Porous Asphalt Pavement Temperature Effects on Overall Urban Heat Island

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ABSTRACT

The trend of increased nighttime temperatures due to retained heat in urban areas is a phenomenon known as the Urban Heat Island (UHI) effect. Rapid urbanization requires an increase in pavement surface area, which contributes to UHI due to unfavorable heat retention properties. In recent years, the use of alternate pavement designs has become more common in attempt to mitigate environmental impacts of urbanization. Specifically, use of porous pavements is gaining popularity in the paving industry due to attractive storm water mitigation and friction properties. However, little information is available regarding thermal behavior of these materials.

This study explores the extent to which porous asphalt pavement influences pavement temperatures and investigates the impact on UHI by considering the diurnal temperature cycle. A one-dimensional pavement temperature model developed at Arizona State University was used to model surface temperatures of porous asphalt, dense graded asphalt and Portland cement concrete pavements. Several scenarios were considered to include variations in pavement thickness, structure and albedo. In addition, thermal conductivity testing was performed on porous asphalt mixtures to obtain values for current and future analysis.

In general, porous asphalt exhibited higher daytime surface temperatures of the three pavement types because of the reduced thermal energy transfer from the surface to subsurface layers. In comparison, porous asphalt showed the lowest nighttime temperatures when compared to other materials with similar or higher albedo. This trend can be attributed to the unique insulating properties of this material along with a high air void content. As anticipated, the outcome of this study indicated that pavements impact on UHI is a complex problem and needs to consider important interaction between influencing factors such as pavement thickness, structure, material type, and albedo.

INTRODUCTION

Urban areas are subject to higher environmental temperatures compared to their rural counterparts due to a higher density of buildings and pavement materials. These engineered materials are not subject to cooling mechanisms such as moisture transpiration between green foliage and its environment common in rural or suburban areas. Instead, their relatively higher solar energy absorption and subsequent thermal energy storage tend to generate higher temperatures *(1)*, which, in turn increases urban air temperatures during the day and/or night. Such a phenomenon is commonly referred to as the Urban Heat Island (UHI) effect *(2)*. A 1993 study by the US Department of Energy, showed an increasing trend in cities' temperatures, where buildings and pavements began replacing agricultural lands and also reported increased energy consumption *(3)*.

Although cities have large numbers of buildings that contribute to UHI, the large surface areas of pavements cannot be ignored. In fact, studies have shown that 29 to 45% of the urban surface area is covered with pavements, and this proportion is expected to further increase *(4)*. It is estimated that by the year 2030, 61% of the world's 8.1 billion people will live in cities *(5)*. Hence, it is important to develop effective UHI mitigation strategies and incorporate them into new construction and maintenance activities.

Researchers, industry and public officials have been exploring innovative uses of construction materials, design procedures and increased use of vegetation to mitigate the effects of UHI. Most research has recommended the replacement of darker materials with lighter-colored, high albedo (or solar-reflective) materials for buildings and roads. However, research has shown that the problem may be more complex and that solar reflectivity may not be the only important factor to evaluate the ability of a pavement to mitigate UHI *(6)*.

This study explores the extent to which porous asphalt pavement influences pavement temperatures and investigates the impact on UHI by considering the diurnal temperature cycle. In essence, this study provides additional appreciation to the complex issue of how pavement structures with different or non-traditional material types impact UHI. It also provides specific thermal properties on porous asphalt mixtures that are gaining popular in the paving industry due to their attractive storm water mitigation, highway noise reduction, and friction properties.

Because there are few studies considering thermal characteristics of porous asphalt mixtures, this study focuses on porous asphalt concrete and open-graded friction course (OGFC) asphalt pavements. The approach also included other pavement material properties that can be used for comparative purposes.

OBJECTIVE

The main objective of this study is to research and model the extent to which OGFC and porous asphalt concrete pavements influence pavement surface temperatures and thus contribute to the overall UHI effect.

LITERATURE REVIEW

Definition of Mixtures

The terms open-graded friction course and porous hot-mix asphalt are commonly referred to as the same material. While the mixtures express similarities, the two types of asphalt concrete mixtures actually serve two different purposes. An OGFC mixture has a smaller maximum aggregate size and also has a very small percentage of aggregate in the mid-range sieve sizes. This open aggregate structure has been found to be very beneficial in allowing water to drain through the asphalt layer which; in turn, reduces tire spray and provides better friction. In addition, the use of an asphalt rubber, open-graded friction course has been shown to reduce traffic noise *(7)*. In comparison, PHMA has a similar gradation as the open-graded structure; however, the maximum aggregate size is bigger which produces a very open structure. This porous mixture allows water to freely pass through and when used in conjunction with an underlying reservoir is effective in managing storm water. According to the National Asphalt Paving Association (NAPA), a porous mixture can be classified according to the gradation provided in TABLE 1 with air voids greater than 16% *(8)*.

