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## A Review of Urban Heat Island-Reducing Pavement Types and Thermal Properties

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**Abstract.** Urban Heat Island (UHI) has led to a rise in temperatures in cities, reaching up to 9 °C higher than that of rural areas. UHI-Reducing (UHI-R) pavements that are designed to mitigate UHI, have gained increasing attention both from practitioners and researchers. While the research on UHI-R multi-material pavements has been focusing on heat transfer within these pavements, there is a need to study their durability over time. The durability of multi-material pavement systems, UHI-R fall under such category, is strongly affected by the interface conditions between different layers. The aim of this literature review is to study and compare the different types of the UHI-R pavement systems, and to gather the properties required to study the bonding performance of their interface. The reviewed papers are grouped into four families according to the type of the studied pavement solution, namely highly reflective, permeable, thermally modified, and energy harvesting pavement systems. These families are critically compared according to their durability, efficiency, and cost. This paper shows example ranges of the thermal properties of UHI-R pavements. Finally, the literature review confirms the need to characterize the thermo-mechanical and mechanical properties of the recent UHI-R pavement systems to improve and optimize their bonding performance to enhance their durability.

**Keywords:** Urban heat island, pavements, durability, review

### 1 Introduction

Climate change has already shown significant effects on the environment. As the scientists predicted in the past, more intense heat waves are now occurring. The intensity of heat waves on cities is strongly linked to the formation of Urban Heat Islands (UHI) [1]. UHI effect, first observed by Luke Howard in 1833, refers to the significantly higher temperatures in urban areas compared to the surrounding rural ones [1, 2].

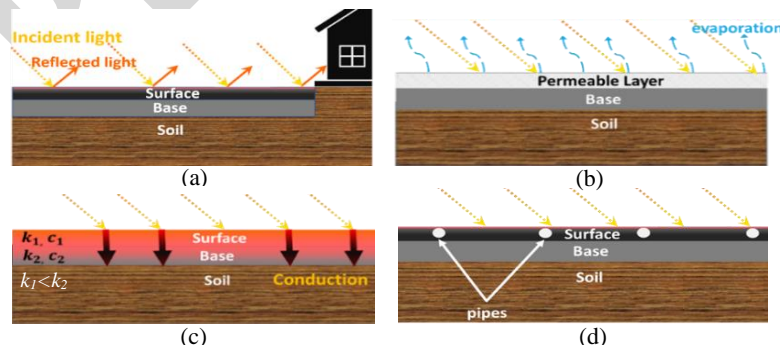
According to Stewart [3], UHI was first defined by Pepler in 1929 [4]. This rise in urban temperatures leads to an increase in the number of deaths, cooling energy demand, and air pollution in cities [5]. In the USA, some studies reported the death of more than

1300 person per year due to the extreme heat [6]. UHI occurs due to urbanization, like replacing the natural land cover by pavements [7] and buildings [8], and other surfaces that absorb, retain, and emit heat [9]. For example, asphalt, which is a common pavement surfacing material, is characterized by its potential to have high surface temperatures during summer [10]. As UHI is increasing with time, many countries including Belgium, China, France, India, Japan, Spain, United Kingdom, and USA are working to reduce it [5, 9–15]. Several solutions have been proposed, such as, increased vegetation, modified urban land-use, and UHI-Reducing (UHI-R) pavements [1]. In this paper, pavements that help lower UHI, including “cool pavements” [1, 16, 17] are referred to as UHI-R pavements. UHI-R pavements succeeded to reduce pavement surface temperatures up to 28 °C.

UHI-R pavements are multi-material systems having different mechanical, thermal, and thermo-mechanical properties. Obviously, the mechanical behavior of these multi-materials linked to temperature, moisture, traffic load and speed may have an influence on their interlayer bonding [18]. Interfaces within multi-material pavements are weak links, mismatching thermo-mechanical and mechanical properties can lead to high interfacial stresses and pavement degradation [19]. To optimize the durability and the resiliency of UHI-R pavement systems, their interface bonding response needs to be investigated. To that aim, the effect of varying the UHI-R pavement properties have to be studied according to bonding performance of interface. This paper presents a literature review of UHI-R pavement types and their thermal properties. The first section presents four families of UHI-R pavements, classified by their mechanisms. The second section of this paper shows examples of the ranges of UHI-R pavement thermal properties. Finally, this paper presents the knowledge gaps that need to be filled to make UHI-R pavement systems durable and sustainable.

