direction, which depends on the geographic location, season/time and the inclination of the pavement surface.

The indirect solar radiation (i.e., radiation reflected form the clouds towards the ground) absorbed by the pavement surface q_a is given by the following empirical formula [4]:

$$q_a = (0.77 - 0.28\ 10^{-0.074\rho})\sigma\, {T_{air}}^4 \tag{4}$$

where, T_{air} is the air temperature, ρ is the vapour pressure and σ is the Stefan-Boltzman constant (5.68 10-8 $W/m^2/^0K^4$). The radiation heat emitted from the pavement surface q_r is given by:

$$q_r = \varepsilon\, \sigma\, T_s^4 \tag{5}$$

where, ε is the emissivity of the pavement surface and T_s is the temperature of the surface. For ACs, the emissivity and the absorptivity, that is 1-α, are considered equal [3].

The convection heat energy component q_c is:

$$q_c = h_e(T_s - T_{air}) \tag{6}$$

where, h_e is the surface heat transfer coefficient, which depends on the condition of the surface, the properties of the air and the wind speed.

The heat conduction component q_k is calculated using:

$$q_k = k\frac{T_d - T_s}{d} \tag{7}$$

where, T_d is the temperature at a depth *d* into the pavement.

Finally, the distribution of pavement layer temperature *T* with depth *z* as a function of time *t* is:

$$\frac{\partial^2 T}{\partial z^2} = \frac{\rho\, c_p}{\kappa}\frac{\partial T}{\partial t} \tag{8}$$

where, ρ is the density, c_p is the mass specific heat capacity and k is the thermal conductivity of the pavement. The term $k/(\rho\, c_p)$ is referred to as thermal diffusivity.

Mitigating UHI effects, requires modifying AC properties to reduce pavement surface temperatures. The properties that can be modified include, the albedo, the thermal conductivity and the heat capacity. The following presents a summary of an analysis conducted to establish the effect of material properties in reducing the high temperatures in AC pavements. It includes a parametric study of the effect of material thermal properties on pavement temperatures and the effect various aggregate substitutes have on these thermal properties.

3. PARAMETRIC STUDY

A parametric study of the effect of AC thermal properties on surface temperatures was undertaken using the computer program TEMPS [5]. A pavement structure consisting of 0.15 m of AC and 0.4 m of unbound limestone base was considered. The analysis involved year-long weather data obtained from the LTPP databases for two geographically extreme locations, namely San Antonio, Texas and International Falls, Minnesota. The thermal properties of the constituents of AC were obtained from the literature (Table 1). The heat capacity of the composite was obtained as the weighted average of the heat capacities of the constituents, given a mix design established in the laboratory.

Table 1 AC Constituent Thermal Properties

Material	Density (kg/m^3)	Heat Permeability $W/m/^0K$	Heat Capacity $J/kg/^0K$
Asphalt Binder	1100	0.8	920
Limestone	2750	1.28	910
Air	1.293	0.025	1004

The coefficient of heat permeability was established through FEM simulation of the heat flow through the AC microstructure. The resulting values were 910 $J/kg/^oK$ and 1.167 $W/m/^oK$, respectively. The albedo of the surface was assumed to be 0.15. For the limestone base layer, a porosity of 0.10 was assumed, which gave weighted average values for the heat capacity and the heat permeability of 919.4 $J/kg/^oK$ and 1.1545 $W/m/^oK$. These were the baseline thermal properties used to establish the benchmark temperature distribution through the AC. A parametric study was conducted through TEMPS for a range of AC heat property values as summarized in Table 2.

Table 2 Range of AC Thermal Properties Considered for Parametric Study.

	Heat Permeability $W/m/^0K$	Heat Capacity $J/kg/^0K$	Albedo -
Baseline	910	1.167	0.15
Range	+20% -20%	+10% -10%	+67% -67%

Examples of the parametric study results are shown in Figures 2, 3 and 4 for thermal permeability, heat capacity and albedo, resp. These figures show average daily temperatures and the standard deviation range for the Texas location for 2 summer-time weeks. Figures 2 and 3 show that increasing the thermal conductivity or the heat capacity of the AC layer results in a small reduction in AC surface average daily temperatures, but also a reduction in the range of these temperatures, suggesting a decrease in the daily max and an increase in the daily min. temperatures. Figure 4 shows that increasing the albedo (i.e., reflectivity) of the pavement surface results in a more pronounced reduction in average daily AC surface temperatures and a less noticeable reduction in their range. These trends were consistent throughout the year for both the Texas and the Minnesota locations analyzed. It can be seen that the albedo has the most significant effect, followed by the heat permeability and the heat capacity.