TABLE 1 NAPA Porous Asphalt Gradation Specification

Sieve Size		Gradation Limits % Passing	
Standard	**mm**	**Upper**	**Lower**
3/4	19.0	100.0	-
1/2	12.5	85.0	100.0
3/8	9.5	55.0	75.0
No. 4	4.8	10.0	25.0
No. 8	2.4	5.0	10.0
No. 200	0.1	2.0	4.0

Pavement Material Thermal Properties

Evaluating the thermal behavior of urban materials requires understanding of the key thermo-physical properties of matter that govern thermal phenomenon. There are two distinct categories of these properties: those related to transport of energy through a system and those related to the thermodynamic or equilibrium state of a system *(9)*. Transport of energy through a system, also referred to as heat transfer, can occur by means of radiation, conduction and convection. Heat transfer properties of materials relating to radiation include albedo (α) and emissivity (ε). Thermodynamic properties differ from transport properties in that they are concerned with the equilibrium state of a system. These properties include density (ρ) and specific heat capacity (cp) which form the basis for volumetric heat capacity and thermal diffusivity. These properties and terms are discussed in further detail in the following sections.

A portion of solar radiation, incident to a pavement surface, will be absorbed by the surface and increase its thermal energy. The rate at which this energy is absorbed per unit of surface area is dependent on the absorptivity (α_{abs}) of the surface material that ranges from zero to one *(9)*. A value of zero implies that no energy is absorbed by the surface. The rate at which energy is reflected by the surface is known as the albedo (α) of the surface. It takes into account the full spectrum of solar radiation and not just those in the visible range. (*3, 10*)

A portion of the thermal energy contained within a pavement is constantly being emitted as radiation back into the atmosphere. The rate at which the energy is emitted per unit area is referred to as the surface emissive power, E (Wm^{-2}) *(9)*. Emissivity, ε, is the ratio of energy radiated by the surface compared to the radiation emitted by a black body at the same temperature. The emissivity of a surface greatly depends on the surface material and its finish.

Density (ρ) and specific heat (cp) are widely used in thermal analysis. Density is a measure of mass per volume of a substance and can affect the temperature of paving materials. Specific heat (cp) is defined as the amount of heat energy required to raise the temperature of one gram of a substance by $1^{o}C$. Thermal conductivity is the rate constant that governs the heat flux through a body and is a transport property characteristic of the material. In essence, it is the ability of a material to conduct heat. Finally, the porosity of a material is commonly defined as the ratio of the volume of pores in a substance to its total volume (*11*). Porosity can affect the surface energy fluxes due to changes in voids and particle contact.

The literature provides limited thermal properties of paving materials and, in most cases the specifics of the materials tested are not reported. These properties can be drastically affected by the physical properties of the materials. TABLE 2 summarizes select thermal material properties found in the literature for different Hot Mix Asphalt (HMA) and Portland Cement Concrete (PCC) pavement materials. It is important to note that studies rarely reported or measured all material thermal properties.

TABLE 2 Pavement Material Thermal Properties

Material	Thermal Conductivity (W/mK)	Specific Heat *c* [J/(kg*°K)]	Albedo	Density (kg/m^3)	Source
Porous Asphalt	2	900	-	2157	*(12)*
Water Holding Porous Asphalt	1.46	520	-	2360	*(12)*
Asphalt	1.2	921	0.1	2238	*(13)*
	2	900	-	2300	*(12)*
	0.8-1.6	879-1600	-	-	*(14)*
	1.3-1.42		-	-	*(15)*
	1.45-1.81	1475-1835	-	2350	*(16)*
	-	-	0.05 – 0.10 (new) 0.10 – 0.15 (aged)	-	(*17*)
	1.21	921		-	*(18)*
	1.003-1.747	-	-	-	*(19)*
PCC	1.1	950	0.25	2100	*(20)*
Porous PCC	1.1	950	0.18	2100	*(20)*

Pavement Temperature Modeling Studies

A one-dimensional mathematical model was developed at by Gui et al. (*10*) at Arizona State University (ASU) in order to quantify surface pavement temperatures. This program requires the following climatic input: solar radiation, air temperature, dew-point temperature and wind velocity. Authors predicted diurnal pavement temperatures for different paving materials in order to evaluate the effects of different thermo-physical properties of the materials. The parameters evaluated during this study included: albedo, emissivity, thermal conductivity, diffusivity and volumetric heat capacity. The model considers the following methods of heat transfer: radiation, convection and conduction. Authors concluded that albedo and emissivity yield positive effects on both the maximum and minimum temperatures, whereas thermal conductivity, diffusivity and heat capacity only affected maximum temperatures. Overall, changes in albedo produced the highest changes in maximum temperatures while changes in emissivity had the most impact on minimum temperatures.