## 2 UHI-R pavements

The following sections presents the pavement systems used to mitigate UHI. The different types of UHI-R pavements studied in the literature are grouped into four families according to the different mechanisms used to reduce UHI (Figure 1) [15].



**Figure 1.** UHI-R pavement families [15] a) Highly reflective pavements, b) Permeable pavements, c) Thermally-modified pavements, and d) Energy harvesting pavement systems

## 2.1 UHI-R pavement families – on the basis of literature

To improve the durability of UHI-R pavements, it is essential to understand their types, advantages, and limitations. This section presents the four families of the UHI-R pavements that have been discussed in the literature. In preparing this classification, the recent UHI-R pavements discussed in more than 160 relevant articles were reviewed, only a limited number is cited in this paper due to space limitations. The cited literature has been selected to be able to describe the classified families, and to document pertinent thermal properties that will be used in the subsequent modelling efforts.

**Family I - Highly reflective pavements (HRP).** Albedo is the ratio between received and reflected radiation. As pavement albedo increases, more solar radiation is reflected into the atmosphere, resulting in a decrease in surface temperatures (Figure 1.a). Li et al. [7] have shown an increase of 0.1 in albedo of pavements can lead to a reduction of 6 °C in pavement surface temperatures. To increase the albedo of pavements, the first way is to cover the surface of pavements by light colored coatings [20]. Pavements' albedo can be increased by using light-colored binders or aggregates in the asphalt. Lopez-Cabeza et al. [5] showed that light-colored pavements can reduce surface temperature by 23.7 °C compared to dark ones. Dark colored near-infrared (NIR) reflective pigments have been used to avoid the drawbacks of light-colored pavements (such as color aging due to tire imprints). Liu et al. [17] studied a dark NIR-reflective coating that succeeded to reduce surface temperatures by 15.5 °C compared to asphalt pavements. Moreover, to avoid reducing the pavement temperatures in cold winters (Table 1), thermochromic pavements have been studied. Thermochromic materials undergo a reversible color change from dark to lighter color at high temperatures. Zhang et al. [10] have shown that reversible colored thermochromic pavements can achieve 10.5 °C reduction in surface temperature.

**Family II - Permeable pavements (PP).** Permeable pavements have succeeded to decrease surface temperatures by enhancing the evaporation process [21]. Rather than releasing absorbed solar heat directly, it is released as latent heat through the process of water evaporation (Figure 1.b). Porous pavements can be constructed by increasing the percentage of large aggregates or reducing that of fine aggregates in pavement [1, 22]. Interlocking concrete pavements can also be used [16]. The presence of abundant surface water or moisture is crucial for the cooling effect of permeable pavements. A permeable concrete pavement studied by Chen et al. [23] succeeded to reduce the surface temperature by more than 10 °C compared to concrete pavement after irrigation. Additionally, water-retaining pavements that store water close to the surface can improve the cooling efficiency. This can be achieved through sealing the bottom and sides of pervious concrete slabs [24].

**Family III - Thermally-modified pavements (TMP).** Thermal properties related to heat transfer inside the pavements can affect their surface temperatures. Increasing the thermal conductivity ( $k$ ) aims to transfer the surface heat to lower pavement layers (Figure 1.c). Aggregates, air voids, binder additives, and fillers can be modified to increase thermal conductivity. This can be done using aluminum oxide powder, carbon fibers, graphite powder, quartzite aggregates, or steel fibers [9, 11, 25, 26]. ShengYue et al. [9] showed that modifying the thermal conductivity of asphalt can lead to a 6.2 °C

reduction in surface temperatures. In addition, phase change materials can be used to store thermal energy in the form of latent heat [1].

**Family IV -Energy harvesting pavement systems (EHP).** This family is based on including pipes that contain circulating liquid (e.g. water) to harvest the heat energy (Figure 1.d). Mallick & Bhowmick studied an energy harvesting pavement system that reduced the surface temperature by 20 °C [27].