4. ALTERNATIVE AC MATERIALS

The analysis presented above points out that UHI effects can be mitigated by selecting AC constituents that suitably modify its thermal properties. The thermal properties of common aggregates and their possible substitutes are given in Table 3. This table suggests that materials, such as graphite, would be a good limestone or granite aggregate substitute due to its higher heat permeability. An AC mixture was modified by replacing its limestone aggregates between sieve sizes no. 4 and 8 with similarly sized graphite. The thermal properties of the graphite modified composite mixture were estimated as follows:

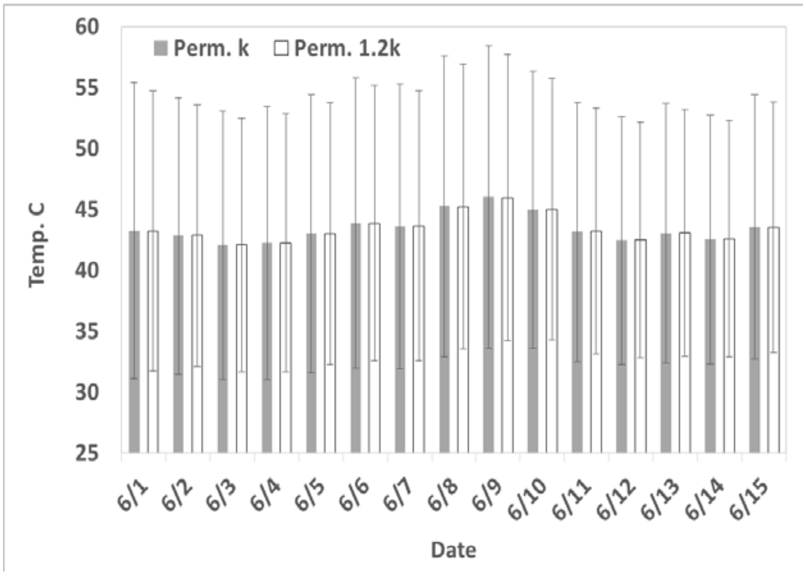

Figure 2 Average Daily AC Temp. (^{0}C); Increasing the Heat Permeability; Texas Site

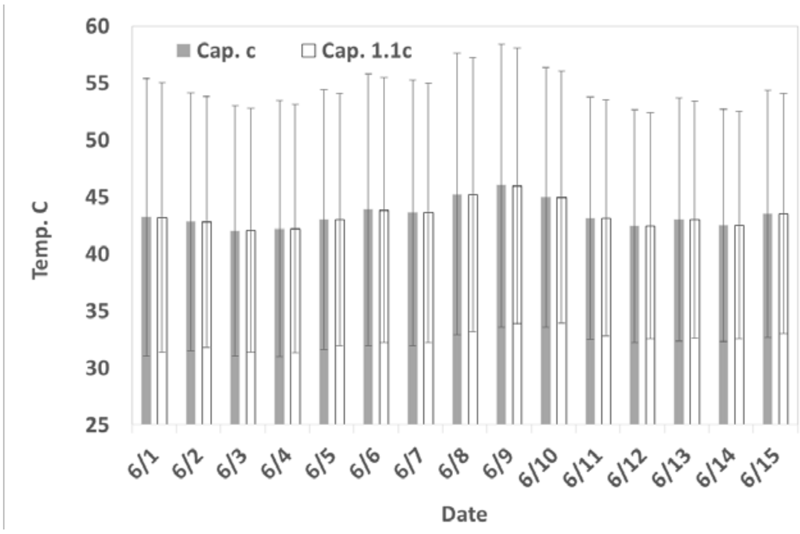

Figure 3 Average Daily AC Temp. (^{0}C); Increasing the Heat Capacity; Texas Site