Another study conducted by Asaeda *(21)* attempted to understand the surface heating processes of various pavements. Thermal characteristics and behavior of materials of porous and traditional dense pavements were studied and field experiments were conducted with various types of alternate pavement materials. A one-dimensional numerical model was developed to simulate processes of heat and moisture transfer at the porous surfaces and in the underlying soil. Authors concluded that the surface of normal porous pavement is rather dry and almost no evaporation was observed at this surface. Also, they found that the normal porous and non-porous pavement surfaces can absorb a large amount of the incoming net radiation, which increases its pavement surface temperature during the daytime.

Nakayama and Fujita *(12)* presented an interesting study dealing with the evaluation of pavements comprised of traditional versus new materials regarding thermal and evaporation properties. They used a model called NICE (NIES Integrated Catchment-based Eco-hydrology) to simulate the water and heat budgets for the various materials and to reproduce the cooling effect by evapotranspiration of water-holding pavement (consisting of porous asphalt and water-holding filler made of steel by-products based on a silica compound). In the study, they used experimental results conducted by JFE Steel Corporation *(22)*. Several blocks of different materials were fastened to the rooftop of the building to study the differences in their responses to the environment. Some of these materials included concrete, porous pavements and water holding pavements. The surface temperatures of the infiltration and water-holding blocks were much lower than those of the other engineered pavements. In particular, they were about 5–10 ◦C cooler than the temperature of the rooftop in the hottest part of the day, mainly because of the cooling effect of evaporation from the materials. The simulation showed that the surface temperature decrease in water-holding pavement is closely related to evaporation from the surface, the water volume of the pavement and the surface reflectance.

Case Studies

In 2006, Belshe et al *(7)* conducted a study to evaluate the thermal effects of asphalt-rubber OGFC overlays on PCC pavements. This practice is typically used in the State of Arizona in order to improve skid resistance, restore smoothness and provide noise reduction. The study instrumented several pavements with temperature sensors to document the thermal gradient in the PCC with and without asphalt-rubber OGFC overlays. Using obtained temperature data throughout the depth of the pavement; stresses were computed by utilizing typical slab theory equations. The study concluded that use of an asphalt rubber OGFC overlay reduced the stresses in the PCC due to thermal gradients by approximately 25% during the day and 8% during the nighttime. These results are for a typical extreme summer day in Phoenix, Arizona. It was also noted that the effects of traffic aeration reduced the magnitude of thermal gradients due to lower surface temperatures. Despite the low albedo of OGFC, the material acted as a thermal blanket over the PCC and reduced thermal stresses.

Similar studies on pervious concrete and its thermal behavior are also reported in the literature. Researchers at ASU *(20)* carried out a study on a pervious Portland cement concrete (PPCC) parking lot in order to determine the role of pervious pavements in UHI mitigation. The study concluded that the PPCC exhibited higher daytime temperatures than conventional PCC. The authors speculated a combination of factors including lower albedo, rougher surface texture trapping air and heat, and high air voids in the mix. However, the PPCC achieved a lower nighttime temperature when compared to the PCC and thus aids in mitigation of UHI at nighttime. Results of this study correspond well with modeled observations by Haselbach *(23)* in South Carolina where PPCC experienced higher daytime surface temperatures than PCC and asphalt concrete. Authors also noted the base material was cooler under the PPCC which demonstrates the insulating capacity of porous pavement. It was observed that the heat transfer rate of PPCC is approximately 59% of the heat transfer rate of PCC. Again, work by Kevern et al *(24)* and expanded by Haselbach et al *(6)* demonstrated that PPCC cooled faster than PCC. However, the low temperatures of the two pavements were similar, indicating less heat storage capacity of the PPCC.

THERMAL CONDUCTIVITY TESTING

Many different factors play a role in the thermal conductivity of a given material. In the past, these thermal transport characteristics have not been given much attention during pavement design or mixture design and are not easily available in the literature. The thermal conductivity of a pavement is generally dependant on the type of mix, aggregates used, percentage of each component in the mix and its level of compaction. In terms of aggregate base materials or subgrade materials, the thermal conductivity is a function of material type, mineral content, moisture content, particle size and overall density *(25)*. Therefore, the thermal conductivity of paving materials can be a very difficult parameter to obtain and generalize for different asphalt pavement types.