**Combinations of the different families of UHI-R pavements.** Several researches have studied combinations between the different UHI-R pavement families [20]. Increasing the thermal conductivity of permeable concrete pavement improved its cooling efficiency by 1-3 °C [23]. Combining the different families have many future studying possibilities [1]. Table 1 summarizes the reported pavement surface temperature reductions, additional advantages, and limitations of each UHI-R family illustrated in Figure 1.

**Table 1.** Reported pavement surface temperature reduction, additional advantages and limitations of UHI-R pavement families.

Family	References	Temperature Reduction	Additional Benefits	Limitations
I. HRP	[20] [12] [5] [10] [7] [17] [16]	4–25 °C	Can act as sealing (preservation) layer	<ul style="list-style-type: none"> <li>• Loss of color with time.</li> <li>• Surrounding buildings may absorb the reflected light, increasing UHI.</li> <li>• Lower thermal comfort for people and animals near pavements due to reflected light.</li> <li>• In winter, increased risk of low temperature cracking.</li> </ul>
II. PP	[24] [14] [22] [29] [21]	5–28 °C	Mitigate noise and can help lower impacts of floods	<ul style="list-style-type: none"> <li>• Need water to cool, which induces moisture damage.</li> <li>• Have higher surface temperature in dry conditions.</li> <li>• Pore clogging can occur at high traffic loads and due to vegetation causing inefficiencies.</li> </ul>
III. TMP	[11] [9] [28] [26]	1.2–17.5 °C	Reduce rutting potential of asphalt	<ul style="list-style-type: none"> <li>• Heat stored in pavements during daytime, causing remission of the heat during nighttime.</li> <li>• In cold regions, the heat transmitted to soil may cause thawing of permafrost beneath highways.</li> </ul>
IV. EHP	[27] [1]	Up to 20 °C	Possibility of harvesting energy	<ul style="list-style-type: none"> <li>• High initial and maintenance costs.</li> <li>• Most systems are non-recyclable.</li> <li>• High potential of voids between pipes and asphalt mixture resulting in risk of debonding.</li> </ul>

## 2.2 Thermal Properties of UHI-R pavements

To improve the durability of UHI-R pavement systems, it is essential to evaluate the effects of varying properties of multi-material pavement layers on the interface. To conduct such evaluations, the possible ranges of thermal, thermo-mechanical, and mechanical properties for UHI-R pavement need to be collected. This section presents examples of the thermal properties of UHI-R pavements gathered from literature review. The following selected properties have been modified in literature to enhance the thermal performance of these pavements [1]. While the thermal conductivity ( $k$ ) controls the rate of heat flow within a pavement, the emissivity ( $\varepsilon$ ) describes the amount of heat emitted from a pavement to its surroundings, and specific heat capacity ( $c$ ) quantifies the amount of required heat to raise the temperature ( $T$ ) of a one-unit weight of material by 1 °C.

**Family I-HRP.** Since highly-reflective pavements are based on increasing albedo, only a few studies on their thermal properties are found, these are summarized in Table 2.

**Table 2:** Examples of the thermal properties of family I - HRP

Material	Ref.	Albedo	$k$	$\varepsilon$	$c$	$\rho$	$e$
PerfectCool-Dark	[17]	0.19	0.25	0.83	-	-	0.06
PerfectCool-Light	[30]	-	0.25	0.69	-	-	-
Red asphalt	[20]	0.27	-	-	-	-	0.50
Yellow asphalt	[20]	0.40	-	-	-	-	0.50
Concrete	[31]	0.45	1.69	0.94	1150	1800	10.00
Beige asphalt	[20]	0.45	-	-	-	-	0.50
Off-white asphalt	[20]	0.55	-	-	-	-	0.50
White concrete	[5]	0.85	1.63	0.96	-	-	-

Ref.: Reference,  $k$ : Thermal conductivity (W/(m.K)),  $\varepsilon$ : Emissivity,  $c$ : Specific heat capacity (J/(kg.K)),  $\rho$ : Density (kg/m<sup>3</sup>),  $e$ : Thickness (10<sup>-2</sup>m)

**Family II-PP.** Table 3 shows examples of the thermal properties of permeable pavements. Permeable pavements usually have low thermal conductivity due to their high air void content.