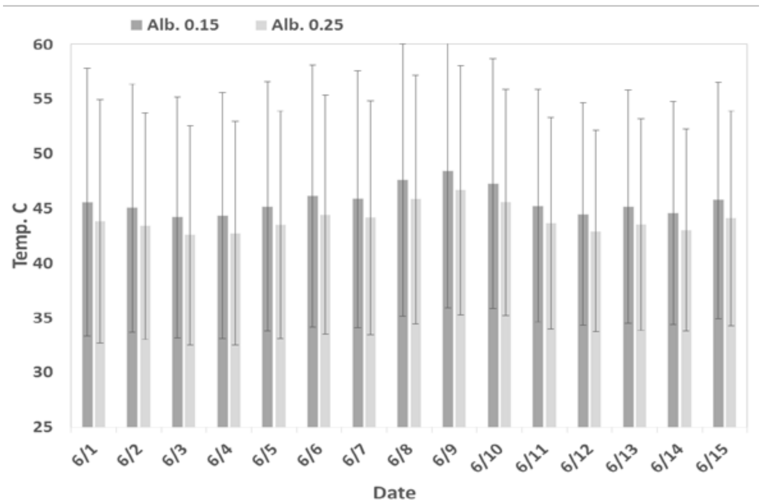

Figure 4. Average Daily AC Temp. (^{0}C); Increasing the Albedo; Texas Site

Table 3 Thermal Properties of Alternative AC Aggregates

Material	Density (kg/m^3)	Heat Perm. W/m/^{0}K	Heat Capacity J/kg/^{0}K
Limestone	2750	1.28	910
Granite	2650	2.85	790
Glass	3750	0.025	1004
Silica	2410	1.4	700
PP	900	0.202	1006
Graphite	2250	30	700

- The thermal capacity c_p was estimated as the weighted sum of the coefficients of thermal capacities of the constituents based on the volumetric properties of the mix. The resulting value was 867.2 J/kg/^{o}K.
- The heat permeability k was simulated using the FEM approach based on the estimated microstructure of the AC established from x-ray computer tomography [6]. The value obtained was 2.555 W/m/^{o}K.

It is noted that these values are 4.7% lower and 119% higher, respectively, than those for the conventional AC. The TEMPS simulations revealed that the graphite modified AC reduces significantly peak summer-time temperatures (Fig. 5). Our on-going work focusses on establishing the mechanical properties of the graphite modified ACs and compare them to those of conventional ACs. Testing includes resistance to cracking and rutting (i.e., indirect tension and asphalt pavement analyzer testing, resp.).

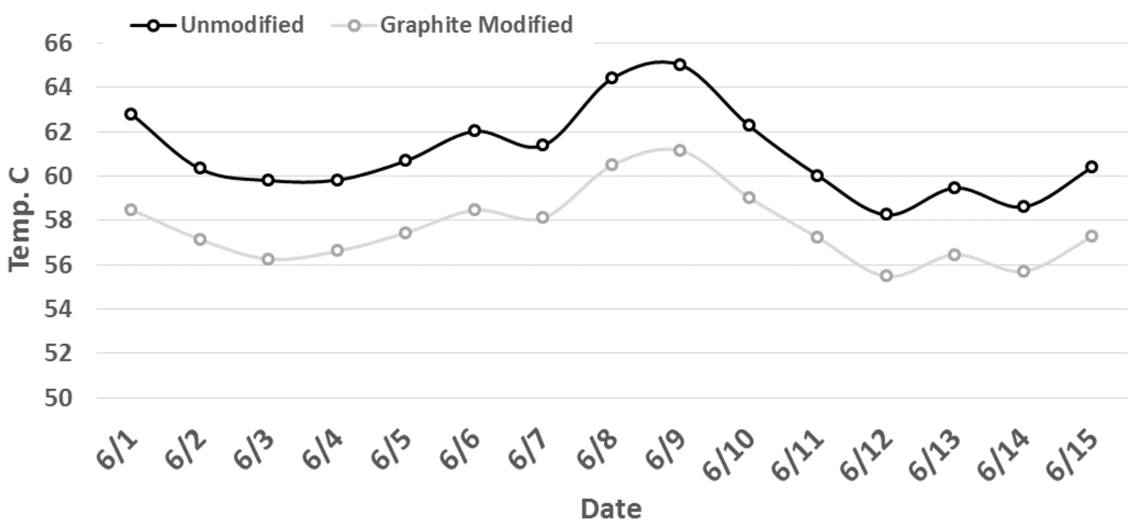

Figure 5: Comparing Peak Daily Summer-time Temperatures, Texas Location

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