A review of the literature proved that thermal properties of asphalt mixtures are rather limited and can be misleading since mixture properties or types are not always reported. In order to verify data and to evaluate the thermal conductivity of a porous asphalt mixture, laboratory specimens were prepared using asphalt mixtures obtained from actual field projects in the State of Washington, Wyoming and Arizona. These mixtures were selected because their gradations resembled the porous asphalt specification defined by the National Asphalt Paving Association (NAPA). TABLE 3 presents asphalt mixture properties used in this thermal conductivity study.

TABLE 3 Summary of Mixture Properties and Gradation

	Mixture		State of Washington	Wyoming	Arizona
Mix Property	Gradation		Porous	Open	Gap
	PG Grade		64-22	64-34	64-16 AR
	% Binder		5.4	5.7	8.5
	G_{mm}		2.587	2.416	2.337
	Ave. Air Void %		21	12.3	4.9
	Modification		None	1 lb/ton (0.5 kg/MT) fibers*	18% AR **
	Thermal Conductivity k (W/m-K)		0.57	0.38	0.9
Mix Gradation	Sieve Size		Percent passing		
	US	SI			
	3/4	19	100	100	-
	1/2	12.5	92	82	100
	3/8	9.5	59	57	87
	No. 4	4.8	16	22	27
	No. 8	2.4	8	12	18
	No. 16	1.2	6	7	14
	No. 30	0.6	5	6	11
	No. 50	0.3	5	4	7
	No. 100	0.2	4	3	5
	No. 200	0.1	3.2	2	3.6

* Blend of polypropylene and aramid fibers
** Type B crumb rubber

The standard procedure for measuring thermal conductivity is outlined in ASTM C 177-04 “Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus”. This method requires the temperature at steady state to determine thermal conductivity, k and mandates slab specimen geometries. However, obtaining such specimens from in-service pavement is very difficult and not recommended for highly inhomogeneous materials where the size of aggregates can exceed 1-inch (25mm). A new experimental method developed by ASU National Center of Excellence for SMART (Sustainable Materials and Renewable Technologies) Innovations allows thermal and mechanical properties of materials to be determined using specimens obtained using standard sampling techniques with minimal additional sample preparation. Detailed discussion of the test methodology can be found in *(13)*. In summary, a 1-inch (25mm) vertical hole is cored through the center a 4-inch (100 mm) diameter specimen that measures 7 inches (178 mm) in height. A heating element is introduced into the hole and thermocouples are mounted on the outside of the specimen.

The average thermal conductivity values, k (W/m-K) obtained in this study for the State of Washington, Arizona and Wyoming mixtures are 0.57 (cov=5.1%), 0.90 (cov=16.2%) and 0.38 (cov=0.9%), respectively. These test values are significantly lower than the range of values found in the literature *(12)*. However, values reported in literature rarely are accompanied by mixture properties. Two of these mixtures tested were similar in porous nature, however; differences in constituent materials and air voids played a major role in the k-values. For example, the Washington State mixture had the highest air voids of the three mixtures, but did not show the lowest thermal conductivity values. In comparison, the Wyoming mixture had polypropylene and aramid (Kevlar) fiber modification. This combination, along with the type of aggregate, resulted in the lowest k-value of the three mixtures tested. The Arizona mixture had the lowest air voids and thus; the high thermal conductivity value is reasonable since more particle contact accelerates heat transfer. As a result, the thermal conductivity parameter of asphalt material is greatly influenced by the constituent materials. Therefore, use of the general k-values may result in improper analysis of a paving material.

PAVEMENT TEMPERATURE MODELING

In order to examine the effect of different factors, a one-dimensional mathematical model developed at ASU by Gui et al. *(10)* was used to calculate the pavement near-surface temperatures using hourly measured solar radiation, air temperature, dew-point temperature, and wind velocity data.

The climatic data used in this analysis were collected from the Arizona Meteorological Network (AZMET) Phoenix Encanto weather station for August 14-16, 2010, representing the hottest days in 2010. The ASU model calculated the pavement temperature in two-minute increments for each of these days at the depth of 0.5 inches (12.5mm) into the pavement and used a 3-day average value to plot the diurnal pavement temperatures.