**Table 3.** Examples of the thermal properties of family II - PP

Material	Ref.	AV	$k$	$\varepsilon$	$c$	$\rho$	$e$
Pervious ceramic bricks	[21]	20 <sup>P</sup>	0.48	0.87	800	1866	6.0
Pervious concrete	[21]	23 <sup>P</sup>	0.68	0.88	800	2105	6.0
Porous asphalt	[14]	30	2.00	0.99	900	2157	3.0
	[29]	-	0.40	0.91	800	2146	5.1
	[16]	-	1.23	0.80	798	2200	20.0
Porous asphalt rubber	[13]	18	0.51	-	664	2004	7.5
	[13]	8	0.77	-	863	2310	7.5
Porous concrete	[23]	27	0.59	0.90	997	1820	10.0
	[22]	25	1.20	0.92	840	1812	15.0

AV: Air void content (%) (<sup>P</sup> represents measurement as open porosity)

**Family III-TMP.** Table 4 shows examples of the thermal properties of thermally modified pavements. Some solutions are formed of multi-modified pavement layers.

**Table 4.** Examples of the thermal properties of family III - TMP

Layer - Material		Ref.	% <i>f</i>	<i>k</i>	<i>c</i>	$\rho$	<i>e</i>
Top - Asphalt + Quartzite (Q)		[11]	100 <sup>V</sup>	2.47	870	2314	10
Multi -	Top - Asphalt + Al <sub>2</sub> O <sub>3</sub>	[9]	10 <sup>m</sup>	1.14	1101	2452	2
Layered	Middle - Asphalt + Gr	[9]	10 <sup>m</sup>	1.20	1067	2422	3
System	Bottom - Asphalt + Gr	[9]	15 <sup>m</sup>	1.25	1004	2425	4
Multi -	Top - Asphalt + Q	[26]	50 <sup>V</sup>	3.026	911	2421	4
Layered	Middle - Asphalt + Q	[26]	75 <sup>V</sup>	3.375	934	2417	5
System	Bottom - Asphalt + Q	[26]	100 <sup>V</sup>	3.650	914	2394	6

*Gr*: Graphite powder, %*f*: Percentage of the modifying material (<sup>V</sup>: by volume of aggregates, <sup>m</sup>: by mass of the mix)

**Combinations of families.** Table 5 shows examples of the thermal properties of combinations of UHI-R families.

**Table 5:** Examples of the thermal properties of combinations of families

Family	Layer - Material		Ref.	% <i>V</i>	<i>k</i>	<i>c</i>	<i>e</i>
I + III	Multi-	Top: Asphalt + Floating bead	[28]	15	0.65	1542	4
	Layered	Middle: Asphalt + Graphite	[28]	5	1.11	1322	6
	System	Bottom: Asphalt + Graphite	[28]	10	1.18	1257	8
II + III	Top: Permeable concrete + steel fibers		[23]	1.5	0.84	978	10

%*V* = Percentage of the modifying material by volume

### 3 Summary, Conclusion and Future Outlook

This review paper presents the Urban Heat Island-Reducing (UHI-R) pavement types with examples of their thermal properties. The literature review showed that the UHI-R pavements can be grouped into four main families according to the mechanisms used to reduce surface temperature: Highly-reflective pavements (HRP), thermally-modified pavements (TMP), permeable pavements (PP), and energy harvesting pavement systems (EHP). Each family presents its own advantages and limitations. Although all the families can lead to a significant reduction in surface temperatures, there are substantial limitations associated with each. For example, HRP can reduce the thermal comfort of citizens, PP require large amounts of water to achieve temperature reductions, TMP may induce UHI at night, and EHP are expensive solutions.

Mismatching properties of the multi-material pavements leads to very high stresses and strains at their interfaces [19]. To improve the durability of UHI-R pavements, it is important to study the effect of varying their properties on the interface behavior. This paper presents ranges of the necessary thermal properties to study the interface response of the UHI-R pavements (Thermal conductivity, heat capacity, and emissivity). The conducted literature review showed that there is a need to characterize the thermo-

mechanical and mechanical properties of the recent UHI-R pavements to optimize the bonding performance of their interfaces.

Following this review, the authors have initiated experimental studies to characterize the necessary thermo-mechanical (such as, thermal dilatation coefficient) and mechanical properties of the different UHI-R pavements. In parallel, finite element modeling has been initiated to model the interface response. Using the outcomes of this review and the experimental characterization of the needed UHI-R pavements' properties, a parametric study to optimize their bonding performance will be conducted.

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