Three types of pavements were considered: porous hot mix asphalt (PHMA), hot mix asphalt (HMA) and Portland cement concrete (PCC). Each pavement type was analyzed using a typical albedo range for the material types. TABLE 4 provides a summary of the pavement properties used in this analysis. Recognizing that the material properties of the subgrade are highly dependent on the type of material, mineral content, particle size and moisture content values, typical values were selected to represent a dry clay subgrade and aggregate base *(25)*. Models are available to predict the thermal properties of subgrade material but are complex and out of the scope of this study *(25)*.

TABLE 4 Material Input Properties

Pavement Structure		1	2	3
Layer 1				
Material	-	HMA	PHMA	PCC
Albedo	-	0.05, 0.1, 0.2	0.05, 0.1, 0.2	0.15, 0.25, 0.35
Emissivity	-	0.91	0.91	0.91
Density	(kgm^{-3})	2238	2146	2350
Specific Heat	($Jkg^{-1}K^{-1}$)	921	800	1000
Conductivity	($Wm^{-1}K^{-1}$)	1.2	0.4	1.5
Thickness	(in)	2, 4, 8, 12	2, 4, 8, 12	2, 4, 8, 12
Interface Resistance	-	0.001	0.001	0.001
Layer 2				
Material	-	Aggregate	Aggregate	Aggregate
Density	(kgm^{-3})	2200	2200	2200
Specific Heat	($Jkg^{-1}K^{-1}$)	890	890	890
Conductivity	($Wm^{-1}K^{-1}$)	1.3	1.3	1.3
Thickness	(in)	6	6	6
Interface Resistance	-	0.001	0.001	0.001
Layer 3 (Ground)				
Material	-	Dry Clay	Dry Clay	Dry Clay
Density	(kgm^{-3})	1700	1700	1700
Specific Heat	($Jkg^{-1}K^{-1}$)	920	920	920
Conductivity	($Wm^{-1}K^{-1}$)	0.9	0.9	0.9
Additional Factors				
Sky View Factor	-	0.95	0.95	0.95
Solar View Factor	-	0.85	0.85	0.85

Evaluation of Porous Hot Mix Asphalt

One goal of this study was to compare the diurnal pavement surface temperatures for PHMA, HMA and PCC. Based on the information presented in the literature review section, studies on pervious concrete indicated higher daytime surface temperatures but lower nighttime temperatures when compared to PCC. It was anticipated that PHMA would perform in a similar manner due to the open void structure of the material and with the absence of significant evapotranspiration effects.

Pavement surface temperatures were modeled for 2, 4, 8 and 12-inch (51, 102, 203 and 305 mm) pavement thicknesses on dry clay subgrade. Although the 8 and 12-inch (203 and 305 mm) sections are unlikely to be used in urban settings (except in cases of heavy loading), they were included in this study to evaluate the thickness effect on surface temperatures. FIGURE 1 presents an example of the diurnal pavement surface temperature comparison for PHMA and HMA.

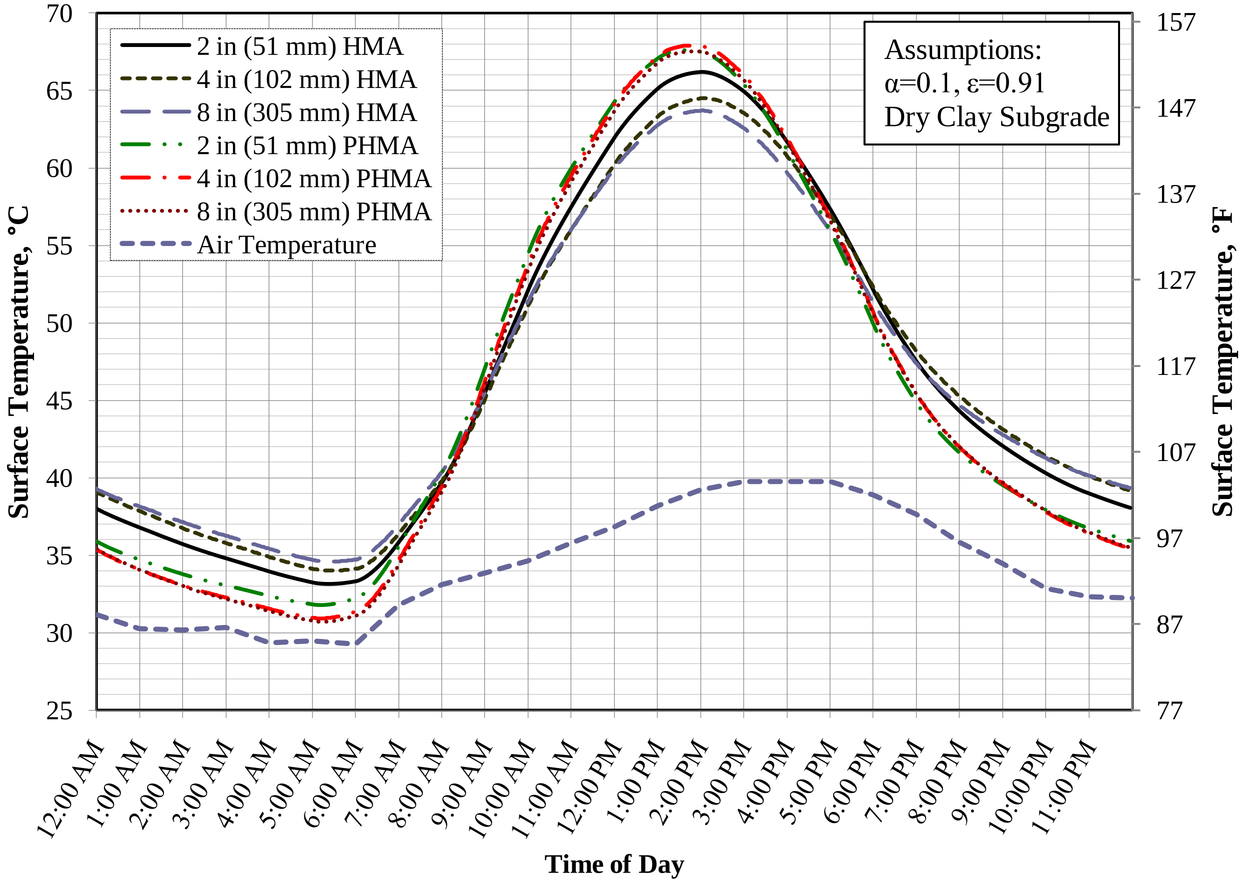

FIGURE 1 Pavement surface temperature comparison for PHMA and HMA, August 15, 2010 in Phoenix, Arizona

Although the PHMA has higher daytime surface temperatures, it is evident from FIGURE 1 that PHMA has cooler surface temperatures for a significant portion of the 24-hour day. This is the case for all pavement thickness values used in this study. It is important to note that after a thickness of about 8 inches (203 mm), the pavement surface temperatures become asymptotic and pavement thickness plays a reduced role in pavement temperatures. These findings are consistent to those reported by Gui et al *(26)*.

High PHMA surface temperatures during peak hours are not surprising because the lower thermal conductivity of the porous material will keep the surface temperature elevated. Also, the open void structure exposes additional surface area to solar radiation resulting in higher peak daytime temperatures. Rough surface texture may contribute to the hotter daytime temperatures by trapping warm air and heat. Finally, the insulating effect PHMA causes less heat to be conducted to the ground. Similar observations have also been documented in porous PCC pavements *(20,23)*.

Thermal Evaluation of Various Pavement Materials

Pavement temperature modeling was performed for PHMA, HMA and PCC using input values provided in TABLE 4. The same pavement thickness values were used but albedo values were varied within typical ranges for each type of materials. However, the analysis was completed two times, once considering no base material and again using a 6 inch (152 mm) aggregate base material under the pavement to model a more realistic pavement section.

TABLE 5 presents the modeled results for maximum and minimum pavement surface temperatures for pavement structure with and without an aggregate base layer. The shaded colors in each cell help to indicate pavement structure combinations that provide similar maximum or minimum pavement surface temperatures. In this table, PHMA, HMA and PCC represent porous hot mix asphalt, hot-mix asphalt and Portland cement concrete, respectively.

TABLE 5 Maximum and Minimum Pavement Surface

	Pavement Type (Thickness)	Max. Temperature (˚C)			Min. Temperature (˚C)		
No Base Material	**PHMA**	**α=0.05**	**α=0.1**	**α=0.2**	**α=0.05**	**α=0.1**	**α=0.2**
	2 in (51 mm)	69.5	67.6	63.7	32.1	31.8	31.1
	4 in (102 mm)	69.9	67.9	64.0	31.2	30.9	30.3
	8 in (203 mm)	69.5	67.5	63.6	31.0	30.7	30.1
	12 in (305 mm)	69.5	67.5	63.6	31.0	30.7	30.1
	HMA	**α=0.05**	**α=0.1**	**α=0.2**	**α=0.05**	**α=0.1**	**α=0.2**
	2 in (51 mm)	68.1	66.2	62.4	33.5	33.1	32.4
	4 in (102 mm)	66.3	64.5	60.8	34.4	34.0	33.2
	8 in (203 mm)	65.5	63.7	60.1	35.0	34.6	33.7
	12 in (305 mm)	65.5	63.7	60.1	34.8	34.4	33.5
	PCC	**α=0.15**	**α=0.25**	**α=0.35**	**α=0.15**	**α=0.25**	**α=0.35**
	2 in (51 mm)	63.6	59.8	56.0	33.2	32.3	31.5
	4 in (102 mm)	61.4	57.8	54.2	34.3	33.5	32.6
	8 in (203 mm)	60.4	56.9	53.4	35.3	34.3	33.3
	12 in (305 mm)	60.5	57.0	53.4	35.2	34.2	33.2
6 in (152 mm) Aggregate Base	**Pavement Type (Thickness)**	**Max. Temperature (˚C)**			**Min. Temperature (˚C)**		
	PHMA	**α=0.05**	**α=0.1**	**α=0.2**	**α=0.05**	**α=0.1**	**α.=0.2**
	2 in (51 mm)	67.6	65.7	61.9	31.8	31.4	30.8
	4 in (102 mm)	68.8	66.9	63.0	30.0	29.8	29.3
	8 in (203 mm)	68.6	66.7	62.8	29.9	29.7	29.2
	12 in (305 mm)	68.8	66.9	63.0	30.2	30.0	29.5
	HMA	**α=0.05**	**α=0.1**	**α=0.2**	**α=0.05**	**α=0.1**	**α.=0.2**
	2 in (51 mm)	65.7	63.9	60.3	34.1	33.7	32.8
	4 in (102 mm)	65.1	63.3	59.7	34.0	33.6	32.8
	8 in (203 mm)	64.5	62.7	59.2	33.7	33.3	32.5
	12 in (305 mm)	64.3	62.6	59.0	33.5	33.1	32.3
	PCC	**α=0.15**	**α=0.25**	**α=0.35**	**α=0.15**	**α=0.25**	**α=0.35**
	2 in (51 mm)	61.5	57.9	54.2	33.7	32.8	32.0
	4 in (102 mm)	60.3	56.8	53.2	34.1	33.2	32.3
	8 in (203 mm)	59.5	56.0	52.6	34.1	33.2	32.3
	12 in (305 mm)	59.3	55.9	52.4	33.8	33.0	32.0

NOTE: ˚F = 9/5 *(˚C) + 32

Independent of the type and the thickness of the pavement, it is clear from the results that a higher albedo results in a lower maximum daily surface temperature. In addition, the minimum daily temperature values for each type of pavement also decrease as albedo increases. Considering the PHMA, the highest surface temperature is associated with the lowest albedo value, and the lowest surface temperature is associated with the highest albedo value.

It is evident from the analysis that the albedo has an important impact on the maximum daily temperature of all pavement surfaces. However, the type of material and properties of the pavement structure have a greater impact on the minimum nighttime temperatures. Factors such as pavement thickness, density, specific heat capacity and thermal conductivity all become important as they affect the ability of a pavement structure to retain heat. Therefore, it becomes important to evaluate the entire pavement structure and material properties when selecting paving materials to mitigate urban heat island. Daytime versus nighttime conditions should be carefully evaluated for the pavement under consideration.

In a comparison of different pavement layer thicknesses, it can be noted that the surface temperature generally decreases as the pavement thickness increases. This trend appears reasonable given the additional material to conduct heat. As a consequence, the maximum surface temperature of a thicker pavement decreases during the day but may cause an undesired increase in the minimum temperature during the night.

In a more detailed comparison using TABLE 5, consider a 4-inch (102 mm) PHMA pavement ($\alpha = 0.1$) that has a maximum daytime temperature of 67.9°C (154.2˚F). PHMA is 3.4°C (6.1˚F) and 10.1°C (18.2˚F) hotter than a 4-inch (102 mm) HMA ($\alpha = 0.1$) and PCC pavement ($\alpha = 0.25$), respectively. However, this same PHMA pavement has a nighttime minimum temperature of 30.9°C (87.6˚F) which is cooler than the same HMA and PCC structures by 3.1°C (5.6˚F) and 2.6°C (4.7˚F), respectively. Thus, PHMA has the ability to dissipate heat more rapidly than other pavements due to the insulating effect of the PHMA in combination of high air void structure. Again, lower nighttime temperatures help to mitigate the effects of UHI.

It can also be observed that a pavement with high albedo does not necessarily translate into lower nighttime temperatures. This was evident in the preceding example and can be further explored by looking at a higher albedo PCC ($\alpha = 0.35$) and a lower albedo PHMA ($\alpha = 0.05$); both with 4-inch (102 mm) thickness. Again, the low albedo PHMA has significantly higher daytime temperatures which are reasonable given the amount of solar radiation that can be absorbed by the material. However, during the nighttime, the PHMA ($\alpha = 0.05$) is cooler than the same thickness HMA ($\alpha = 0.20$) and PCC ($\alpha = 0.35$) by 2°C (3.6˚F) and 1.4°C (2.5˚F), respectively.

Similar trends are observed when a 6-inch (152 mm) aggregate base was included in the modeling. The notable difference was that the addition of the aggregate base reduced the minimum temperatures of the PHMA (same material properties) by a greater amount than PCC and HMA. Again, this can be attributed to the insulating effect of the porous structure in that the materials below are exposed to less heat via conduction and thus release less heat during the night.

Effects of Pavement Structure

Throughout this analysis, it is evident that surface temperature of pavement materials is a much more complex interaction than simply analyzing a single aspect or factor alone. Granted albedo has the greatest effect on pavement surface temperature during day conditions. However, selection of pavement materials to mitigate UHI must consider nighttime temperatures as well. In general, the reference to UHI mitigation is directed more toward the nighttime phenomenon. The preceding analysis showed examples on how the selection of the entire pavement structure and material type can affect surface temperatures of pavements during day as well as night conditions.

Studies in the literature are vague on the specific thermal properties of paving materials used including subgrade and aggregate materials. The specific heat capacity and thermal conductivity of aggregates and subgrade materials are very dependent on factors such as moisture content and type of minerals present *(25)*. In the case of PHMA, it would seem reasonable that additional moisture increases the thermal conductivity of the subgrade resulting in higher temperature. However, this is offset in that pavements with open void structures also allow evapotranspiration, which in turn cools the pavement surface *(23)*. Evaporation through the porous pavement has also been shown to reduce the moisture content of the underlying soil *(20)* thus reducing the volumetric heat capacity of the soil.

Thickness (or thermal mass) plays a key role in the mitigation of UHI especially for nighttime temperatures. However, surface temperatures approach constant values after a certain pavement thickness value, which confirms observations by Gui et al. *(26)*.

CONCLUSIONS

Researchers, industry and public officials have been exploring innovative uses of construction materials, design procedures and increased use of vegetation to mitigate the effects of UHI. Many studies in the literature recommend the replacement of darker materials with lighter-colored, high albedo (or solar-reflective) materials for buildings and roads. However, other research has shown that the problem may be more complex and that solar reflectivity may not be the only factor used to evaluate the ability of a pavement to mitigate UHI.

This study explored the extent to which porous hot-mix asphalt (PHMA) pavements influence pavement temperatures and contribute to the overall UHI effect. Three porous asphalt mixtures were obtained and subjected to thermal conductivity testing. These mixtures were obtained from actual field projects and resembled the definition of porous asphalt according to NAPA. It was found that the thermal conductivity parameter of asphalt material is greatly influenced by the constituent materials. Therefore, use of the general k-values provided in the literature may result in improper analysis of a paving material.

A one-dimensional pavement temperature model was used to model pavement temperatures for PHMA, HMA and PCC pavement structures. Albedo and thickness were varied while holding other material properties constant to their respective material types. Regardless of the type and the thickness of the pavement, it was clear from the analysis that a higher albedo resulted in a lower maximum daily surface temperature. However, the type of material and properties of the pavement structure had a greater impact on the minimum nighttime temperatures. In comparison to HMA and PCC, PHMA pavements had the highest predicted daytime surface temperatures and lowest nighttime temperatures. This trend can be attributed to the unique insulating properties of this material along with a high air void content. Thus, it is possible to have a low albedo pavement that may reduce nighttime UHI.

In summary, pavement surface temperature is a complex interaction of many different factors including; albedo, pavement thickness, material type and subgrade properties. Thus, evaluating the overall pavement structure must be considered when selecting a pavement to help reduce UHI.

RECOMMENDATIONS

This study considered only hot weather scenarios in Phoenix, Arizona. Follow up studies should consider pavement temperature modeling for cooler climatic conditions. The pavement temperature modeling indicated that PHMA has a higher daytime surface temperature, which may be beneficial in cold weather climates. In addition, the literature indicated that the subgrade temperatures under porous pavements may remain warmer later into the fall season due to the insulating effect of this material. These effects should further evaluated in subsequent studies.

Future research should be conducted to develop additional thermal and physical properties of PHMA or HMA mixtures to better capture the range of data variations for the different mixes. Research should be also directed to further study the effects of aggregates and subgrade material properties on pavement surface temperatures. The moisture content, mineral content and evapotranspiration will play a significant role in the thermal behavior of porous asphalt pavements and should be considered in future analysis.

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